MODELING OF RIVER-AQUIFER INTERACTIONS: A TOP-DOWN APPROACH

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

HARISH KUMAR S

145006AM14F02

DEPARTMENT OF APPLIED MECHANICS AND HYDRAULICS

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE – 575 025

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Under the guidance of
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DECLARATION

By the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled **"MODELING OF RIVER-AQUIFER INTERACTIONS: A TOP-DOWN APPROACH"**, which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in the **Department of Applied Mechanics and Hydraulics** is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Place: NITK-Surathkal

Date: 23/08/2019

CERTIFICATE

This is to certify that the Research Thesis entitled **“MODELING OF RIVER-AQUIFER INTERACTIONS: A TOP-DOWN APPROACH”** submitted by **HARISH KUMAR .S** (Register Number: 145006 AM14F02) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.

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ACKNOWLEDGEMENT

With deep sense of gratitude, I express my heartfelt thanks to my research supervisor Dr. M. K. Nagaraj, Professor, Department of Applied Mechanics and Hydraulics, NITK for his invaluable guidance, encouragement and motivation throughout my research work. I am indebted to him for his wholehearted interest and keenness in every phase of research work and thesis preparation. His moral support, guidance, interactions, discussions and precious suggestions have greatly helped me to complete this research work. It has been my greatest opportunity and pleasure to work under him. His crucial comments have guided me to publish my research work in acclaimed International Journals. I am grateful to Prof. Amba Shetty, Head of the Department of Applied Mechanics and Hydraulics, NITK, Surathkal for her continuous support during the thesis review communication process, viva-voce conduction as well as many help provided by her throughout my stay at NITK campus.

I acknowledge my sincere thanks to Research Progress Assessment Committee members, Prof. Subhash Yaragal, Dept. of Civil Engineering and Dr. Manu, Dept. of Applied Mechanics and Hydraulics for providing valuable suggestions, comments and encouragement at various stages of this research work.

I wish to thank former HODs of Department of Applied Mechanics and Hydraulics, NITK, Surathkal for their support and permitting me to use the departmental computing, laboratory facilities that helped in completing my research work. I am grateful to Prof. A. Mahesha, former Head of the Department for his indispensable help extended during the thesis submission process and further. I also extend my heartfelt gratitude to Prof. Lakshman Nandagiri, Prof. Paresh Chandra Deka, Dr. Pruthviraj and all the faculty members of Applied Mechanics and Hydraulics Department for their help and support.

My special thanks to Mr. Balakrishna, GIS Lab, who made sure that laboratory facilities were working fine all the time and helped me out whenever in trouble. My sincere thanks to Mr. B. Jagadish, Asst. Executive Engineer (Rtd.) and Seetharam Sir, Applied Mechanics and Hydraulics Department for their help in procuring data and department facilities. I am grateful for the help and co-operation rendered by non-teaching staff and office staff of Applied Mechanics and Hydraulics Department.

I gratefully acknowledge the emotional support and encouragement provided by my dear colleagues Mr. Praveen Kodalingana, Mr. PramodKumar Kappadi and other fellow lab-mates, who pushed me every time to walk extra-mile towards the goal. I am indebted to the support, technical suggestions and all the help rendered by Mr. Kiran Kumar L. Janadri and Mr. Anoop Shirkol, whose contributions during field data collection is incredible.

I extend my sincere thanks to Mr. H. P. Jayaprakash, Scientist-C and Staff of Central Groundwater Board (CGWB), South-west division, Bangalore for providing the groundwater and aquifer data that greatly helped me during the research. I am grateful to Mr. Subramanya, Assistant Engineer of Karnataka Public Works Department, Mangalore for sharing the hydrological data. I honestly thank Staff of Central Water Commission, Mangalore regional office and Staff of Mines and Geology Department, Karnataka, Mangalore Division for providing the necessary data. I am grateful to Mr. Ramesh Rai of Bellare village for allowing us to carry out pumping test in his house premises and Mr. Honnappa K., Sneha Electricals, Bellare for providing pump to conduct pumping test. In particular, I would like to express my gratitude to Mr. Kelu Maniyani, Bellare for being of such a great help during pumping test.

My special thanks to Dr. Bhojaraja B.E., Assistant Professor, NMAMIT, Nitte, a best friend of mine who stood by me throughout this journey with his support, suggestions and timely help extended at NITK. I would like to cherish the love and support shown by my Uncle Mr. Muralidhar K. S., Sub-divisional Engineer, BSNL, Kadri, Mangalore and Aunt Mrs. Geetha Muralidhar during my stay at NITK.

I am forever grateful to my father Sri. M. Subramanya Chari, mother Smt. Nirmala Subramanya Chari and my elder brother Mr. Roopesh Kumar who provided me the best available education and encouraged in all my endeavors. I am grateful to my wife Mrs. Suneetha, who has been influential in motivating me in this journey with her moral support and cooperation. I lovingly acknowledge the moral support and help extended by my best friends during this journey. Their informal support and encouragement has been very crucial. I am grateful to everybody who helped and encouraged me during this research work.

HARISH KUMAR .S

Dedication

I dedicate this thesis to my beloved parents, my kind-hearted
elder brother and my caring wife,
for their eternal love
&
My dearest Cousin Late R. Mithilesh Kumar,
who stays in my heart forever

Along with those close to my heart
Family members and Friends

ABSTRACT

Surface water interacts with groundwater in many types of physiographic and hydro-geological conditions. The heterogeneity in hydrological processes over a catchment affects the location, time and extent of interaction phenomenon. Exchange of water varies spatially and temporally due to the effect of natural and anthropogenic factors. It is essential to identify and quantify the surface water and groundwater (SW-GW) exchange, since the quantity and quality of these resources affect each other. The SW-GW interactions are characterized at various scales of flow systems such as regional, intermediate and local scale. Driving forces influence the SW-GW exchange depending upon different flow scales but the challenge of the present research is to bring out its relevance. In the past, studies related to SW-GW interactions using integrated models are not dealt in detail for smaller scales. Small-scale processes may seem insignificant when accounted for a larger perspective of consideration. Therefore, an effort is put to analyze the effect of driving forces on a larger scale and a small scale in the present study. The objective of the present study is to investigate the surface water and groundwater interactions at two different hydrological extents of a catchment. The present study proposes a new approach based on the top-down hierarchy from regional scale to sub-catchment scale to assess the SW-GW flux. For the regional scale study, Nethravathi basin is chosen whereas for the intermediate scale, sub-catchment of Gowri-hole, a tributary of Nethravathi River is considered. In this study, river-aquifer interaction processes are simulated by using RIVER package of MODFLOW for an unconfined aquifer system. A regional groundwater flow model is built as a pre-requisite to identify the dynamic exchange occurring over the catchment area using potentiometric maps and flow budgets. In the present study, a MODFLOW-based regional groundwater model was simulated under steady-state condition for a calibration period of 2004 - 2009 and validation period of 2010 - 2011. The calibrated model was validated using the observed groundwater level data of 15 open wells measured by Department of Mines and Geology, Government of Karnataka. The simulated regional groundwater model is in good agreement with most of the wells reasonably matching the observed and computed groundwater heads. It shows that the simulation of regional groundwater model is reasonable and well suitable for the studies related to SW-GW interactions. In the present study, intermediate scale model for the Gowri-hole sub-catchment was calibrated for transient analysis from June 2004 - May 2010 with a daily step input. Automated Parameter Estimation analysis was carried out to get better results from the study. The calibrated model was validated from June 2010 - October 2012 for two monthly observation wells of Department of Mines and Geology and one seasonal observation well of Central Ground Water Board (CGWB). Groundwater heads gradually increase from June - August with the arrival of monsoons and decline significantly from September upto the month of May. Groundwater swelling is noticed near Well No. 3 of Bellare village in the month of October. River leakage decreases from 10 – 11 % in June to 4 – 5 % in July with the commencement of peak monsoon flows. It steadily increases from 12 – 14 % in September and continues to occur up to 41 – 42 % until the end of May. Aquifer discharge increases from 24 – 25 % in June to 34 – 35 % in July due to quick saturation during monsoon. From September, aquifer contribution into the river flow significantly decreases upto 9 – 10 % in May. The contribution of aquifer discharge into the river flow is consistent at the confluence points. Some parts of river segments are under the influence of aquifer discharge. However, majority of river segments are dominated by river leakage areas throughout the year. Consequently, Gowri hole acts as a Gaining River during monsoons due to aquifer discharge. And, it acts as Losing River due to river leakage throughout post-monsoon and summer months. SW-GW interactions are driven by aquifer parameters such as recharge rate and hydraulic conductivity. In the present study, these driving forces are calculated for the simulation of both the regional scale and sub-catchment scale groundwater flow model. During the calibration, the driving force values are adjusted until the model is simulated with a good match between computed and observed groundwater heads. The study identified that recharge rate is the driving factor influencing the SW-GW interactions at regional scale and hydraulic conductivity is the driving factor of sub-catchment scale SW-GW interactions.

Keywords: Surface water and groundwater interactions; Regional scale; Sub-catchment scale; Groundwater flow model; River leakage; Aquifer discharge.

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K_{xx} : Hydraulic conductivity values in the direction of Cartesian coordinates x

K_{yy} : Hydraulic conductivity values in the direction of Cartesian coordinates y

K_{zz} : Hydraulic conductivity values in the direction of Cartesian coordinates z

h : Potentiometric head

S_S : Specific storage of the unconfined aquifer

T : Time

V : Volumetric flux per unit volume and represents sources, sinks of water

L : Length of river feature in the modeled cell

W : Width of the river

B : Thickness of the river bed

K_{RIVER} : Vertical hydraulic conductivity of the riverbed material

Q_{RIVER} : Flow exchange between river and the aquifer

C_{RIVER} : Hydraulic conductance of seepage layer

H_{RIVER} : Head of the stream

R_{BOTTOM} : Bottom elevation of the seepage layer

Q : Discharge of water from the well

H : Depth of water in the well

G : Acceleration due to gravity

HP : Power required to withdraw the water

ABBREVIATIONS

SW-GW	:	Surface Water And Groundwater
MODFLOW	:	Modular Finite-Difference Flow Model
USA	:	United States of America
MSL	:	Mean Sea Level
GMS	:	Groundwater Modeling System
GUI	:	Graphical User Interface
LPF	:	Layer Property Flow
WEL	:	Well
RCH	:	Recharge
PCG	:	Preconditioned Conjugate Gradient
GEC	:	Groundwater resource Estimation Committee
PEST	:	Parameter Estimation
CGWB	:	Central Ground Water Board
GIS	:	Geographic Information System
SRTM	:	Shuttle Radar Topography Mission
GSI	:	Geological Survey Of India
CWC	:	Central Water Commission
KPWD	:	Karnataka Public Works Department
M&G	:	Mines And Geology
MOWR	:	Ministry Of Water Resources
GOI	:	Government Of India
SOI	:	Survey Of India
USGS	:	United States Geological Survey
RL	:	River Leakage
AD	:	Aquifer Discharge
DEM	:	Digital Elevation Model
ERT	:	Electrical Resistivity Tomography
GPR	:	Ground Penetrating Radar

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Groundwater is a vital fresh water resource available for potable use, agriculture, public and industrial requirements. It has many advantages over surface water in terms of quality, seasonal fluctuation and spatial existence. In many parts of the world, the groundwater reserves are facing a continuous threat to its quantity and quality due to poor management practices. The ever-growing increase in demand has led to the over-exploitation of these resources by means of excessive pumping. As a result, the decline in groundwater levels has resulted in streamflow depletion, loss of dependent ecosystems and land subsidence (Zektser and Lorne 2004).

The variation in storing up of groundwater resources is fundamentally dependent on rainfall, run-off and recharge processes. Accordingly, input to the groundwater systems originate from the surface water features through a permeable medium. The conductance of water from the river into the underlying aquifer mainly exists through the riverbed by means of riverbed conductivity. Depending upon the landscape, surface water tends to recharge the aquifers and excess groundwater discharges back to the surface (Kalbus et al., 2006).

1.2 SURFACE WATER AND GROUNDWATER INTERACTIONS

Surface water interacts with groundwater in many types of physiographic and hydro-geological conditions. The nature and degree of connection describes the scope of water availability in the systems (Kalbus et al., 2006). The heterogeneity in hydrological processes over a catchment affects the location, time and extent of interaction phenomenon. Flow exchange between surface water and groundwater across an area leads to upwelling or down welling of aquifers. The hydrological response of aquifer systems with that of surface water confines and characterizes the nature of connection. It also influences the structure and functions of connected ecosystem within and around (Valett and Sheibley 2009).

The surface water and groundwater (SW-GW) interactions are dynamic in nature. Water from an entity travels to the other one according to the variation in hydraulic gradient. It varies spatially and temporally due to the effect of natural and anthropogenic factors. Inconsistent climate and seasonal variability in precipitation influence the availability of water over a catchment area. Anthropogenic activities such as groundwater withdrawals, land use practices, etc perturb groundwater-river stage interface by varying the hydraulic gradients.

The exchange processes between surface and groundwater entities are complex to understand. Consequently, the interconnection remains poorly perceived in many catchments. It is necessary to be aware of the basic principles and mechanisms of interactions to understand the complexity involved (Ivkovic 2006).

1.2.1 Types of Interactions

Primarily, surface water and groundwater interactions are classified into three types (Winter et al., 1998):

1.2.1.1 River leakage

The percolation of surface water into the groundwater sources beneath through the riverbed is termed as river leakage. In this process, the water body acts as a losing stream/river since the groundwater table is below the bed elevation. Figure 1.1 gives a schematic representation of river leakage process.

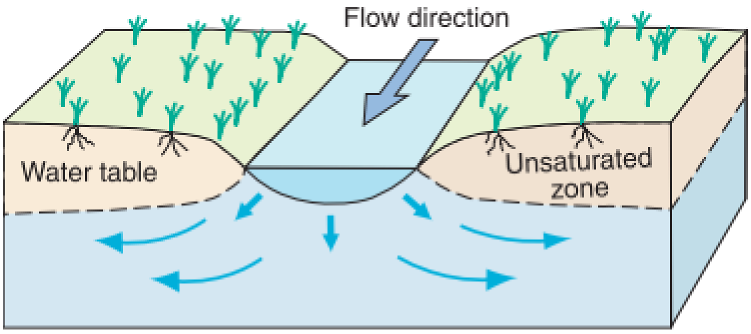


Figure 1.1 River leakage in an influent stream (Winter et al., 1998)

1.2.1.2 Aquifer discharge

The contribution of excess groundwater from unconfined aquifers to the river through riverbed is termed as Aquifer discharge. Here, the surface water body acts as gaining stream/river due to rise of groundwater table above the bed elevation. Figure 1.2 provides an illustration of the aquifer discharge into the river.

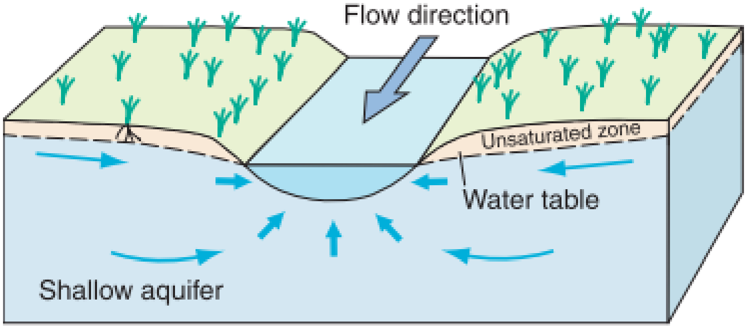


Figure 1.2 Aquifer discharge in an effluent stream (Winter et al., 1998)

1.2.1.3 Bank storage

When there is an unexpected flood event, river stage rises quickly and stores the excess water in the banks of the river as Bank storage. The groundwater table in the connected aquifer progressively increases above the bed elevation during flood. At a later period when the flood subsides, water stored in the sub-surface layers of the riverbank slowly return to the river flow depending upon the aquifer properties. Hence, river leakage and aquifer discharge both occurs sequentially in this process. Figure 1.3 demonstrates the bank storage occurring in this process.

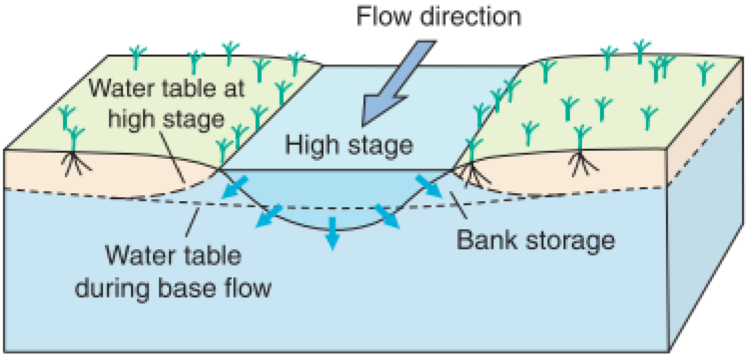


Figure 1.3 Bank storage in an influent/effluent stream (Winter et al., 1998)

Gaining streams/rivers are persistently connected with the groundwater resources underneath. Whereas, losing streams/rivers are either connected with the underlying aquifers through a saturated zone or disconnected with an unsaturated zone. Hence, losing stream can act as a disconnected stream, when it loses the capacity to flow by drying up resulting in fragmentation of the river regime. Although it doesn't qualify under the classification of interaction process, disconnected status is a significant topic to discuss.

1.2.1.4 Disconnected stream

Aquifer systems can be deep below the riverbed separated by a thick unsaturated layer. Such kind of surface water bodies tend to disconnect from interaction. They continuously leak water through the unsaturated zone but fails in sufficiently recharging the aquifer to reconnect. Figure 1.4 describes the disconnected status of a stream.

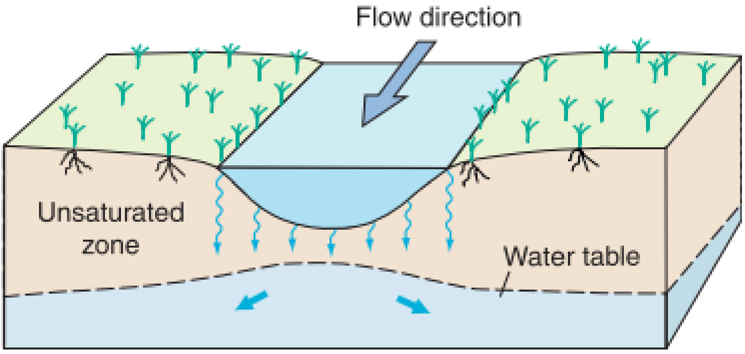


Figure 1.4 Disconnected stream (Winter et al., 1998)

1.2.2 Complexity and importance of interaction process

The hydrological nature of the connection is complicated by agricultural tasks such as groundwater pumping (Baalousha 2011), surface water diversion (Tian et al., 2015) and irrigation activities (Sanz et al., 2011). It further leads to flow variability in the river, which adversely affects the availability of water in the basin (Shekhar 2016).

The significance of interaction varies at different scales of the hydrological cycle. For regional/basin scale, the importance is evaluating the water availability whereas, for a sub-catchment scale, identifying the dynamic exchange of the water resources. In case of a reach/local scale, the concern would be to understand the groundwater exploitation at a local aquifer leading to stream depletion. The interactions occurring between surface water and groundwater resources are often difficult to observe and measure. Moreover, the quantity and quality of these resources affect each other due to the interconnectivity. Thus, it is essential to identify and quantify the dynamic SW-GW exchanges for sustainable management of water resources (Kalbus et al., 2006).

1.3 SCALE-BASED INTERACTION PROCESSES

Scale-based processes discover the direction and duration of flow paths in the riverbed and sub-surface layers. The duration of exchange process between unconfined or confined groundwater sources with the surface depends upon the residence time of water in the sub-surface. Factors such as geography, climate, soil classification, and hydrogeology influence the groundwater residence rate linked with surface water bodies. The residence time of water in the ground increases with the increase the extent of flow system (Dahl et al., 2007).

Scale-based interactions processes are regulated by the hydraulic conductivity of fluvial plain, the hydraulic gradient at the interface and alignment of stream channel. The direction of interaction changes with the hydraulic gradient whereas the flow exchange depends upon the river/stream bed conductivity. Sediment deposition and erosion processes in the flow regime of surface water sources affect the intensity of SW-GW interaction processes. When the stream channel is parallel to the alluvial plain, gaining, losing as well as parallel flows, occur. Parallel flows occur when groundwater and surface water heads are equal at the interface. When stream channel is perpendicular to alluvial plain, maximum flow exchange occurs through the reaches at one side of the bank where channels stage is below groundwater table. Flow exchange is less on the other side of the bank where the groundwater head is much below the channel bed (Sophocleous 2002).

1.3.1 Characteristics of interactions at different flow scales

Surface and groundwater interactions are characterized at various scales of flow systems such as regional, intermediate and local scale. The hydrological flow scales are classified according to the significance of scale-based interaction processes as presented in the Figure 1.5.

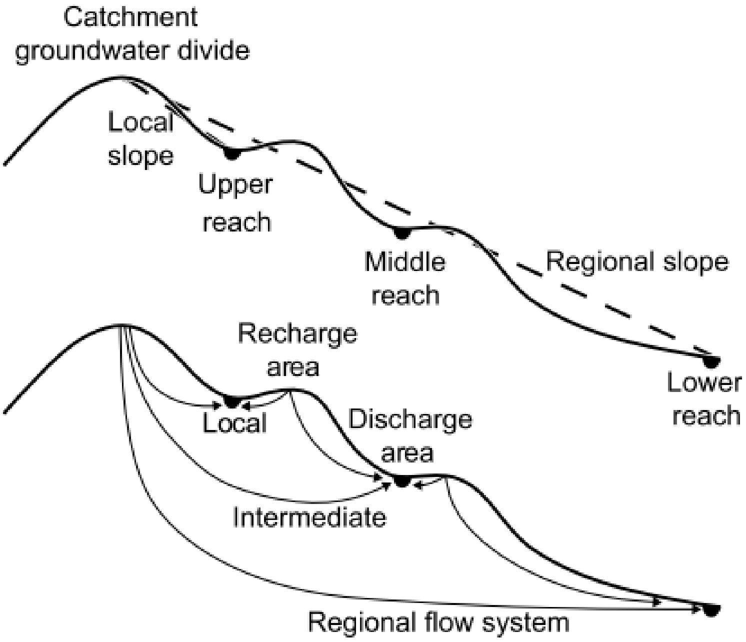


Figure 1.5 Classification of flow systems (Dahl et al., 2007)

Consequently, interactions are described based on the influence of prevalent surroundings on surface and groundwater entities.

Local flow systems are limited to a particular reach of the stream and its surroundings. The interactions may be subjective to floods or influenced by human activities affecting the locale. Daily or weekly changes in the river stage due to unprecedented natural/un-natural events affect the hydraulic gradient varying the flow exchange. In the reach/local scale, stream might leak into the aquifer in the upstream and again the discharge back into the streambed in the downstream depending upon the bed slope.

Intermediate flow systems allow the surface water sources to recharge the groundwater systems quickly because of shallow depth of space for the storage. The recharge rate is quick but the rate of aquifer discharge at this scale is slow and even become non-existent in summer season. The interaction process in this scale is monthly or seasonal due to unsteady exchange of flow between surface and the groundwater.

Regional flow systems allow the surface to recharge the groundwater at slower rate due to the consideration of enhanced aquifer extents. The exchange of water can occur in a decadal time-scale where surface water is resident in the sub-surface layers for years to recur to the surface. The aquifer discharge is slow but steady due to continuous flow exchange of groundwater with the surface along the vast flow path in the sub-surface (Dahl et al., 2007).

1.3.2 Significance of interaction processes at different flow scales

The interactions occur in surface and groundwater flow systems at different spatial scales of hydrological cycle. They are:-

1.3.2.1 Regional/Catchment scale interactions

When the catchment area is ≥ 1000 km^2, the model is referred to Regional scale. The interaction within the catchment varies with reference to space and time depending upon the surface and subsurface heterogeneity. The regional scale interactions cover the catchment processes which lead to change in volume, saturation and concentration of water above and beneath the surface. The environmental impacts on the socio-economic aspects are extensively associated with the regional scale of hydrology. Hence, an integrated approach is important for the effective management of water resources over the area.

1.3.2.2 Intermediate/Sub-catchment scale interactions

Intermediate scale is spread across an area ≥ 100 km^2. The interactions between a lower order river and the underlying aquifer at a small catchment are studied at this scale. Aquifer properties influence the residence time, which play a vital role in the temporal variation of flow exchange with surface water. Closed water balance is evaluated at the sub-catchment scale to analyze the SW-GW fluxes. The sub-catchment is a complex system due to variation of aquifer parameters with reference to different geological units. Yet it is a very essential hydrological space acquiring importance for the sustainable future of SW-GW resources. The characteristics of flow exchange are evaluated along the regime of the river flood plain in the sub-catchment.

1.3.2.3 Reach/Local scale interactions

Local or reach scale interactions are limited around an area ≥ 10 km^2. Essential interaction processes such as river leakage and aquifer discharge occurring through the riverbed are observed at the local scale. An in-depth interpretation of interaction event is possible with the hydro-geological data accompanied by field measurements. Since there is no definite area bounded by the river cross-section, closed water balance cannot be determined for a local scale. The interactions are relevant to the physical conditions of the aquifer and its properties affected by the surface and sub-surface processes (Barthel and Banzhaf 2016).

1.3.3 Relationship of SW-GW interactions at different scales

Daily, monthly, seasonal and inter-annual flow paths occur at different levels of fluvial hydrology. An enhanced physical view of the stream provides an opportunity for understanding the association in the hydro-geological context as represented in Figure 1.6.

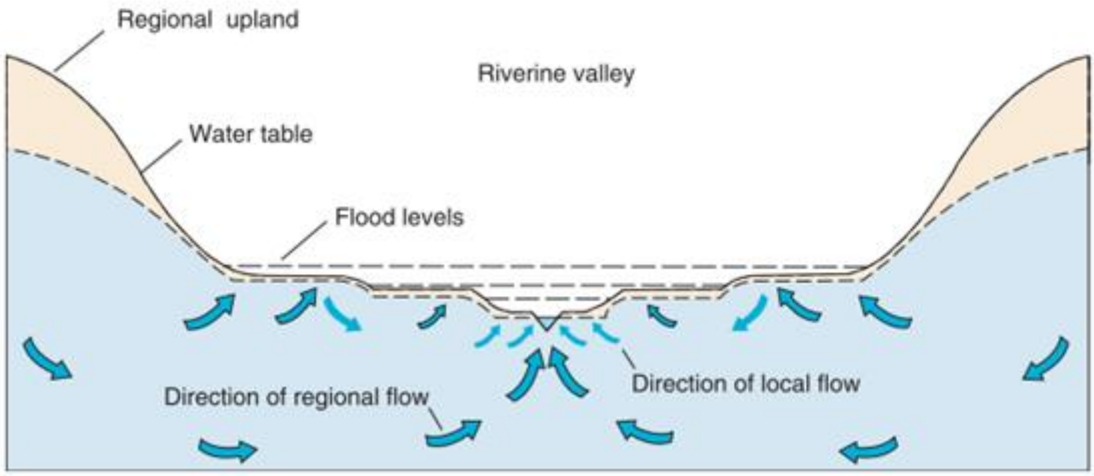


Figure 1.6 Local, intermediate and regional flow paths (Winter et al., 1998)

The river-aquifer interactions vary from the higher elevation to the valley due to the transition of runoff. However, interactions take place conceptually within a boundary layer at certain section of the fluvial channel. The depth of permeable streambed characterizes the boundary governing the SW-GW exchange. Change in stream flow, sediment deposition and erosion in the channel bed affects the scope of the interactions. Consequently, the flow pathways governing the exchange process are affected by the riverbed geomorphology. The main flow channel includes the critical flow paths of streambeds, sub-surface flow and riparian contributions. The significance of main channel depends upon the spatial characteristics of interactions in the river flood plain (Bencala et al., 2000). Monitoring and assessment of the exchange at different levels of valley morphology is crucial with reference to suitable watershed boundaries.

1.4 DRIVING FORCES INFLUENCING SW-GW INTERACTIONS

The characteristics of SW-GW interactions are driven by the functions of scale-based processes. Consequently, the scale-based processes that influence the occurrence of interactions constitute the driving forces. In general, driving forces are the factors that affect the temporal and spatial dynamics of flow exchange.

The common factors of influence are recharge rate, riverbed conductance, aquifer characteristics such as thickness, hydraulic conductivity and storativity. The driving forces may vary from scale to scale but the challenge of the research is to bring out its relevance. A detailed understanding of these factors over different scales is vital to analyze their impacts on interaction processes.

1.4.1 Regional-scale driving forces

Regional-scale driving forces are rainfall recharge, river flow and groundwater movement and recharge. These prevalent processes occur within the area of interest but practically far away from the location of interaction phenomenon. Regardless of the distance, they play a crucial role in affecting the flow variability of SW-GW resources within a closed system. Heterogeneity in the stream and aquifer characteristics manages the extent of interaction in the sub-surface feature of the hydrological divide.

1.4.2 Sub-catchment scale driving forces

The sub-catchment scale driving forces are aquifer properties namely hydraulic conductivity and storativity of the hydro-geological setting besides the interface. Low flows in rivers are often regulated with aquifer contributions governed by riverbed hydraulic properties. Spatial distribution of aquifer heterogeneity influences the interaction processes at the riverbed. The extent of aquifer characterization in the saturated depth of sub-surface directs the significant exchange in aquifer volumes.

1.4.3 Local-scale driving forces

The driving forces affecting the local scale SW-GW interactions are riverbed conductance and hydraulic gradient existing at the riverbed-aquifer interface. The interaction occurring at the fluvial channels of the stream alter the geo-morphological and topographical conditions of the streambed. Geo-morphological characteristics such as channel bed slope, cross-section, river sinuosity, fluvial processes, and bed lineament determine the flow exchange in the streambed (Bencala et al., 2000).

1.4.4 Significance of driving forces

Over the years, interaction processes haven’t been addressed exclusively on the factors affecting the phenomenon at various levels of a catchment. Regional scale possesses importance when observed entirely at a larger scale than closely at a smaller area of influence. The small-scale processes may seem insignificant when accounted from a larger perspective. Nevertheless, local-scale driving forces ascertain a greater accuracy in determining the nature and extent of SW-GW exchange. The challenge is regarding the scope of importance of the specific area under consideration. Hence, in order to analyze the effect of driving forces at a smaller scale from a larger perspective, top-down approach is employed in the present study. The present study is carried out to establish and associate the relevance of driving forces across different levels of hydrological scales.

1.5 MULTI-SCALE MODELING OF SW-GW INTERACTIONS

The interconnection between surface and groundwater resources is well distinguished at different hydro-geological settings and scales. However, simulating the interaction mechanism is a challenge because of the complication that exists at multiple spatial and temporal scales. The development of new conceptual framework for modeling at multiple scales is a major research task in the present day context.

1.5.1 Multi-scale Modeling Process

Scale-based exchange processes are more relevant to the spatial extents that are considerably smaller than that of regional importance. The interpretations of local scale interactions are restricted to the extent of local scale hydrological processes. The results obtained from local scale interaction studies are difficult to be extrapolated into a larger scale of river basin. However, the conjunctive management of the water resources are carried out atleast at the catchment level. It remains unresolved to select a suitable technique to convey the knowledge of local scale processes into a broader scope.

In this regard, many efforts have been made in the past to upscale or downscale the model with the help of field data. Upscaling process corresponds to the generalization of suitable model parameters from a smaller area to a larger area of study. However, the disadvantage of the upscaling process is that it decreases the severity and seriousness of the problem and this may deviate from the original focus. For example, the stream depletion due to continuous drawdown from a local aquifer may not be of regional or national importance. Downscaling refers to the attenuation of the larger magnitude model parameters into a smaller domain of concern. The governing equations applied to the small-scale interactions may not be suitable to recognize the hydrological responses of larger scale interactions due to spatial heterogeneity (Barthel and Banzhaf 2016). Hence, an alternative approach is necessary for having better comprehension on the importance of interactions at different scales.

1.5.2 Top-Down Modeling Approach

A methodology namely, top-down modeling approach based on numerical model is proposed for the assessment of river-aquifer interactions at multiple-scales of a river basin that involves proper understanding of the physical processes. However, the technique utilized in the present study is revised from the field data-driven top-down approach (Ivkovic 2009) which doesn’t consider acknowledgement of concerned physical processes. The approach helps to understand the significance of interactions in the larger catchment area perspective first and then scaling down to comprehend the relevant intermediate/local scale for evaluating the surface water and groundwater exchange. Based on significance, occurrence, and data availability, the interactions are assessed in a hierarchically downward scale of river basin from catchment to reach/local scale. Accordingly, the interactions are studied at suitable scales of the catchment that are left unevaluated for flow exchange.

One of the basic features of the top-down modeling approach is to analyze SW-GW interactions sequentially from regional to reach/local scales. The approach improves the efficiency with reference to the assessment of interaction in a river basin. GW–SW exchange volumes are evaluated using the catchment-scale hydro-geological data. Specifically, these data examine the groundwater contribution to the river regime and river leakage into the aquifer. Suitable areas are selected for improved interpretation at the sub-catchment scale. Potentially significant SW–GW exchange locations in a sub-catchment are identified using the sub-surface heterogeneity data. The assessment is compared using reach-scale estimates of groundwater contribution into the river with that of field data.

1.6 CLOSURE

GW–SW interactions play a significant role in understanding the complexity of hydrological cycle at different scales. One of the main concerns from the water resources point of view is to assess the water-balance component of a hydrological cycle where stream-aquifer interactions play a significant role. Several driving factors and scale effects are the research concern in order to evolve an efficient management strategy for a basin.

The conjunctive decline in both the SW-GW resources due to the interconnection tends to affect the water security and management policies. In addition, the exchange of flow has the potential to change the physiological, biological and ecological conditions of the landscape. An integrated approach of considering both SW-GW resources in a river basin is required to analyze the impacts of these factors.

For the broader perspective on interactions, a detailed understanding of hydrological processes over different scales, associations, characteristics and variability is essential. The primary knowledge of interaction processes between surface water and groundwater systems is derived from hydrological cycle An easily understandable approach based on fundamental concepts is necessary to highlight the significance of interactions. Depending upon the applicability, it is realistic to choose an approach for specific characteristics or specific circumstances of the region.

Due to the variation in the hydrological processes of a basin, the evaluation of SW-GW interaction in all spatial scales remains indefinite. Consequently, an effort is required to assess the SW-GW interactions at different spatial and time scales of a river basin, incorporating the hydrological heterogeneity. The impact of smaller scale interactions on a river basin is essential to be analyzed to determine the influence of interactions on various aspects of environment.

The aim of the present study is to evaluate interactions at different scales of river basin and to establish the significance of driving forces using top-down approach. An effort is also made to demonstrate the application of multi-scale approach in a river basin. The approach provides a framework to resolve the complication in simulating the interactions in different spatial and time scale. The current research identifies the relevance of the scale-based interaction processes in a better perspective.

1.7 ORGANIZATION OF THE THESIS

Chapter 1 presents introduction to the concept of surface water and groundwater interactions and its characteristics. The significance of interactions at different spatial scales, impact of driving forces, multi-scale modeling of interactions are discussed.

Chapter 2 reviews literature related to the assessment of interactions at different flow scales. A brief summary of literature followed by identified research gaps and framed research objectives are presented.

Chapter 3 provides detailed methodology framed to achieve the research objectives. The selection of suitable numerical model based on governing equations and the new approach followed in the present study to analyze interactions are discussed in detail.

Chapter 4 focuses on the model development process for Nethravathi basin supported by data collection and analysis. The steps involved in building the conceptual model followed by model calibration and validation are presented.

Chapter 5 presents the application of conceptual model for the Gowri-HoLe sub-catchment with relevant hydro-geological data. The boundary conditions, model calibration, validation with simulation and error statistics of the model are discussed.

Chapter 6 presents the investigative results of regional scale interactions and sub-catchment scale models derived from groundwater head fluctuations. The analyses of interactions temporal and spatial pattern of interactions followed by its characteristics at different river segments of Gowri-HoLe are presented.

Chapter 7 is devoted to presentation of the conclusions drawn from the research. Important findings based on the interpretation of the results are listed.

In order to achieve at the objective of research, literature focused on selected themes and presented in the following chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

In recent times, the hydrological significance of surface water and groundwater interactions has acquired a renewed research interest. A broad spectrum of literature is published in the context of surface water-groundwater association. Sophocleous (2002) provided a good state of the art review covering various aspects such as principles, mechanisms, and impacts of interaction processes.

There is a great scope for research on SW-GW interactions at different hydrological scales of a river basin. The hydrological processes are subjected to various anthropogenic and non-anthropogenic issues at any spatio-temporal extent of a hydrological divide. Factors such as change in random climate setting and extreme weather conditions may affect the river basin at catchment and sub-catchment level. The excessive groundwater pumping or other human activities may have an effect on the basin at watershed and local setting.

Most researchers have agreed upon the fact that integrated management of water resources is essential at a basin scale. Yet, the human and environmental relationship extensively developed at the regional scale is linked with the local hydrological events. Among them, interaction between surface and groundwater entities at multiple-scales of a river basin is a distinct topic of research focus. However, the prospective challenges associated with respective scales are addressed independently for that particular area of focus.

In the past, much of the research was concerned with the local and regional issues lacking consideration of fundamental processes involved. Little research has been carried out focusing solely on the interaction phenomenon using basic concepts at a regional scale with field/local observations. There is a need for an integrated approach with the physical understanding of both surface water and groundwater reserves at various levels of catchment to manage both of them sustainably. The major concern of current research is to determine the impact of flow parameters on SW-GW interconnection at different hydrological scales.

2.2 QUANTIFYING THE SW-GW INTERACTIONS

There are different methods and approaches available for quantifying the interactions depending upon dimension, volume and duration. However, estimating the SW-GW flow exchanges faces a major hurdle due to hydro-geological heterogeneity and scale issues. Previously, various methods were followed to characterize the river-aquifer systems at separate scales leading to uncertainty in the results. Many efforts were made in the recent years to approximate the interactions from relatively straightforward analytical methods to complex numerical solutions. Depending on the purpose of the study, suitable techniques were adopted for the respective spatial and temporal scales (Sophocleous 2002; Kalbus et al., 2006).

Even though the field investigation studies give the actual estimate of both GW-SW components, employing them alone are expensive and inconsistent. Accordingly, many authors suggested comparison of direct flux measurements with numerical estimates to reduce the uncertainties (Kalbus et al., 2006; Hatch et al., 2010). These methods include field measurement techniques such as streambed piezometers, differential streamflow measurements and temperature as groundwater tracers.

A remarkable effort has been put in the last decade to develop combined methods to estimate SW-GW flux that varies with time and space. Among them, coupled models are highly desired ones for the integrated study of water resources. Coupled modeling approach improves the efficiency of the model by reducing the size and incorporating only necessary functionalities. Several categories of coupling approaches were attempted along with numerical models to analyze GW-SW interactions. The categories consist of fully coupled, semi-coupled, sequential and integrated modeling. The combined approach provided substantial insight into the complexity of the hydrological connection (Barthel and Banzhaf 2016).

Both analytical and numerical methods have been continuously improved to simulate the observed hydraulic head condition convincingly. Yet, previous studies have demonstrated the limited applicability of experimental and analytical methods to different scales (Kalbus et al., 2006). Analytical approaches are easily applicable for the standard situations rather than complicated circumstances. Numerical solutions are largely used since analytical solutions do not consider the entire complexity of the system. Numerical models are appropriate to simulate complex scenarios of influence of sensitive parameters on sub-surface heterogeneity (Griebling and Neupauer 2013).

Earlier, researchers utilized several numerical models for analyzing interactions at various environment, geography, climate and geomorphology. Most studies have applied one-dimensional hydrological models to describe the nature of flow exchange. Until year 2000, models were not capable of simulating the local interaction phenomenon very precisely. Various studies have been carried out to assess interactions at individual scales of catchment using numerical modeling. Yet an integrated approach hasn’t been applied for assessing SW-GW interactions across all dimensions of a river basin using a stand-alone numerical model.

The numerical model MODFLOW (McDonald and Harbaugh 1988) is an extensively used finite-difference model for addressing flow problems of GW–SW systems. It is one of the best tools for understanding the responses of river and aquifer systems with time in the context of anthropogenic water use. There are less detailed studies carried out focusing the investigation of SW-GW interactions using a numerical groundwater flow model. MODFLOW is capable of modeling the interaction at different scales, based on scale-based sub-surface heterogeneity data.

Many researchers demonstrated the applicability of the RIVER package of MODFLOW for simulating the river-aquifer relationship at local/reach scale, sub-catchment/intermediate scale, and catchment scale/regional scale. Modeling of interaction studies using MODFLOW gained significance in the pretext of groundwater budget. Dynamic flow exchange values obtained from flow budget proved to be very sensitive to groundwater level fluctuations due to increased groundwater abstraction. Although some conclusions were qualitative, the river-aquifer relationships were confirmed to exist from the interpretation of flow budget values. MODFLOW was used to investigate the occurrence and verify the estimate of river-aquifer flow exchange with the help of gauged streamflow measurements. Past studies efficiently illustrated the spatial and temporal variations of the interaction using MODFLOW. Henceforth, MODFLOW proved as a useful tool to evaluate, quantify, predict and characterize the complex groundwater-surface water interaction dynamics.

In order to understand the recent status of research on above issues, a detailed literature survey was conducted from 1994 – 2018 for the present study and discussed in the following 4 categories:

2.2.1 Regional-scale modeling using MODFLOW

Aradas and Thorne (2001) investigated the groundwater induced flooding and water-logging for Rio Salado catchment, Argentina by modeling SW-GW interactions. Hydrological Simulation model was coupled with the groundwater model to generate flood risk maps for the drainage network of the basin for the removal of floodwater. The study recommended floodwater diversion schemes and managed recharge of groundwater for the efficient management of SW-GW resources.

Miller et al. (2003) applied response functions of the aquifer systems in Snake River basin, Idaho, USA to simulate SW-GW interactions. Steady state and transient state responses to multiple aquifer stresses were developed using code modified from the groundwater model to determine the flow exchange. Steady state responses classified the aquifer into different zones based on the stresses in the basin. Transient state responses exhibited increase in aquifer discharge in the downstream due to the recharge induced from surface water diversion in the upstream.

Said et al. (2005) simulated long-term SW-GW interactions in Big Lost River Basin, Idaho, USA by integrating Hydrological Simulation program and the groundwater model. Rapid SW-GW interaction was witnessed with note-worthy rainfall recharge, dominant base flow and river seepage equal to that of amount of water pumped. Model indicated seepage losses due to increased groundwater extraction with negligible return flow in the downstream. The study recommended decrease in drawdown rates to avoid groundwater stress in few sub-catchments and encouraged artificial recharge in the lower part of the basin.

Fleckenstein et al. (2006) observed the SW-GW disconnection during low-flow condition of Cosumnes River in California, USA by using the groundwater model. The interaction status affected the aquatic life due to the presence of groundwater table much below the riverbed. River seepage losses were observed along the channel with negligible baseflow due to aquifer heterogeneity in the flow regime. The study suggested local re-connection of river and aquifer systems to increase the flow and sustain the aquatic ecosystem.

Zume and Tarhule (2008) explored the impacts of groundwater pumping on SW-GW interactions in Beaver-North Canadian River, North-Western Oklahoma, USA using the groundwater model. The study estimated the streamflow depletion due to over-exploitation of regional aquifer systems with increasing demand in irrigation and public sector. The model predicted decline in baseflow by 29% and increase in stream leakage by 18% adding up to 47% of losses from the stream. Model results confirmed that the streamflow majorly depended on the baseflow contribution of the alluvial aquifer.

Cho et al. (2009) indicated decrease in stream flow and groundwater head due to impact of land use changes in Virginia watershed, USA. Increase in impervious land use areas was observed to disturb the SW-GW interaction processes through the riverbed. A lumped surface water model was linked with the groundwater model to estimate the volume of surface water recharging the groundwater. The significant effect was recognized under the urban scenario of the stream and groundwater flow than in the forest areas.

Eastoe et al. (2010) noticed high salinity interaction in the downstream of Rio Grande River in Texas, USA due to increased drawdown using isotopic analysis and the groundwater model. During the pre-construction period of Elephant Butte Dam, deep recharge of Hueco Bolson Aquifer was observed near El Paso town of Texas, USA. For the post dam construction period, the study indicated a decrease in recharge near

El Paso town and a reversal in the characteristics of interaction as well as groundwater movement.

Valerio et al. (2010) linked SW-GW interaction model with a river management model for the allocation of water in Middle Rio Grande Basin, New Mexico, USA. An operation plan to effectively manage river water subjected to surface diversion, seepage, discharge, return flow, groundwater extraction and contribution was devised. The model improved the water management due to flow variability in connected river-aquifer systems during low-flow conditions of the river.

Lam et al. (2011) evaluated the groundwater contribution to evaporation in Danube basin of Central and Eastern Europe by modeling SW-GW exchange. The groundwater model results demonstrated that more than 30% of groundwater contributed to evaporation during summer months. The aquifer discharge occurring due to rainfall influence predicted to affect summer evaporation for many years. The study suggested that the lateral exchange of groundwater was negligible compared to local-scale contribution.

Sanz et al. (2011) predicted the spatial and temporal variation of interaction between Jucar River and Mancha Oriental Aquifer in Spain using the groundwater model. The simulated model was utilized to assess the impact of groundwater abstraction on Jucar River. The calibrated model estimated the groundwater decline lesser than expected due to river leakage into the aquifer induced by excessive abstractions. Continuous drawdown disconnected the interaction between river and water table in the downstream 20 kms from the pumping location.

Adhikary et al. (2012) characterized gaining and losing conditions of river by analyzing flow exchange using mass balance results of the groundwater model. The study simulated the SW-GW interactions for a regional scale unconfined aquifer of southwestern Bangladesh under transient-state. Model computed flow exchange values were highly responsive to the groundwater fluctuations proving interaction between river and aquifer systems.

Baalousha (2012) quantified gain-loss relationship of rivers with underlying aquifers in the Ruataniwha Basin, New Zealand using the groundwater model. The simulation was carried out for 12 river and streams using stream routing package for past gauging data. The river-aquifer exchanges varied from place to place distinguishing that the gaining of rivers from the aquifers was more than losing. The study revealed that streams and rivers were gaining in the upstream, losing further down and gaining again at the catchment outlet. Model results were consistently verified with the concurrent gauging data of rivers at 30 locations spread across the catchment.

Wang (2012) determined stream-aquifer connectivity in Elkhorn River Basin, Nebraska, USA by analyzing time series data of hydraulic gradient, stream stage and groundwater head. The groundwater heads was obtained from the regional scale groundwater model built using hydrostratigraphy data. The study described that the Elkhorn River was a gaining one throughout the year having strong hydrologic connection with the aquifer. Model results revealed that baseflow from the aquifer was one of the major component of stream flow. The streambed conductance was calculated to be higher in upstream than the downstream part of the river. Cross-correlation analysis was used to verify the accuracy of stream-aquifer connectivity.

Rassam et al. (2013) derived SW-GW flux estimates from the groundwater model by simulating river management model in Upper Namoi Catchment of New South Wales, Australia. The study highlighted the reversal of gaining characteristics of Boggabri and Narrabri reach into losing one due to impact of pumping activities during dry period. The sequential modeling helped the river management model to improve the predictions for the management of water resources during low-flow conditions.

Varalakshmi et al. (2014) studied the contribution of streams, drains and lakes into the ground by using the groundwater model. The surface water features were simulated for the regional scale Osmansagar and Himayathsagar catchments in Telangana, India. Model results indicated progressive decline in groundwater levels due to increase in groundwater withdrawal compared to aquifer recharge in the study area.

Sutton et al. (2015) analyzed spatial and temporal variations in SW-GW interactions for Suwannee River, Florida, USA using the transient groundwater model. The study demonstrated that the considered 80-km stretch of Suwannee River was losing one throughout the year even at high and low-flow conditions. Potentiometric maps revealed that river loses maximum inside the larger meander and continue to lose across it instead of rejoining the river as return flow. The simulated model described that the aquifer transmissivity values were higher for the inside end of larger meander than the outside end. The numerical model results satisfactorily matched with that of fluxes estimated from the differential stream gauging analysis.

Tian et al. (2015) assessed the impact of irrigational activities on SW-GW interaction in Heihe River of Gansu province, China by integrating the Groundwater and Surface water Flow model with Storm Water Management Model. Due to surface-water diversion, increase in river-stage was noticed in higher order stream leading to dynamic river leakage compared to aquifer discharge. The losing and gaining characteristics of upstream and downstream segments respectively proved that surface water diverted for agricultural use returned back in a shorter period. However, net exchange of flow was relatively small compared to the groundwater extraction. Model results predicted decline of groundwater due to pumping activities in the agricultural-oriented area. The study suggested that water availability was unsustainable with the current use for long-term.

Zhu et al. (2015) evaluated the impact of heterogeneity in conductivity on SW-GW interactions in the Middle Heihe River basin of Gansu province, China using groundwater modeling. The regional scale model based on local-scale heterogeneity in hydraulic conductivity values produced lesser aquifer discharge than that of simulated with zonal-scale heterogeneity. Stream leakage values were affected in downstream segments than ones in the upstream due to local heterogeneity in conductivity. The study found that aquifer heterogeneity at local-scale consistently slows down the rate of groundwater movement resulting in the reduction of aquifer discharge.

Kahil et al. (2016) developed a hydro-economic framework considering SW-GW interactions in Jucar Basin, Spain using the groundwater model. The study suggested reduction in water diversion, induced recharge for economical development of river-aquifer systems under climate change and policy scenarios. Sustainable policy achieved better economical target leading to increased environmental benefits under climate change scenarios compared to unsustainable policy.

Maheswaran et al. (2016) demarcated the losing and gaining streams of River Ganga and its principal tributaries in India using zone-budget values of the groundwater model. The study noticed rapid decline in baseflow contribution to streams due to groundwater pumping in agriculture areas under general head boundary conditions.

Surinaidu et al. (2016) used semi-coupled surface water and groundwater model to check the possibility to increase sub-surface storage for Ramganga Sub-basin in Uttar Pradesh, India. Temporal variations of sub-surface recharge were analyzed under increased rainfall, artificial recharge and controlled pumping scenarios. The study found that it was able to increase sub-surface storage through natural SW-GW interactions under increased rainfall scenario. Even though induced recharge improved sub-surface storage, baseflow found to decrease due to controlled pumping.

Yihdego and Paffard (2016) revealed that seasonal and long-term interaction of spring flow with aquifer systems sustained the yield in Lake Nyasa Basin, Tanzania. The groundwater model results predicted substantial increase in the safe yield extraction in the Lake Nyasa Basin for future groundwater usage. The study suggested re-estimating the safe yield of extraction for climate change and population growth scenarios that extensively affect the spring flows in the basin.

Yang et al. (2017) noticed decline in the flow of Hailiutu River, middle part of Yellow River Basin in Northwest China due to excessive groundwater pumping. The study was carried out using the groundwater model and baseflow separation method. Baseflow was observed to be negligible due to surface water diversion in the Wushenqi river reach at the upstream. The negative effect on the Hailiutu River due to increase in groundwater recharge and evaporation at the upstream reservoirs was evaluated by using seepage estimation, numerical and isotopic analysis.

Lin et al. (2018) studied the impact of surface-water diversion project on SW-GW interactions in Dunhuang basin of Gansu Province, northwestern China using the groundwater model. The reversal of groundwater discharge into recharge was observed due to diversion work resulting in the control of groundwater budget by intensive SW-GW interactions. The study predicted increase the groundwater availability over the catchment saving the lakes from depletion.

Wang et al. (2018) denoted that SW-GW interactions affect the hydro-dynamic, hydro-chemical and ecological processes in the arid zone of Junggar Basin, Northwest China using numerical, geological and isotopic analysis. The study noticed extensive occurrence of river-aquifer interaction throughout the flow regime of river in the basin. The spatial reference of the surface water features specified the extent of flow exchange in the regional flow systems. Hydro-dynamic processes emerged in the direction of groundwater flow predicting increase in total dissolved solids due to higher SW-GW flow velocities.

Wöhling et al. (2018) assessed SW-GW interaction characteristics of extremely transmissive gravel-bed rivers of Wairau Plain, New-Zealand during low-flows. The groundwater simulation results found upstream reach of the river as losing one and downstream reach as gaining one. Streams disconnected from the aquifer systems due to the vulnerability of groundwater resources to the hydrological extremes such as drought and climate change.

2.2.2 Sub-catchment scale modeling using MODFLOW

Rodriguez et al. (2006) examined groundwater swelling in Choele Choel island of Argentinean Patagonia based on stream-aquifer response using the groundwater model. Seepage losses from the irrigation canals and high stream stage values were simulated to assess river-aquifer interactions in the canal drainage network. The model results indicated that stream leakage volume was more compared to the canal recharge resulting in the groundwater rise. However, stream-aquifer interface was more responsive to increase in groundwater caused due to irrigation. Surface percolation through canals and agricultural fields were responsible in characterizing the stream reach into gaining from losing in the downstream.

Werner et al. (2006) implemented groundwater based - hydrologic modeling system for coastal aquifers in Pioneer Valley of North Queensland, Australia to study river-aquifer interactions. The model was simulated for coarser and finer resolution of the catchment using channel bed conductance values obtained by field experiments. Coarser model for regional scale over-predicted the river leakage values compared to finer resolution model for the sub-catchment scale. The study concluded that finer refinement of spatial resolution would lead to much accurate representation of stream-aquifer interaction. The model results were inadequate to be extrapolated from the small-scale estimates to a regional scale due to inappropriate time scale between them.

Krause and Bronstert (2007) identified the sensitive parameters controlling the water balance of Havel River sub-catchment, Germany by using a coupled model. Watershed simulation model coupled with the groundwater model revealed that lateral river-aquifer interactions have stronger impact on runoff. The spatial pattern of flow exchange demonstrated by the coupled model was verified with extensive experimental investigations carried out at the outlet of sub-catchment.

Kim et al. (2008) tested integrated SW-GW model on Musimcheon Basin, South Korea and recognized the importance of aquifer discharge during low-flow condition. Model successfully demonstrated the interaction of saturated unconfined aquifer with river reaches and reduction in streamflow due to increased drawdown.

Rejani et al. (2008) indicated that Balasore aquifer system in Orissa, India was susceptible to river seepage and interflow by using the groundwater model. The river-aquifer interaction study established the aquifer response to different pumping scenarios affecting the seepage rate. Fresh water reserves found to be replaced by salt water due to excessive pumping in the coastal sub-catchment.

Ahmed and Umar (2009) predicted groundwater decline in non-command areas due to increased drawdown at Yamuna-Krishni sub-catchment of Uttar Pradesh in India using the numerical model. Spatial behavior of river-aquifer interactions was studied by evaluating the groundwater contour patterns. The influence of groundwater pumping was observed at the floodplains of Yamuna River resulting in variation of flow characteristics. The study recommended surface water diversion through canals to the non-irrigated areas.

Barber et al. (2009) studied the impact of artificial recharge on seasonal low-flow of Spokane and Little Spokane Rivers in Washington, USA using groundwater modeling. The model was calibrated using winter surface diversions and artificial recharge by strategically located infiltration basins and injection wells. The model quantified river-aquifer interactions and observed significant amount of baseflow contributing to the flow in the river. The study implied that infiltration basins, injection wells of aquifer with upto 30% of surface water diversions could enhance low stream flow conditions.

Pruneda et al. (2010) investigated the feasibility to sustain summer flows at Bertrand and Fishtrap watersheds near British Columbia, Canada - Washington, USA border. The stream response to groundwater pumping was generated for conserving aquatic ecosystems by employing the steady-state regional scale groundwater model. The model was refined to stream reach scale using field measured hydro-geological data to precisely analyze river-aquifer interactions. The impacts of low-flow conditions on endangered species were studied based on measured streamflow response to groundwater pumping. The study suggested a prospect of replacing the usage of surface water with groundwater withdrawal from wells located away from streams.

Simpson et al. (2011) introduced a new approach to assess drain-aquifer interactions for Thurne River Sub-catchment, UK by using drainage co-efficients. The spatial variation of fresh water and salt-water intrusion for different pumping zones of surface water drains were assessed using flow path lines. The groundwater inflow into the drainages calculated from the groundwater model adequately matched with values obtained from hydrograph separation.

Bokar et al. (2012) studied the impact of climate change on Kolondieba Sub-catchment in the south of Mali by using the groundwater model. The steady-state model results indicated that the groundwater discharged into the river. The sensitivity of groundwater head towards the aquifer recharge indicated that groundwater availability depends on the river-aquifer interaction. The study predicted decreasing trend in groundwater heads due to decadal affect of climatic invariability in the basin.

Gaaloul (2012) included river-aquifer interaction as a part of groundwater modeling framework to analyze the effect of continuous drawdown in El Hicha Basin, Tunisia. Stream leakage into the aquifer and aquifer seepage into the stream was simulated using a numerical groundwater model. The study predicted huge amount of drawdown and increased saltwater intrusion into the aquifer systems of El Hicha Basin.

Huntington and Niswonger (2012) illustrated the impact of snowmelt runoff on groundwater within three watersheds of the eastern Sierra Nevada, USA using integrated runoff-groundwater model. Model results acknowledged the recharge of groundwater by bank storage due to the effect of snowmelt runoff and its reversal with the recession of snowmelt. The study predicted decrease in streamflow upto 30% with the decrease in snowmelt runoff and might get worse with during summer. The study recommended measurement of streambed hydraulic gradients during snowmelt cycle.

Martínez-Nájera et al. (2013) analyzed the river-aquifer response to excessive groundwater pumping for Papagayo River, Mexico by using coupled SW-GW model. The transient study determined that the river sustained flow with controlled pumping rate for well since the river-aquifer interactions were less influential. Model indicated that river-stage reaches minimum level of flow after the recession of bank storage with the acute rate of drawdown.

Hendriks et al. (2014) proposed a method to calculate threshold values of baseflow contribution to streams for environmental flow needs using the groundwater model. An attempt was made to check the applicability of the technique to assess the ecological condition of streams w. r. t. baseflow in the sandy sub-catchments of the Netherlands. Merkske Sub-catchment with thick aquifer layers showed sustained baseflow even under meteorological drought condition. Hollandse Graven sub-catchments characterized with thin unconfined aquifers were deeply affected with strong baseflow reductions due to the climate change and anthropogenic activities.

May and Mazlan (2014) observed the effluent condition of stream at no pumping state for a river segment in Langat Basin, Malaysia using groundwater contour maps. The stream flow changed into influential condition one near the industry and sand mining areas due to increased abstraction. The incorporation of river stage in the transient groundwater model improved the assessment of variation in river-aquifer interaction due to pumping activities.

Hughes et al. (2015) simulated the effect of sea-level increase on river-aquifer interactions in the Snapper Creek area of Miami-Dade County, Florida, USA using the groundwater model. The study predicted inversion of hydraulic gradients due to a sea-level rise of 0.25 m resulting in reduction of river flow and aquifer discharge into the bay area. Model results showed increase in groundwater level with salt–water intrusion due to rise in sea-level posing risk to the quality of SW-GW systems in the Snapper Creek area.

Taviani and Henriksen (2015) revealed that groundwater discharge saved the Bracciano Lake located in the northwest Rome, Italy from depletion during shorter dry periods using the groundwater model. The groundwater and lake interaction dynamics was analyzed by simulating the hydraulic heads of groundwater and lakes in the area. Simulated groundwater head results showed the baseflow contribution of streams into the lake. The water level in the lake was found to be sensitive towards groundwater pumping and climate invariability.

Guzmán et al. (2016) calculated river-aquifer flow exchanges for Cumbe River Catchment in the south of Ecuador by extensive field measurements and groundwater modeling. Vertical SW-GW fluxes were inspected by using field temperature measurements. Numerical model results and temperature as a groundwater tracer exhibited dynamic SW-GW interactions. Losing and gaining river segments were observed in wide and narrow alluvial valley portions respectively due to the influence of riverbed morphology. The study illustrated that more than 92 % of recharge originated from lateral flow of the alluvial deposits between the valley portion and hillslopes.

Korkmaz et al. (2016) developed a computer code to obtain water-diversion function for drainage network in Eskisehir Basin, Turkey using the numerical groundwater model. The transient model simulated the stream–aquifer interactions in the drainage basin considering artificial recharge, flood prevention and ecosystem conservation. Flood prone areas were discovered using steady state simulation results. The flood-diversion function balanced the diversion of augmented flood allowing sustainable flows to conserve eco-systems by an iterative procedure. Artificial recharge was obtained from the increased discharge of the flood-diversion function to meet agricultural and industrial requirements.

Movahedian et al. (2016) emphasized the impact of river-stage fluctuations on river-aquifer interactions of Gotvand–Aghili Plain, Iran using groundwater modeling. Model results indicated that river acted as gaining one in the upstream and central portion of the sub-catchment and losing one in the downstream areas. The study revealed that upstream storage and release of water from the Gotvand dam affected the river-stage fluctuations in the sub-catchment area.

Essaid and Caldwell (2017) analyzed the river-aquifer interactions in Smith River, a tributary of Missouri River located in west-central Montana, USA using stream temperature sampling and numerical model. Model results predicted that excessive withdrawals decreased the groundwater discharge affecting the aquatic life. Interaction processes and stream temperatures were found to be altered by irrigational activities. The study suggested the use of irrigation to enhance the groundwater discharge for conserving fish ecosystem by allowing return flow into the streams.

Kerebih and Keshari (2017) revealed the domination of aquifer contribution into the streams of Aynalem Sub-catchment, Ethiopia using groundwater flow budget. The study observed the lateral outflow of groundwater at the downstream part of the basin influenced by the stream leakage at the upstream into the sloping aquifer.

Du et al. (2018) recognized the influence of river-stage fluctuations on the river-aquifer interactions in Jianghan Plain, the middle reach of Yangtze River in China.

The vertical exchange of flow between Yangtze River and the aquitard was examined to be more near the river than the riverbank. The lateral influence of interactions was found to be significant around 500 m to 1000 m from the river. The study analyzed the consistency of groundwater modeling results for short time scale of interactions and tritium modeling results than long time scale interactions.

Han et al. (2018) studied the effect of natural and anthropogenic factors on groundwater reserves in Cedar Creek Watershed of Wisconsin, U.S.A. using the numerical model. Model results suggested that aquifer systems were unresponsive to the variation in surface water features. The study indicated that Cedar Creek acted as an ephemeral stream with the reduction in groundwater heads as well as river-aquifer interactions.

2.2.3 Local-scale modeling using MODFLOW

Van Lanen and Van deWeerd (1994) studied the impact of groundwater abstraction on Voer and Noor streams in the Margraten Plateau of southeast Netherlands. The numerical groundwater study predicted dynamic stream-aquifer interaction due to climate change resulting in huge decrease in groundwater discharge and head values. The depletion Stream depletion rate of Voer (0.57 to 0.02) was more compared to Noor stream (0.15). Model results implied that increase in the distance of the well location reduced the impacts of abstraction rates on streamflows.

Lal (2001) tested the analytical solution by using the numerical groundwater model to calculate stream-aquifer interactions for the hypothetical cross-section of a stream. The analytical solution obtained from 1-D Saint Venant equation coupled with 2-D groundwater flow equations was compared with the numerical model. The comparative study found to incorporate the effect of small-scale stream-stage fluctuations on the interactions in numerical model discretization. However, the trivial difference or minor error in results was noticed due to the consideration of finite boundary in the numerical models.

Chen and Chen (2003) analyzed the effects of stream-stage fluctuations and aquifer properties on stream-aquifer exchange during a flood period. A local-scale groundwater model was designed to simulate the interactions for a hypothetical stream-aquifer system. The study revealed that the stream acted as a losing one during the flood, whereas, stream acted as a gaining one after the flood. Bank storage was observed to be less compared to the storage volumes of aquifer system due to rapid rise and fall in stream stage during the flood.

Panday and Huyakorn (2004) applied groundwater-based hydrologic modeling system for conjunctive modeling of SW-GW systems. The study was implemented for a tilted V-catchment having network of stream, channels including hydraulic structures. Stream-aquifer exchange volumes were calculated for highly implicit non-linear circumstances attenuated using Newton–Raphson's method. Surface and sub-surface domains were discretized based on finite-volume concept and block-centred finite difference technique respectively. The difference in time and spatial scales compelled to be the principal obstacle during coupling of surface water and groundwater model.

Koussis et al. (2007) validated the analytical estimation of stream-aquifer interaction using the numerical groundwater model for a local cross-section of Cedar River in Iowa, USA. The response functions of sloped aquifer using linearized 1-D Boussinesq equation improved accuracy in the estimation of seepage rate and bank storage estimation. Sediment layer was found to disturb the interaction process by clogging the conductivity of the streambed. The numerical model established the influence of recharge during the validation process confirming the accuracy of the analytical equation.

Martínez-Santos et al. (2010) indicated that river-stage fluctuations regulated the groundwater flow in Nolan River reach of Langreo, Spain by using the transient groundwater model. Model results revealed gaining characteristics of river in winter and vice-versa in the summer when pumping activity wasn't considered. River exhibited losing characteristics with pumping however sustained the flow from depletion. The volume of baseflow was found to be negligible compared to total streamflow due to the relevance of the reach scale considered for the study.

Munz et al. (2011) measured river-aquifer flux using streambed piezometers and compared with estimates of the groundwater model for 30 m reach of River Leith in UK. Field measurements indicated that groundwater contribution into the river was pre-dominant with the absence of river leakage. Numerical simulation results verified the irrelevance of leakage through the streambed for the post-monsoon period considered for field observations. Model indicated increased groundwater discharge at flood boundary of the river characterized by high hydraulic conductivity in the streambed.

Okkonen and Klove (2011) studied the effect of climate inconsistency on stream-aquifer interactions for Pudasjärvi Aquifer in Finland by sequentially linking surface water model with the groundwater model. The study predicted an increase in river inflow due to snowmelt during warm climate conditions and reduction in groundwater storage during winter period. Recharge areas proved to be susceptible to climate change increasing the risk of droughts and aquifer discharges found to be vulnerable to variations in interactions.

Mas-Pla et al. (2012) observed losing behavior in the upper reach and gaining behavior in the lower reach of Arbúcies River located in the Montseny-Guilleries Range of Northeast Spain using the numerical model. Potentiometric maps obtained from the transient groundwater simulation were used to analyze the spatio-temporal variation in interactions. The characteristics of stream-aquifer relationship determined by using isotopic and hydro-chemical analysis were validated by the numerical model results.

Engelhardt et al. (2013) quantified the exchange of wastewater contaminants into the sub-surface for a hypothetical stream-aquifer cross-section using the groundwater model. The study was compared with the temperature tracer and chemical analysis to recognize the flow and transport behavior of contaminants in the sub-surface.

Griebling and Neupauer (2013) solved adjoint equations using modified stream flow routing package in the groundwater model to estimate stream depletion. The adjoint equations were developed for a local scale hypothetical stream-aquifer system to analyze the depletion of stream subjected to groundwater pumping. The study found that hypothetical system was sensitive to mean hydraulic conductivity and hydraulic gradient between stream and aquifer.

Ou et al. (2013) developed a new flow-routing package for simulating stream-aquifer interactions across channel cross-sections broader than MODFLOW grid cells. A hypothetical reach-scale model was simulated using the Cross-section Streamflow-Routing package based on Muskingum-Cunge equation. The model accurately represented the complicated geometry and heterogeneous streambed properties in the longitudinal and horizontal direction. Streambed seepage calculated as a product of bed conductance and the hydraulic gradient was considered as lateral flow. Hence, spatial variability of stream-aquifer interactions along and across the cross-sections of stream segments was determined with time.

Surinaidu et al. (2013) estimated river-aquifer interactions for local mining area of Katni in Madhya Pradesh, India using the groundwater model. The study found significant river leakage from the cavernous zone exposed in the mining area. Lateral inflow of river into the aquifer system was noticed from the western boundary of the mining area while the eastern part of the mining area had no considerable interaction. Water budget calculations were utilized to estimate the groundwater flux due to interaction with river.

Chinnasamy and Hubbart (2014) built a groundwater flow model to verify SW-GW interactions for analyzing nutrients transport in the Ozark Forest Region of Missouri, USA. The river-aquifer interactions were assessed at the river reach of Brushy Creek in the forest area as a requisite to accurately predict the flux. Model results indicated that the major part of stream reach was losing during low-flow periods and interaction was absent during dry periods.

Dujardin et al. (2014) employed numerical modeling, hydraulic gradient analysis and temperature tracers for the characterization of stream-aquifer interactions. The considered canal cross-section of Zenne River in Belgium was found to be gaining groundwater from the south-eastern bank of the canal. The comparative study improved the accuracy of assessment of local-scale interactions.

Mayaud et al. (2014) noticed increased baseflow at a stream reach between Hammerbach and Schmelzbach Sub-catchments of Austria using groundwater model. The overflow of groundwater was observed in the upstream of stream reach acting as inter-catchment flow. The time-series analysis characterized the behaviour of interactions between stream and the local aquifer. The inter-catchment flow was found to be varying with the heterogeneity of the aquifer below the stream reach connecting the sub-catchments.

Roy et al. (2014) conducted a hypothetical study to assess the impact of groundwater exploitation on river reach in Purulia of West Bengal, India using groundwater modeling. The model was simulated with the hydraulic parameters obtained from pumping tests to estimate the stream-aquifer flow exchange by using conceptual modeling approach. The study predicted decline in river level due to excess pumping from a well located near the riverbank.

Alfaro et al. (2017) determined that decrease in groundwater abstraction by 40% improved the stream-aquifer interactions in southern Jordan Valley and Wadi-Shueib surface water catchment. The local-scale groundwater model study demonstrated the disconnection of groundwater from the river during dry period at the north-west part of the study area. The groundwater lost due to pumping was recovered due to surface recharge during rainy months.

Stefania et al. (2018) analyzed the effect of pumping well location on the stream flow depletion of Dora Baltea River, Italy using the groundwater model. Model results indicated that wells near the riverbank in the upstream were recharged from the riverflow and wells in the downstream were recharged from the baseflow. The study observed that groundwater pumping from the wells near the stream influenced the stream depletion.

Tr´asy et al. (2018) verified the stream-aquifer flow exchange using a groundwater model for one of the 9 sites in the Danube River, Hungary. The numerical study confirmed the decline in floodwater infiltrated into a well near the river soon after the flood event despite of steady hydraulic conductivity. Inverse in hydraulic gradient and reduction in seepage rate was perceived to be reason for the decrease in groundwater table after the flood event.

Zhou et al. (2018) analyzed local stream-aquifer interactions for the flood-plain area of Schwarzbach River, Germany using a numerical model. The study observed increased streambed conductivity during stream inflow and decreased streambed conductivity during aquifer outflow. The study evaluated the time-variant streambed conductivity by inversing the aquifer-response to the flood and incorporating the aquifer heterogeneity.

2.2.4 Multi-scale modeling

Loheide and Gorelick (2006) estimated the spatial variation of stream-aquifer interactions at 1.7 km reach of Cottonwood Creek in California, USA by comparing remotely sensed infrared images and point-scale stream-temperature measurements. The study found baseflow contribution and flow exchange rate to be relatively higher than the streamflow at restored stream sites compared to un-restored stream sites. The flow exchange rate estimated using infrared images was verified against on-site measurements with less than 10% error. The multi-scale study suggested the restoration of ponds and un-restored points to gain flow in the regime.

Poole et al. (2006) identified multi-scale geo-morphological drivers that influence SW-GW interactions in the Nyack Floodplain of Middle Fork Flathead River, Montana, USA using a hydro-geologic model. The topography and aquifer properties affect the reach-scale interactions along the floodplain. The geo-morphological structure, dynamics and environment at the riverbed cross-section affect the point-scale interactions. The river-stage fluctuation in the floodplain was observed to affect the dynamics in flow exchange in point scale extensively compared to reach-scale.

Ellis et al. (2007) quantified river-aquifer interactions for multiple scales of Tame River, UK using a saturated–unsaturated flow and transport model. The flow exchanges found to be varying by different factors at sub-catchment, reach, local and point scales of Tame River Catchment. Groundwater movement affected the flow exchange across the flood plain of the river. River-stage was observed to affect the rate of flux along the bed slope. Riverbed morphology was found to be influencing the extent of flow exchange at the interface. Riverbed material was found to alter interactions due to the effect of hydraulic properties in the hyporheic zone. The study highlighted the significance of depth of connection between river and aquifer flux. River bank infiltration and flow reversal was noticed during and after the flood event respectively.

Scibek et al. (2007) evaluated the impact of climate change on SW-GW interactions by down-scaling the global-scale model to basin-scale of Kettle River located along the south-central British Columbia, Canada - Washington State, USA border. The transient groundwater model indicated that the river infiltrated into the aquifer due to increase in the river stage during snowmelt. Post-decline in snowmelt, the baseflow dominated the river flow for rest of the year. Although flow exchange occurred within the floodplain, pumping activity was found to reduce the base flow contribution. However, the climate change exhibited lesser impact compared to groundwater abstraction affecting the timing of peak flow than the volume.

Hu et al. (2009) divided large-scale irrigated areas into sub-catchment scale for the sustainable management of Shiyang River Basin in Gansu Province, China using a coupled SW-GW model. Model simulated influx volumes from individual upstream sub-catchments into the Hongyashan Reservoir to assess the outflux volumes for sub-catchments in the downstream. Groundwater recharge from the reservoir storage, surface water diversion, river inflow was evaluated using basin-scale groundwater budget estimation. The study recommended intra-basin water transfer for the groundwater-deficit areas to meet the agricultural demand.

Ivkovic (2009) characterized the SW-GW interactions for different reaches of Namoi river catchment in northeast-central New South Wales, Australia through a top-down approach using hydrometric data. The pattern and trend were analyzed from the data obtained from the stream-gauging stations without considering driving forces influencing the phenomenon. The study described the gaining and losing characteristics of the river reaches using a map depicting connectivity and dominant flux. Reduction in baseflow was noticed by using stream and bore hydrographs due to groundwater pumping.

Engdahl et al. (2010) compared multi-scale stream-aquifer estimates of Rio-Grande River reach near Albuquerque of New Mexico, USA using transition probability framework. Regional scale model over-estimated the river leakage values compared to small-scale model due to the consideration of homogeneous hydraulic conductivity values. The study recommended the small-scale model that considered heterogeneous hydraulic conductivity values based on spatial variability of fluvial deposits in the riverbed.

Mehl and Hill (2010) described the importance of grid refinement for the better representation of streams to simulate river-aquifer interactions at different scales. The SW-GW flux estimates of a local grid refined for a limited part with equivalent representation of features satisfactorily matched with the estimates of the globally refined grid. The study suggested employing approaches to calculate streambed conductance independent of grid-size. However, the magnitude of spatial variation of stream leakage and aquifer discharge areas varied with the discretization of finite-difference numerical model at multiple scales.

Kikuchi et al. (2012) applied spatially telescoping approach to assess SW-GW interactions for the catchment, reach and point scale of Lucile Creek in Alaska, USA using field measurements. Different field investigations were carried out to evaluate river-aquifer interactions at different scales. Locations of dynamic SW-GW flow exchange were identified using flow-transects and geomorphological indices at catchment scale. Increase in basefow was observed in the middle and downstream river reaches of the catchment. The catchment scale assessment was verified using differential discharge measurements and chemical tracers at river reaches. Upward fluxes due to baseflow were measured using seepage meters and temperature tracers at point scale of the river reaches. The spatially magnifying technique improved the efficiency of the field investigation and interpretation of local/reach scale interactions.

Mouhri et al. (2013) introduced a methodological framework to establish a sampling network of SW-GW interactions at multiple scales of Orgeval catchment in Paris, France. The sampling was carried out using geo-physical exploration by piezometers at catchment scale and electrical resistivity topographies at intermediate scale. At local scale, a network of observation stations were established along the river regime accompanied with stream gauging stations to measure water and heat transfer. The sampling network was simulated by using a coupled 2-D thermo-hydrodynamic model and gaining characteristics of upstream part of river reaches was noticed.

Flipo et al. (2014) designed an iterative procedure to downscale the regional and upscale the intermediate scale interactions using a riverbed conductance model. A graphical framework was proposed to upscale the parameters from local to watershed scale by using field observation data. The study recommended the use of regional remote sensing data to improve the assessment of stream-aquifer fluxes from local to continental scale.

Marzadri et al. (2014) estimated stream-aquifer interactions for local and reach scale of Deadwood River in Idaho, USA associated with alluvium aquifer. The river-stage fluctuations due to release of water from Deadwood Reservoir in the upstream influence the interactions in the 37 km long river reach. The stream-stage and groundwater head variations for cross-sections of the river were used to simulate the local-scale interactions using a 1-D hydraulic model. Bed topography and flow velocity along the bathymetry were used to simulate the reach-scale interactions using 1-D wavelet. Small-scale and reach-scale interactions were found to be dominated with shorter and longer duration of groundwater residence times respectively.

Li et al. (2015) introduced a multi-scale hierarchical approach for Osceola County in Michigan, USA to assess SW-GW interactions using an interactive groundwater model. The approach was developed to generate water budget function for the assessment of stream depletion of Chippewa Creek and Twin Creek subjected to pumping. The model was initially calibrated in regional scale by using observed groundwater heads for modeling groundwater budget. A sub-set of the calibrated model was created for the analysis of impact of groundwater abstraction on river-aquifer systems at sub-catchment scale. However, the sub-catchment scale study demonstrated that groundwater abstraction would not affect the ecological flow in the streams.

Sampath et al. (2015) analyzed the multi-scale variability of groundwater fed-wetland (fen) - Ives Road Fen located in Michigan, USA using a GIS-based groundwater modeling. A hierarchical approach of coupled geologic and the groundwater model, along with the particle tracking, highlighted the effect of surrounding hydro-geology on the water quantity and quality of the fen. Model indicated that River Raisin recharges confined space of groundwater below the fen in the regional scale. However, at local scale, model found that fen gains significantly by the recharge from nearby pond and local recharge area. The study predicted the impact of change in land use pattern in the study area affecting the inflow of water to the fen.

Feinstein et al. (2016) evaluated stream depletion in the Lake Michigan Basin, USA by incorporating the local effects of stream and aquifer using unstructured model grid. The study simulated the stream network to evaluate local SW-GW interactions refined from the regional scale model. The refined local-scale model enhanced the accuracy in the quantification of flow exchange between stream and connected wells. The study predicted that first order streams were vulnerable to depletion due to groundwater pumping.

Rugel et al. (2016) analyzed the SW-GW interactions for coarse and fine scale of Lower Flint river basin, south-western Georgia, USA using stable isotope and principal component analysis. The sampling of stream was carried out at reach and sub-catchment scale using isotopes to recognize the stream-aquifer connectivity and its variation. The sub-catchment sampling results predicted the contribution of groundwater upto 42% of total flow in the streams. Low flow in few stream reaches was observed by reach scale sampling in the upstream part of the basin due to groundwater pumping and severe drought. The study suggested considering the reach scale sampling estimates to characterize vulnerable flow exchange areas.

Varli and Yilmaz (2018) adopted a hierarchical multi-scale methodology to characterize SW-GW interactions for 2 km reach length of Kirmir stream in Turkey. Groundwater discharge sites were located and measured at the intermediate scale using thermal infrared images and discharge measurements respectively. Vertical flow exchanges were measured by using hydraulic gradient analysis, electrical conductivity and streambed temperature profiles. The stream reach was characterized into losing upstream, gaining downstream and seasonally variable mid-stream along the stream length. The study found that increase in stream stages due to operation of dam gates affected the interactions by reversing the flow exchanges.

2.3 SUMMARY OF THE LITERATURE REVIEW

In the past, many integrated models were developed and analyzed for regional/zonal/site specific problems. Studies related to SW-GW interactions using integrated models are not dealt in detail for smaller scales. There is lack of effort to identify and select appropriate model for the assessment of interactions depending upon the availability of data. Shortfall exists in the investigative research on SW-GW interactions covering all aspects at different levels of spatial scales. The applicability of driving forces affecting small-scale interactions to a larger domain and vice-versa is a subject of concern. However, there is no evidence of any standard outline or structure guiding the significance of interaction processes with scale.

2.4 RESEARCH GAP

From the literature, it is observed that there has been enough work carried out in the past two decades with reference to the use of MODFLOW and associated integrated models in the study of SW-GW interactions. However, it is noticed that the exact process with scale effects have not been dealt in detail. Moreover, there exists a very few literature with reference to top-down approach in the use of regional and catchment scale models. It is also observed that the extensive study of SW-GW interactions coupled with field investigations for west-flowing rivers in India is very limited. Based on the above research gap, the present study is chosen to address a few of such issues that in turn helps a design engineer to take an appropriate decision while considering interactions in hydrological models.

2.5 RESEARCH OBJECTIVES

In the present study, the following research objectives are set:

1. To build a regional scale groundwater model for Nethravathi river basin using MODFLOW and examine the SW-GW interactions by employing Top-Down Approach.
2. To build an intermediate scale groundwater model for Gowri-HoLe sub-catchment and predict the river-aquifer interactions using MODFLOW.
    a. To analyze the spatial and temporal pattern of river-aquifer interactions in the Gowri-HoLe sub-catchment.
    b. To characterize the flow exchange in different river segments of Gowri-HoLe sub-catchment.
3. To compare the driving forces influencing the regional and sub-catchment scale interactions.

CHAPTER 3

METHODOLOGY

3.1 GENERAL

The evaluation of spatial and temporal variation of interactions at multiple hydrological scales of a river basin is of sustainable significance. Assessment of flow exchange volumes at the catchment scale is essential in investigating the dynamic interactions. Temporal assessment of interactions is useful in understanding the change in flow characteristics of the river/stream segments that actively respond with aquifers. The study would lead to understand the condition of both the resources and manage them efficiently.

The theoretical formulation for the assessment of volume of surface water leakage into the aquifer and groundwater contribution to the river is discussed in this chapter. The SW-GW interactions are quantified for the entire flow regime of the river basin to determine the condition of hydrologic connection. Numerical model is quite effectively used for simulating river-aquifer interactions at multiple scales of a catchment. The distinctive flow paths of hydrological processes at different locations and scales are included in the estimation. The numerical approach provides a framework to resolve the complications in simulating the interactions changing with time and space. The present study focuses on the characterization and quantification of river-aquifer interactions for the Nethravathi basin using Top-Down approach. It is carried out to establish and associate the relevance of driving forces across different levels of hydrological divides in concern.

3.2 RIVER-AQUIFER INTERACTION MODELING USING MODFLOW

In the present investigation, river-aquifer interaction modeling is carried out using MODFLOW for an unconfined aquifer system. It is a 3-dimensional finite-difference model with flow domains divided into grids of cells. MODFLOW is a cell-centred saturated flow model capable of building and simulating groundwater flow and mass transport. It is widely used to simulate most appropriate situations of sub-surface conditions. Conceptual models are built on the same lines of consideration for examining new hypotheses of dynamic interactions.

3.2.1 Groundwater Modeling System (GMS)

Groundwater Modeling System (GMS) Version 10.0 software is used as a graphical user interface (GUI) for the functioning of MODFLOW. GMS provides a platform to build a groundwater flow model representing the flux between surface water and groundwater systems. It comprises of tools for every step in the groundwater simulation including domain characterization, model development, calibration, post-processing and visualization. Different steps involved in modeling process are described in Figure 3.1.

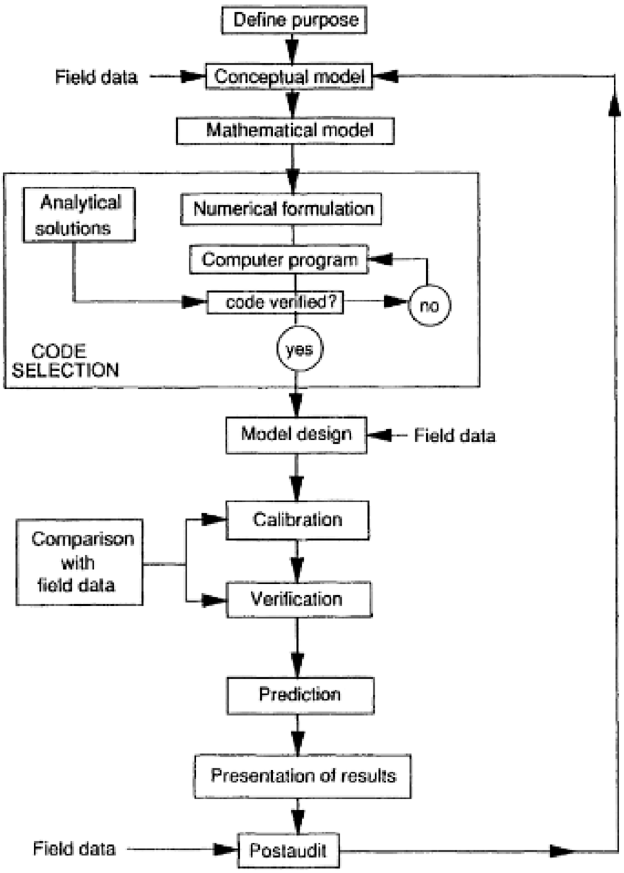


Figure 3.1 Flow chart of the modeling process (Anderson and Woessner, 1992)

Model calibration is a process in which the hydraulic parameters are varied until the simulated values of groundwater heads match with the observed ones, thus improving the accuracy of the model. Sensitivity analysis is carried out wherein effects of hydraulic parameters on hydraulic heads are studied.

In the present study, a new conceptual model is developed using RIVER package of MODFLOW in GMS for the simulation of river-aquifer interaction processes both at regional and sub-catchment scale.

3.2.2 MODFLOW Package Supported in GMS

GMS is capable of simulating both the steady state and transient state conditions of groundwater flow. It provides various options to consider time independent and space dependent data. GMS consists of multiple modules for simulating different components of a groundwater system with the capability of modifications. It includes all aspects of solving the flow equation, including the formulation of the finite difference equations, data input, solving the simultaneous equations, and data output.

GMS offers flexibility in incorporating the real-field situations in the modeling process for accurately analyzing the flow conditions at the selected scale of study. It allows building a conceptual model consisting of scale-based hydrological processes to characterize SW-GW interactions using conceptual modeling approach. GMS is supported by various flow packages as shown in the Table 3.1.

Table 3.1 MODFLOW Packages in GMS

Package Name	Description
Layer Property Flow (LPF)	Performs cell by cell flow estimations. The inputs are layer properties such as hydraulic conductivity.
Well (WEL)	Draft rates are assigned for pumping wells.
Recharge (RCH)	Recharge rate values are assigned for the delineated recharge zones.
River (RIV)	Riverbed conductance values are assigned for river segments.
Preconditioned Conjugate Gradient (PCG)	Solves the simultaneous equations obtained from the finite-difference method.
Parameter Estimation (PEST)	Determines sensitive parameters affecting the result.

The program is divided into pieces called packages. A package is a group of modules that deals with a single aspect of the simulation. Each hydrologic capability, such as leakage to rivers, recharge, stream, etc, is included within the groundwater flow model as a separate package.

Suitable supporting packages such as WELL, RECHARGE, RIVER are used for simulating different components of the conceptual model. Layer-Property Flow (LPF) package is selected for defining layer properties of hydraulic conductivity values. Preconditioned Conjugate Gradient (PCG) is used as a package for solving the governing equation.

3.2.3 Groundwater flow Modeling

The theoretical background of the model is described by the governing equation for the three-dimensional groundwater flow through a heterogeneous and anisotropic medium as:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S_S\frac{\partial h}{\partial t}+V\left(x,y,z,t\right) \qquad 3.1$$

Where,

K_{xx}, K_{yy} and K_{zz} are Hydraulic conductivity values in the direction of Cartesian coordinates x, y, z (LT^{-1});

h is the potentiometric head (L);
S_S is specific storage of the unconfined aquifer (L^{-1});
t is time (T); and
V is volumetric flux per unit volume and represents sources, sinks of water (T^{-1}). The flux represents the withdrawal, recharge etc.

NOTE: The present study is limited to two-dimensional movement of groundwater and its interaction with surface water.

3.2.4 River-Aquifer Interaction Modeling

In current simulation, river boundary conditions are defined according to Darcy's Law. The river-aquifer interaction processes are simulated by the RIVER package (developed by Harbaugh et al., 2000) of MODFLOW through a seepage layer. Each cell of river feature in the model is defined by a conductance term represented as:

$$C_{RIVER} = \left(K_{RIVER} / B\right) \; WL \qquad 3.2$$

Where, L is length of river feature in the modeled cell (m),

W is width of the river (m),

B is thickness of the river bed (m) and

K_{RIVER} is vertical hydraulic conductivity of the riverbed material (m/day).

The flow from river to the aquifer Q_{RIVER} is defined by equations:

$$Q_{RIVER} = C_{RIVER} \left(H_{RIVER} - R_{BOTTOM}\right) \text{ for } h \leq R_{BOTTOM} \qquad 3.3$$

$$Q_{RIVER} = C_{RIVER} \left(H_{RIVER} - h\right) \text{ for } h > R_{BOTTOM} \qquad 3.4$$

Where, Q_{RIVER} is flow exchange between river and the aquifer (m^3/day),

C_{RIVER} is hydraulic conductance of seepage layer from Equation 3.2 (m^2/day),

H_{RIVER} is head of the stream (m),

h is head in the grid cell (m) and

R_{BOTTOM} is the bottom elevation of the seepage layer (m).

Equation 3.3 is used for the calculation of river leakage into aquifer, and Equation 3.4 for the calculation of groundwater discharge into the river. The above equations are used to quantify the gain-loss relationship between rivers and aquifers.

3.3 CONCEPTUAL MODELING

Conceptual modeling is a process in which data about hydro-geological conditions are gathered in an organized way to explain interaction processes over a specific area. A new conceptual model describing the components of the GW-SW system based on theoretical understanding of the interactions is presented in Figure 3.2.

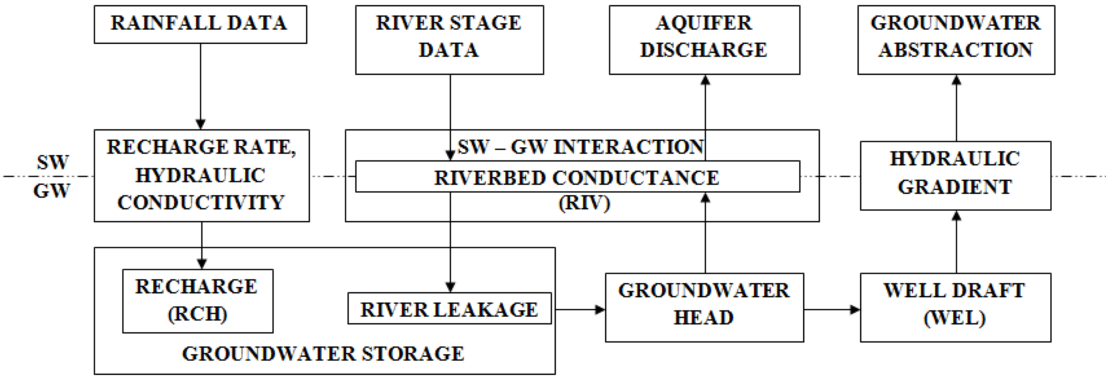


Figure 3.2 Conceptual model

The surface water input to the groundwater storage is guided by aquifer parameters such as recharge rate, hydraulic conductivity and riverbed conductance. The hydraulic head of groundwater may be either above or below the riverbed elevation depending upon groundwater storage. When the groundwater head is above the riverbed elevation, it is called Gaining River but if it is reasonably below the riverbed, then the river is called a Losing River.

Aquifer parameters, riverbed conductance and groundwater draft plays an essential role in the characterization of the interactions. Thus, it is imperative to calculate these values for various aquifer units, sources and sinks of the study area.

3.3.1 Aquifer Parameters

Aquifer parameters such as transmissivity, specific yield and rainfall recharge factor plays a significant role both in the estimation of groundwater resources and management of aquifers. The volume of water entering into the aquifer depends on the relative magnitude of these parameters. The estimation of these parameters is very essential in order to get a precise value of groundwater flux.

Generally, transmissivity and specific yield are determined by using pumping/recuperation tests while rainfall recharge factor is estimated by using infiltration tests or rainfall recharge models. Though rainfall recharge is non-linear in nature, in many cases a linear relationship is used.

Recharge rate is calculated by using rainfall infiltration factor method as a percentage of normal rainfall that recharges the corresponding aquifer unit of the study area. The ranges of rainfall infiltration factor are recommended as per the guidelines suggested by Groundwater resource Estimation Committee (GEC) Report (CGWB 2009).

Hydraulic conductivity values are considered from the representative values of various unconsolidated sedimentary and crystalline rocks (Domenico and Schwartz 1990).

3.3.2 Riverbed Conductance

Riverbed conductance is the conductivity of surface water through the riverbed across the unit cross-sectional flow area of river reach. In GMS, bed conductance for river/stream was assigned in terms of conductance per unit length. The hydraulic equation for the riverbed conductance per unit length is expressed as:

$$C_{RIVER} = (K/B)\, W \qquad 3.5$$

3.3.3 Groundwater draft

Groundwater storage decreases due to groundwater withdrawals through open wells connected to the aquifers underneath. The flow rate of water pumped from a well with depth of water 'H' below the ground surface is given by,

$$Q = (0.7457 * HP) / (g * H) \qquad 3.6$$

Where, Q = Discharge of water from the well in m^3/s.

H = Depth of water in the well in m.

g = Acceleration due to gravity, which is 9.81 m/s^2.

HP (Horse Power) = Power required to withdraw the water.

3.4 BUILDING THE MODEL

Geographic Information System (GIS) is a technology which is used to create, collect, manage, analyze and share the spatial data of surface features of the earth such as river, streams, urban area, forest area, various land use and land cover classes, administrative and watershed boundaries. The digital spatial data are created from scanned toposheets, georeferenced maps or from remotely sensed data such as satellite images and digital elevation models. It identifies the geographical location and extent of earth surface features using latitude, longitude and elevation values. The GIS data can be empowered with additional information such as name, physical condition and importance of the earth features. With the introduction of GUI to many numerical models, the spatial data of sources and sink features of earth surface are developed to carry out 2-dimensional or 3-dimensional visualization of surface water and groundwater flow. Lately, the GIS data has been utilized as a data input for many hydrological and environmental analysis. The application of GIS in the numerical models has greatly benefited the water resources management and research community for predicting the floods, sea-level rise, and groundwater scarcity.

In the present study, GIS has played a key role in the preparation of input datasets desired for the model. It was used to delineate different hydro-geological layers such as sub-catchment boundary, river, stream features, recharge zones and aquifer boundaries of the study area. GIS layers created in the form of shapefiles were imported into GMS and then converted into different arcs and coverages for building a conceptual model. Hydro-geological data such as riverbed conductance values were assigned for river arc features. Aquifer properties such as recharge rate and hydraulic conductivity were assigned properly. Then, the feature-object based conceptual model was converted into gridded model for simulating river-aquifer interactions. Thus, a conceptual model was developed.

3.5 MULTI-SCALE MODELING

Local-scale interactions are estimated by means of methods employed for sub-surface domain. The measurements made at a several points of a location provide accurate analysis for that place but overlooks river reaches. Interactions at a larger-scale are computed by using techniques applied for the surface water divide. The flow exchange approximation is consistent but the spatial variability of interaction inside the sub-surface zones of influences are not characterized precisely. The scale of assessment plays an important role in determining the hydro-geological parameters that calculate the interaction phenomenon. The better way to demonstrate the influence of scale on local scale processes is by measuring interactions at multiple scales of a catchment.

The multi-scale modeling process is concerned with the significance of physical processes occurring at every scale under consideration. The approach provides insight into the factors influencing the interaction processes. The determination of parameter uncertainty is essential to understand the reliability of various methods in the assessment of interactions. Due to uncertainties and limitations connected with different methods at different scales, multi-scale approach is recommended to characterize the interactions. Multi-scale modeling is competent and adaptable for different scales to reduce the uncertainties.

Past studies reveal that field measurement techniques were widely used for characterizing the interactions. Multi-scale measurements of flow exchanges using field instruments are practically strenuous and time consuming. Even though an extensive range of methods and techniques are available to measure the flow exchange at multiple spatial scales of catchment, the methods are selected based on the flexibility of integrating field heterogeneity and field measurements in the study. Advanced techniques such as numerical models are needed to be utilized for better understanding of the processes occurring at multiple scales. Numerical modeling of river-aquifer interactions at multiple scales of watershed agrees for consideration of multi-scale field measurements. The distinctive flow paths of hydrological processes at different locations and scales are considered in the numerical approach.

3.5.1 Top-Down Approach

The current study presents a new approach that utilizes a technique of identification and selection of site based on the top-down hierarchy from catchment scale to local scale for analyzing SW-GW interactions in a river basin. The aspect confers profound understanding of the interaction phenomenon by advancing the characterization of scale-dependent hydrological processes. The approach accords flexibility of selecting suitable sub-scale determined by flow estimates based on data availability and potential of dynamic interaction. A comparative study on the application of proposed approach for different geographical limit based on data availability is preferable.

Preliminary assessment is carried out to identify the potential locations of intensive SW-GW exchanges in the catchment. Based on hydro-geological heterogeneity and geomorphologic characteristics at the sub-catchment scale, the nature of hydraulic connection is evaluated. The characteristics of flow exchange are studied for different river segments in the sub-catchment by using interaction estimates. Figure 3.3 presents flow-chart of Top-Down Approach.

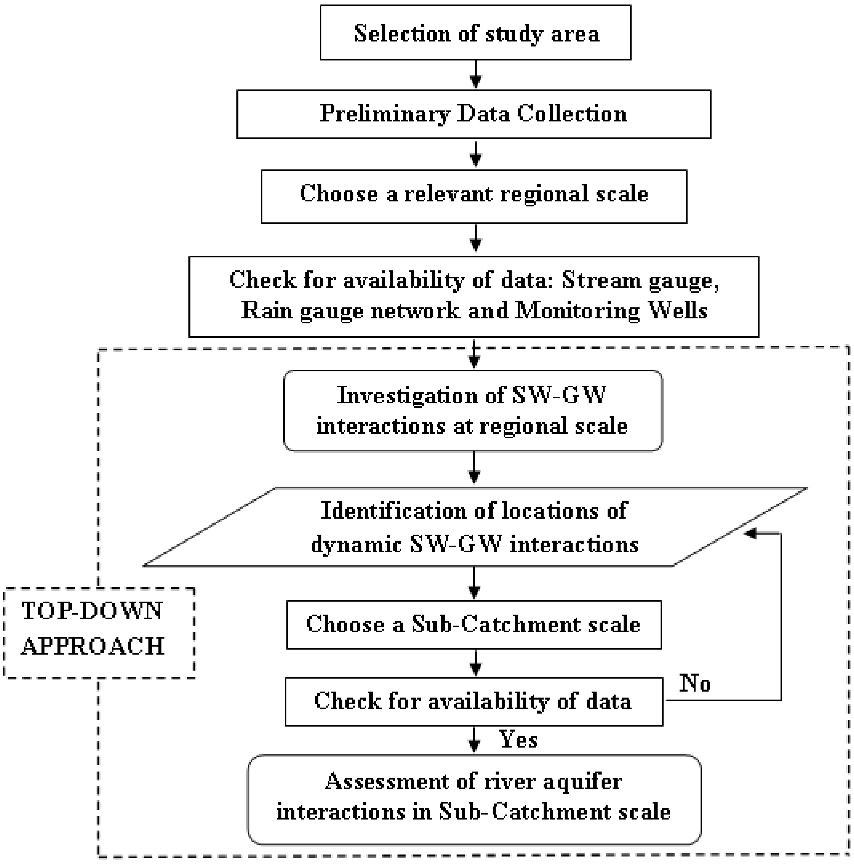


Figure 3.3 Flow-chart of Top-Down Approach

In the present approach, the scale-based processes are associated to the catchment and sub-catchment scale interactions. The interactions are evaluated at different spatial scales to address the challenges faced by resources at respective scales. The new perspective links the driving forces influencing the interaction processes occurring at the respective scales.

3.6 CLOSURE

In the present study, MODFLOW is extensively used for SW-GW interactions. The suitable sub-modules RIVER, RCH and WELL packages are used for the conceptual model developed. The various spatial data applied in GMS for the study are delineated using GIS. The present study focuses on understanding SW-GW interactions with reference to different hydrological components both at regional and sub-catchment scale. For this purpose, Nethravathi basin, in the coastal part of Karnataka is considered as the study area and details are discussed in subsequent chapters.

CHAPTER 4

MODEL DEVELOPMENT: REGIONAL SCALE

The present research is carried out to study SW-GW interactions at two different hydrological extents of a catchment. For the regional scale study, Nethravathi basin is chosen whereas for the intermediate scale, sub-catchment of Gowri-HoLe, a tributary of Nethravathi River is considered. A regional groundwater flow model is built as a requisite to estimate the SW-GW interactions at a sub-catchment scale. It identifies the dynamic interactions occurring over the catchment area using potentiometric maps, flow budgets and flow hydrographs.

4.1 NETHRAVATHI RIVER BASIN

Nethravathi River is a west-flowing river in Karnataka, India originating at Bangarabalige Gudda located at Western Ghats at an elevation of 1686 m. The river descends fast from the hills into steep valleys up to the foot of the Western Ghats and flows to join the Arabian Sea. The basin is spread over an area of 3314.43 km^2 lying between 12°30’ to 13°15’ north latitudes and 74°45’ to 75°45’ east longitudes as shown in Figure 4.1.

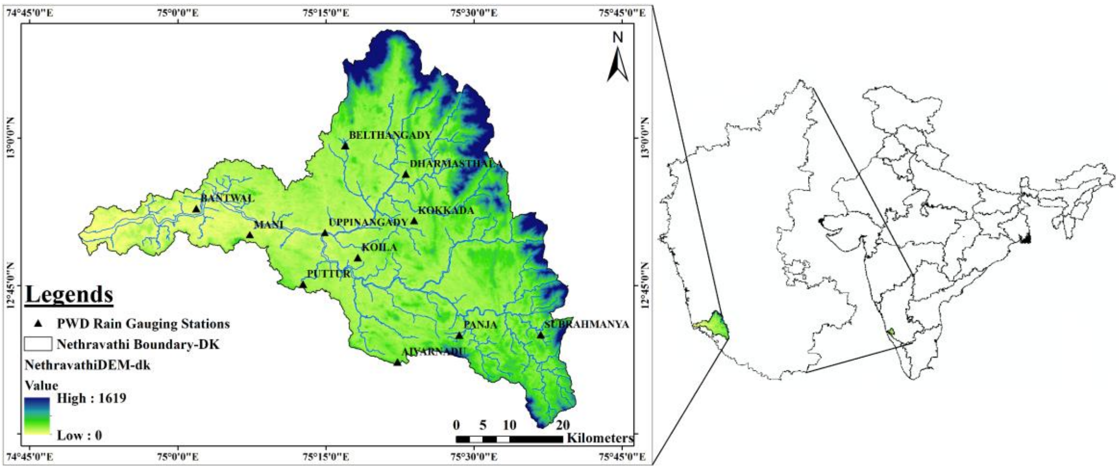


Figure 4.1 Geographical location of the Nethravathi Basin

The area is marked by high intensity rainfall during monsoon, suppressive weather conditions in hot season and humidity throughout the year. The weather is cooler in the upstream part of the study area i.e., along the Western Ghats, compared to the coastal areas. The rainfall in the area being plenty gives birth to numerous streams that flow through Western Ghats in small meandering channels. During monsoons, streams spread out and occupy the valley flood plains due to heavy rainfall. The river basin consists of sub-catchments namely, Nethravathi HoLe, Kumaradhara, Kallaji HoLe, Gowri-HoLe, Belthangadi HoLe, Neriya HoLe, Shisla HoLe and Gundya HoLe. Some of the prominent towns on the Nethravathi riverbanks are Belthangady, Dharmasthala, Uppinangady, Bantwal, Panemangalore, and Mangalore.

4.1.1 Climate

The average annual rainfall over the area for the last decade is about 3700 mm. Rainfall in the Western Ghats occurrence varies during March to May (Pre-monsoon), June to September (South-West monsoon), and October to December (North-East monsoon). These three seasons contribute about 4%, 90% and 6% respectively out of the total annual rainfall. The South-West monsoon period is relatively cooler with the daily mean temperature around 20°C. Whereas in the summer months of March to May, the daily mean temperature is around 35°C. The weather is humid throughout the year especially during South-West monsoon season since the mean humidity is always more than 85%. The sky is covered with dense clouds on most of the days and winds are strong mainly in the South Westerly direction during South-West monsoon period. Whereas, the number of such heavy clouded days is less during the post monsoon season. Otherwise, the area experiences a typical maritime climate, since it lies on the West Coast of India.

4.1.2 Geology and Soils

Migmatite and Tonalitic Gneisses are the major rocks underlying the basin, which are of Archean age and are termed as one of the oldest rock formations in peninsular India. Metabasalt with thin iron stone formations are found in the upstream and thick patches of Charnockite (Orthopyroxene Granite) are noticed across the catchment.

Laterites are found to overlay on the preliminary rock formations. Laterites are formed due to weathering and leaching process because of heavy rainfall with alternating wetting and drying periods. Due to intense leaching in the rainy season, a thin clay layer is formed below the porous laterites. The clay layer is about 1 - 2 m in thickness. The thickness of the laterites gradually decreases towards the coast. Thin alluvial sand covers these laterites. Alluvial, sandy and clayey-skeletal soils are observed in the coastal belt whereas fine, fine-loamy, loamy-skeletal soils are found in the top-surface of upstream hilly areas, forest, vegetation and river plain of the basin (Putty and Prasad, 2000).

4.1.3 Hydrogeology

Fractured and weathered Gneiss is the major water-bearing unit followed by Charnockite occurring as thick patches in certain areas. Groundwater exists in phreatic condition in the weathered zones and semi-confined to confined state in the fractured zones of both Gneiss and Charnockite formations. Lateritic aquifers present in isolated patches of inland and near shoreline are part of unconfined space for storing groundwater. Alluvial aquifers are found beneath the river flood plain and along the shoreline that are affected by saltwater intrusion.

During pre-monsoon season, the depth to water level ranges from 4.12 mbgl to 15.2 mbgl and it ranges from 0.75 mbgl to 8.65 mbgl during post-monsoon season. 36.5% of the wells show rise in seasonal fluctuation data whereas 63.5% of the wells show decline in water level. During post-monsoon season, the increase in water level ranges from 0.15 m to 16.0 m above mean sea level (MSL) and the decrease ranges from 0.65 m to 4.62 m. The long-term trend in the groundwater fluctuation over the last 10 years (2001-2010) indicates that 58% of the wells show an annual ascent in water level ranging from 0.014 m to 0.12 m. Whereas, rest of the wells (42%) show descent in the range of 0.01m to 0.19 m (CGWB 2012).

4.2 DATA COLLECTION

The primary step of data collection is useful in characterizing the surface water and groundwater systems of the catchment, and their connectivity. Table 4.1 summarizes the datasets and their sources.

Table 4.1 List of datasets and sources

Sl. No.	Datasets	Data Sources
1	Toposheets of scale 1:50000	Survey of India (SOI)
2	Digital Elevation Model data of resolution 27.8 m	Shuttle Radar Topography Mission (SRTM)
3	Printed lithology maps and soil maps	Geological Survey of India (GSI)
4	Aquifer parameters data such as transmissivity values, hydraulic conductivity.	Published Central Ground Water Board (CGWB) Reports, Literatures, Reference Text Books
5	Aquifer characteristics data such as depth/vertical extent of aquifer, discharge, depth to groundwater level.	CGWB Reports. Field data.
6	Bore-log data.	CGWB
7	Groundwater observation data of open wells	Department of Mines and Geology, Government of Karnataka.
8	Pumping wells data such as no. of pumping wells & depth, pumping hours, pumping capacity.	Ministry of Water Resources (MOWR), Government of India.
9	Gauge and discharge data of rivers/streams	Central Water Commission (CWC) and Karnataka Public Works Department (KPWD)
10	Daily rainfall data	KPWD

4.3 DATA PRE-PROCESSING AND ANALYSIS

In the present study, a conceptual model framework is developed by collecting and integrating the data pertaining to (a) catchment, (b) hydro-geology and (c) hydrology, using GIS. Figure 4.2 shows flowchart for the conceptual modeling framework.

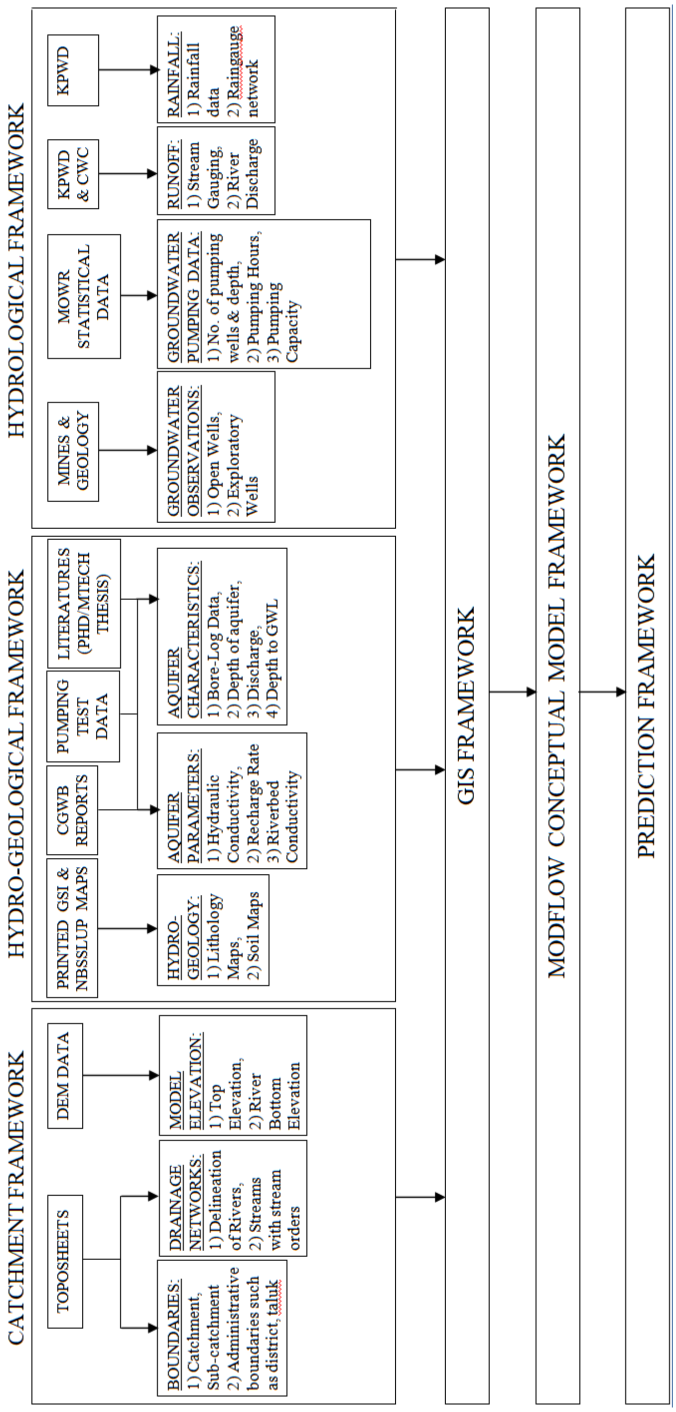


Figure 4.2 Flowchart of Conceptual Modeling Framework

4.3.1 Catchment Framework

(i) *Boundaries and drainage networks*:

Catchment and sub-catchment boundaries, administrative boundaries such as district boundary, taluk boundary, surfacewater features such as rivers, streams are digitized in the GIS format using ArcMAP 10.3 by using Survey of India (SOI) toposheets of scale 1:50000. The delineated catchment boundary is used as model boundary for the regional scale conceptual MODFLOW framework. Rivers and stream networks of different stream orders are delineated for attributing values of surface water contribution such as river stage into the model.

(ii) *Model Elevation*:

Digital Elevation Model (DEM) data of approximately 30 m resolution obtained from SRTM is used for the top layer elevation values of the conceptual model as well as for defining the river bottom elevation values. The river network is overlaid on DEM data by using GIS tools in GMS Map Module for the purpose of modeling and analysis of the SW-GW interactions. Figure 4.3 shows the river network of Nethravathi basin along with the DEM data.

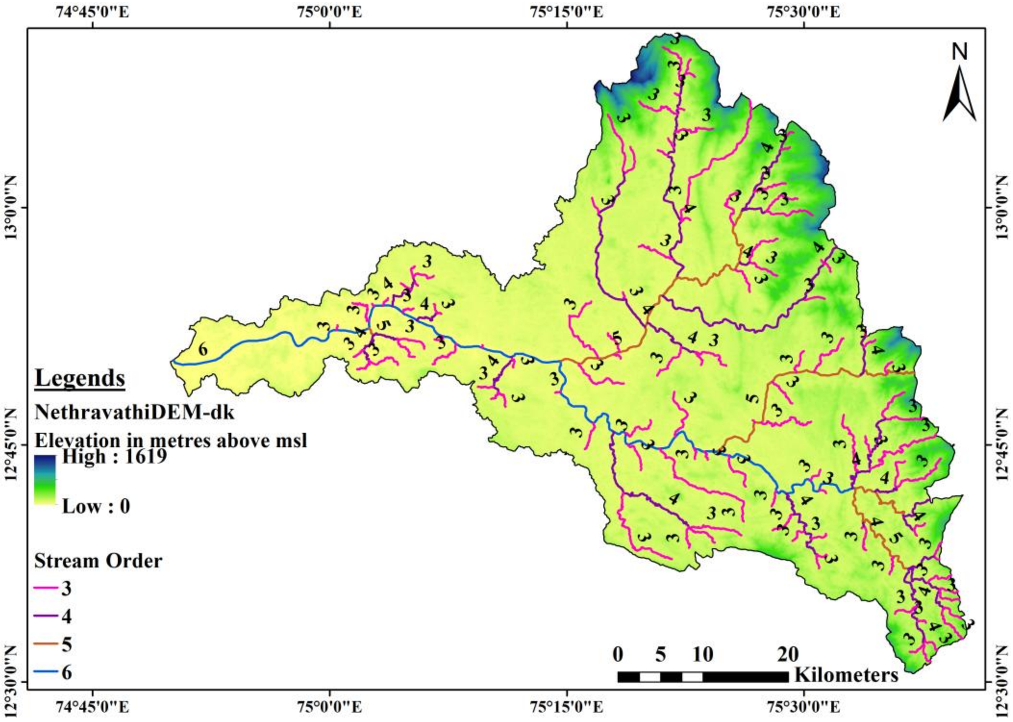


Figure 4.3 Nethravathi River network with DEM (DEM data source: USGS)

4.3.2 Hydro-geological Framework

(i) *Hydro-geology*:

Lithology maps are digitized in the GIS format by using the maps printed and published by Geological Survey of India (GSI). These maps are analyzed by identifying the weathered zones of geological units that store groundwater within. Aquifer map is delineated using above geological data to define the spatial extent of different water-bearing zones in the model. Figure 4.4 shows the aquifer recharge zones of Nethravathi river basin.

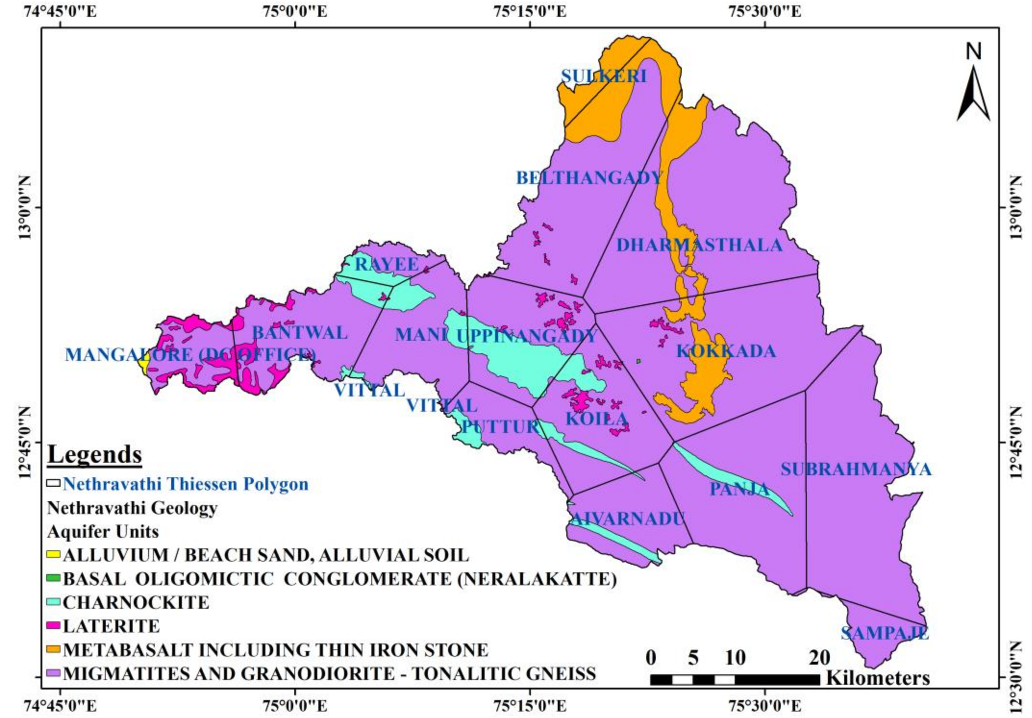


Figure 4.4 Aquifer recharge zones of Nethravathi river basin (Source: GSI)

The delineated aquifer map is used as groundwater divide for attributing values of aquifer parameters such as recharge rate, hydraulic conductivity values for respective geological units into the conceptual MODFLOW framework.

(ii) *Recharge rate and Hydraulic Conductivity in the study area*:

In the Figure 4.4, the Thiessen polygons of rain-gauge stations related to Nethravathi basin are overlaid on the geology map. The intersecting areas of Thiessen polygons with those of aquifer boundaries constitute Aquifer recharge zones. These zones are utilized for assigning recharge rate values into the conceptual model.

Recharge rate is estimated by using rainfall infiltration method as per the guidelines suggested by Groundwater resource Estimation Committee Report. In this method, recharge rate value is considered as percentage of normal rainfall that is recharging the corresponding aquifer unit of the study area. The ranges of rainfall infiltration factor are recommended as a guideline in the following Table 4.2 and is employed in each groundwater assessment unit (geological unit) based on their applicability to prevalent hydro-geological situation (CGWB 2009).

Hydraulic conductivity values are assumed for different aquifer units of Nethravathi river basin by using the representative values of various unconsolidated sedimentary and crystalline rocks (Domenico and Schwartz 1990) as shown in the Table 4.2:

Table 4.2 Rainfall Infiltration Factor and Hydraulic Conductivity Values for aquifer units of Nethravathi river basin

Sl. No.	Geological Units	Recharge Rate = Percentage of normal rainfall in the area (GEC guidelines)	Hydraulic Conductivity Values in m/day
1	Migmatites And Granodiorite - Tonalitic Gneiss	5 - 15	0.0006912 - 25.92
2	Charnockite	10 - 15	0.28512 - 4.4928
3	Laterite	4 - 10	0.03456 - 1728
4	Metabasalt Including Thin Iron Stone	4 - 10	0.000001728 - 0.036288
5	Basal Oligomictic Conglomerate (Neralakatte)	10 - 15	0.07776 - 518.4
6	Alluvium / Beach Sand, Alluvial Soil	20 - 25	0.01728 - 17.28

(iii) *Aquifer characteristics*:

Figure 4.5 shows the borehole lithology data available from Central Ground Water Board, for 5 different locations of Nethravathi basin.

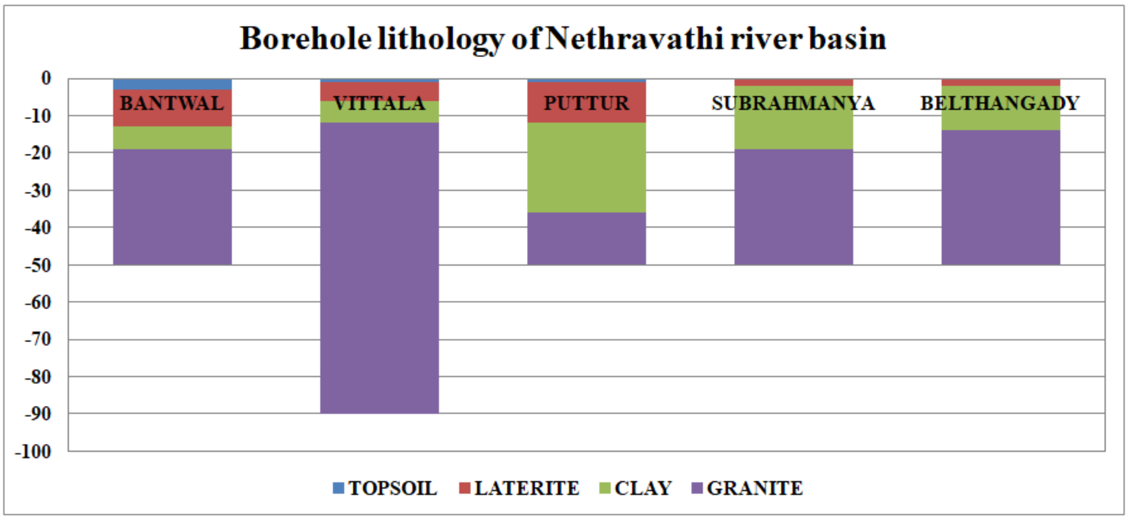


Figure 4.5 Borehole lithology of Nethravathi river basin

Since the borehole data available is very scanty, compared to the vast study area, multi-layered modeling approach is not advisable.

Using the available information, model is defined for the single-layered unconfined aquifer. The vertical extent of the single layer model can be assumed to vary upto depths of 20 - 40 m below the ground surface for different places of the study area depending upon the lithology since it can be observed that permeable layers from top soil to clay vary upto depths of 20 - 40 m below the ground surface.

Other aquifer characteristics such as discharge, depth to groundwater level are collected from published Central Ground Water Board (CGWB) Reports, field pumping test data and other literature.

4.3.3 Hydrological Framework

(i) *Groundwater level observations*:

Monthly groundwater level observation data of 15 open wells are collected from Department of Mines and Geology (M&G), Karnataka. Figure 4.6 shows the network of observation wells considered in the study area.

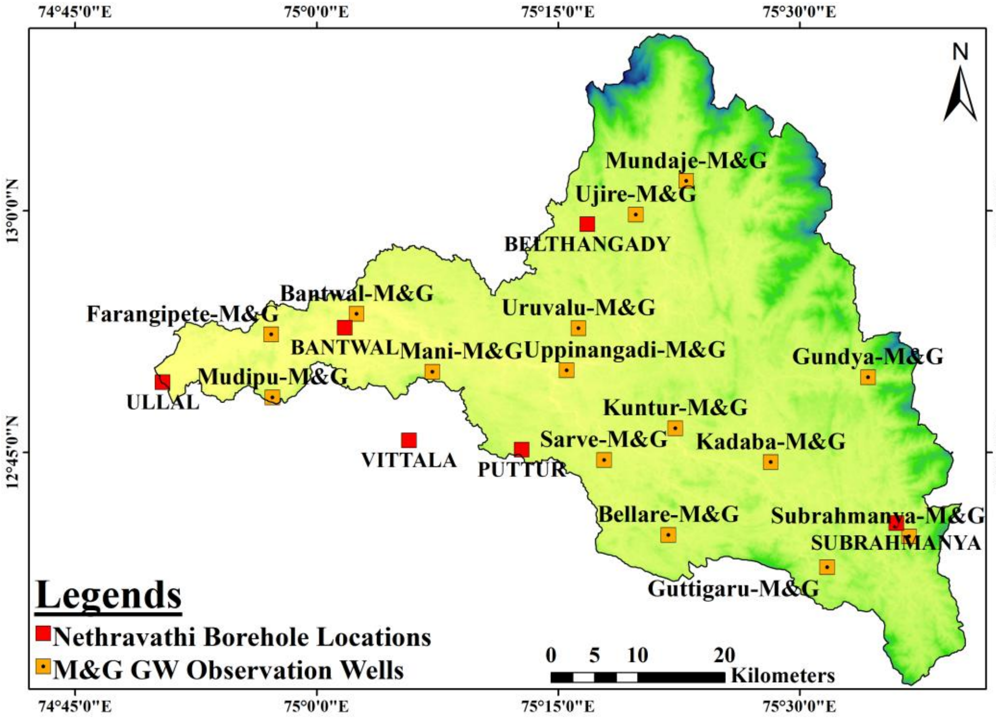


Figure 4.6 Groundwater observation wells of Nethravathi River Basin

(ii) *Groundwater pumping data*:

Groundwater pumping data of dug wells are collected from statistical data disseminated by Ministry of Water Resources, Government of India in the website *data.gov.in*. Village-wise distribution of open wells in the study area has been utilized to calculate pumping rate of wells based on the information available such as number of pumping wells, average daily pumping hours, wells in use, depth of wells, and pumping capacity of wells. Figure 4.7 shows the distribution of pumping wells in the study area.

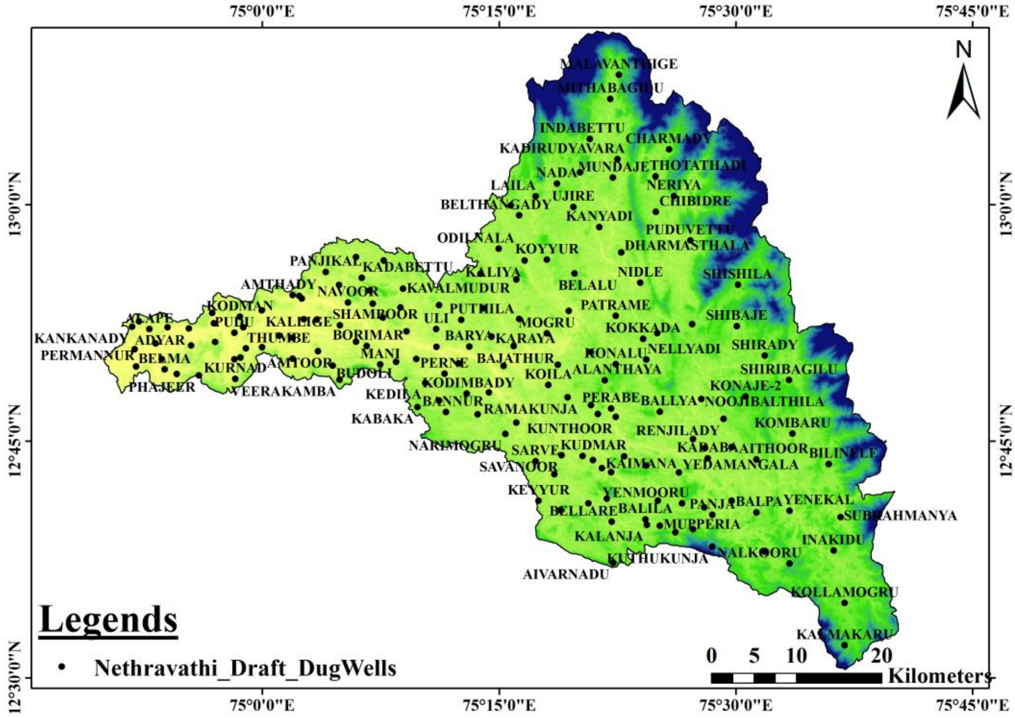


Figure 4.7 Distribution of pumping wells in Nethravathi River Basin

(iii) *Runoff data*:

Stream-gauge and discharge data are required as an input data into the conceptual modeling framework. In the study area, daily stream stage and discharge data are available only for 3 stations and details are as shown in Table 4.3.

Table 4.3 Streamgauging Stations of Nethravathi River Basin

Sl. No.	Latitude	Longitude	Location	River	Stream order	Agency
1	12° 44' 33.04" N	75° 17' 48.03" E	Sarve Bridge	Gowri-HoLe	4	KPWD
2	12° 50' 29.2" N	75° 14' 53.71" E	Uppinangadi	Nethravathi	5	KPWD
3	12° 52' 48.26" N	75° 2' 28.77" E	Bantwal	Nethravathi	6	CWC

(iii) *Rainfall data*:

Rainfall data is required to calculate recharge rate which is one of the key input data to the model. Daily rainfall data is collected from 16 rain-gauge stations of Irrigation Investigation Section, Karnataka Public Works Department (KPWD). Figure 4.8 shows the locations of rain gauge and stream gauge stations in the study area.

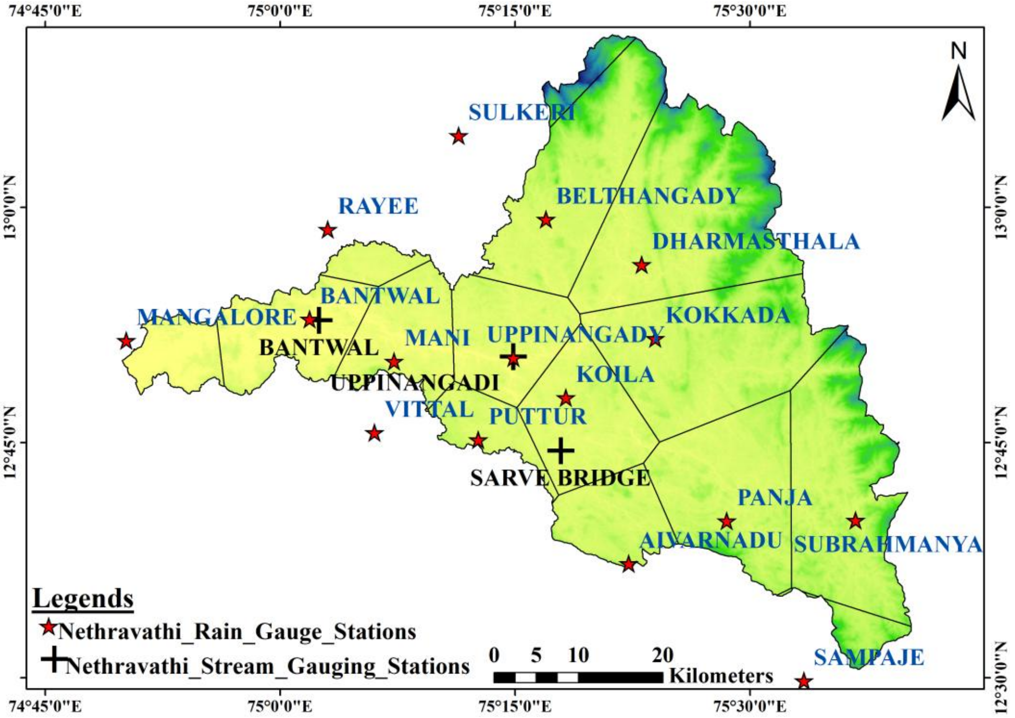


Figure 4.8 Rain-gauge and stream gauge stations of Nethravathi River Basin

4.4 MODEL DEVELOPMENT

In the present study, a MODFLOW-based regional groundwater model is developed to represent the SW-GW interactions of the Nethravathi river basin, using conceptual modeling approach.

The model is designed with GMS Map Module using hydro-geological data for modeling process along with the help of ArcGIS for spatial data. GMS Map module consists of a set of processing tools for model domain characterization, conceptualization, grid generation, geostatistical analysis, and output post-processing.

4.4.1 Steps in building a MODFLOW Conceptual Model

In the present study, conceptual modeling is adopted to build a regional groundwater system. In this technique, all input data are represented in terms of physical features, such as wells, rivers and recharge zones, which are converted into a gridded model.

(i) *Importing the data*

In GMS Map-Module, a new conceptual model is created to build the model and units. Boundary and sources/sinks coverages are created in the conceptual model by importing different hydro-geological layers into the map module of GMS.

(ii) Defining the coverages

Five coverages are built in the conceptual model by selecting suitable MODFLOW packages such as well (WEL), river bed conductance (RIV), recharge (RCH) and layer property flow (LPF). These coverages contain information such as flow rate of wells, river stage, recharge rate and hydraulic conductivity values. The fifth coverage is the observed groundwater head data utilized for calibrating and validating the model.

(iii) *Locating the grid frame to the model and creating the grid*

Grid frame is defined for the extent and boundary of the model by selecting the location and orientation inside the frame. The grid frame is utilized to discretize the model that represents the feature objects in the grid format.

(iv) *Selecting the flow package*

The LPF package of MODFLOW-2000 is selected to run the model for grid-wise groundwater flow calculations for all applicable coverages.

(v) *Initializing the MODFLOW data and defining active/inactive zones*

Once the grid is constructed, MODFLOW data for the whole grid is initialized and then active/inactive zones of the model boundary are delineated. Each of the cells inside the model boundary is designated as active and that outside the model boundary are designated as inactive.

(vi) Interpolating layer elevations

After initialization of the MODFLOW data, DEM data representing the terrain of the study area is imported into GMS and interpolated into the top elevation of the MODFLOW grid.

(vii) Checking and running the simulation

Prior to the simulation, the Model Checker is used to rectify the mistakes/errors if any are made during the preparation of the conceptual model. Gridded model is run for the simulation after removing all the errors and warnings.

(viii) Viewing the results

A set of contours representing the groundwater heads and flow budget values are available for all time steps from the simulated model. The MODFLOW result consists of a head file and a cell-by-cell flow (CCF) file. GMS uses the CCF file to present flow budget values.

4.5 MODEL DISCRETIZATION

The conceptual model grid for the regional scale consists of 291 rows and 367 columns and one layer. In the horizontal direction, each cell has an approximate dimension of 281 × 273 m. The inactive cells do not allow flow into or out of the cell.

There are total of 33,281 active cells representing the study area. Figure 4.9 represents the regional scale conceptual model grid with boundary conditions.

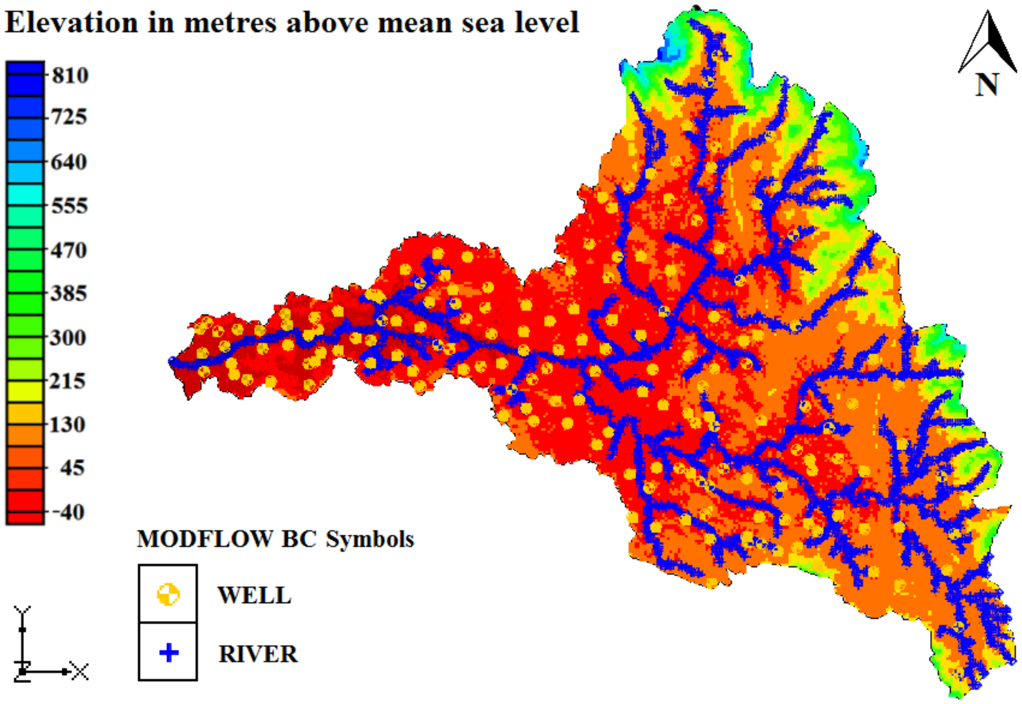


Figure 4.9 Regional-scale Conceptual model grid

From CGWB borehole data, it is identified that the study area consists of shallow unconfined aquifer with the thickness ranging from 20 to 40 m. Hence, the bottom elevation value for the single-layered model is assigned to be -30 m with respect to mean sea level, which corresponds to the base of the shallow unconfined aquifer.

The model area is represented on a two dimensional grid in the horizontal direction and as a single unconfined layer in the vertical direction. Digital Elevation Model (DEM) data of approximately 30 m resolution obtained from SRTM is interpolated into the top elevation of the conceptual model grid by importing into GMS.

4.5.1 Initial and Boundary Conditions

The initial/starting heads of groundwater flow is considered equal to that of top elevation of the aquifer. Monthly river stage values are assigned for the river segments. The riverbed conductance values are calculated by considering hydraulic conductivity for the riverbed material, fine loamy sand as 2.5 m/day (Todd and Mays, 2005) as shown in Table 4.4.

Table 4.4 River bed conductance values of Nethravathi basin

Sl. No.	Location	River	Width of the river in m.	River bed conductance per meter length (m^2/day)
1	Sarve Bridge	Gowri-HoLe	60	150
2	Uppinangadi	Nethravathi	180	450
3	Bantwal	Nethravathi	350	875

4.6 MODEL CALIBRATION AND VALIDATION

During calibration, model input parameters are systematically changed to match field data within satisfactory condition. Model calibration is carried out to simulate groundwater heads by analyzing set of parameters, boundary conditions and factors that influence GW fluxes.

GMS is a user-friendly interface for MODFLOW with sound GIS connection for allocating model input parameters either cell-by-cell or by zone-based approach. In the present study, model inputs are assigned into the model by dividing the model domain into a number of zones for the single-layered model assuming similar hydro-geological properties, since cell-by-cell allocation is a time-consuming task especially in a regional-scale model.

4.6.1 Steady State Modeling

Steady-state modeling generally gives initial estimates of model parameters. It also helps to understand the groundwater flow-budget and verify the assigned boundary conditions of the model. Steady-state simulation is a requisite to evaluate the groundwater head distributions for the transient-state simulation.

The model was calibrated under steady-state condition for monsoon months of June, July, August and September from 2004 - 2009. In the calibration task, aquifer parameters namely, hydraulic conductivity and recharge rate values are varied by trial and error method until, a good match between computed and observed heads are obtained. The observed groundwater head data of 15 open wells available from Department of Mines and Geology, Government of Karnataka is collected. A regional groundwater flow model is built as a pre-requisite to identify the dynamic exchange occurring over the catchment area using potentiometric maps and flow budgets. The calibrated values of recharge rate and hydraulic conductivity for different aquifer property zones are noted. The developed regional groundwater model was validated for the monsoon months June, July, August and September of 2010 - 2011 using 15 open wells utilized during calibration process. Model results were used to examine the SW-GW flow exchange.

CHAPTER 5

MODEL APPLICATION: SUB-CATCHMENT SCALE

5.1 GOWRI HOLE SUB-CATCHMENT

In the present study, Gowri-HoLe sub-catchment is considered for the intermediate scale study of SW-GW interactions. Figure 5.1 shows the sub-catchment area of Gowri-HoLe, which is a tributary of Kumaradhara River.

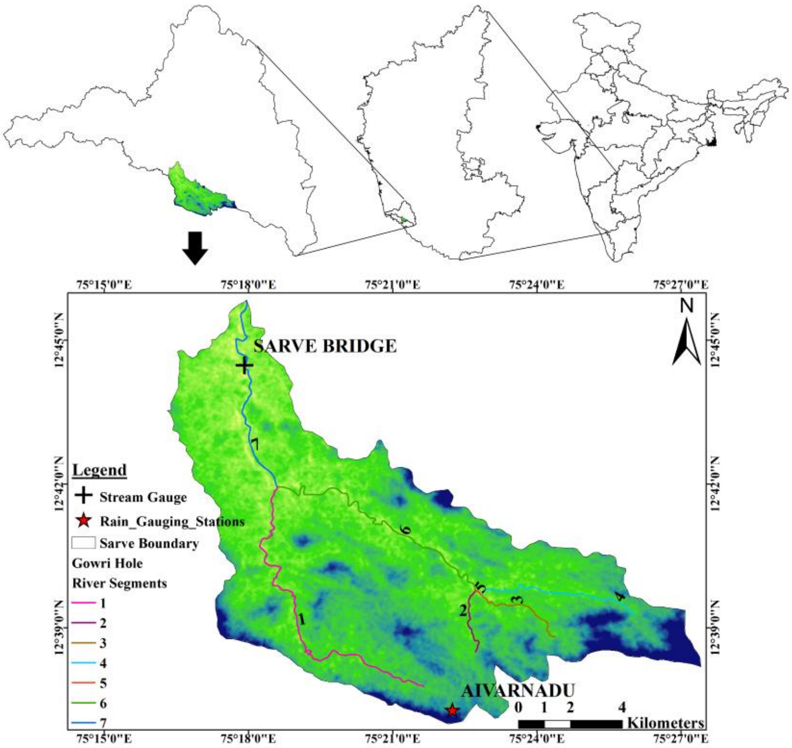


Figure 5.1 Gowri-HoLe sub-catchment

It flows further to join river Nethravathi, a major west-flowing river of Karnataka, India. Gowri-HoLe is a 4th order stream resulting from the union of Madalu hole and few other streams taking birth at Aivarnadu and Kalmadka forest. The sub-catchment covers an area of 134 km^2, geographically spread between 12°37’ to 12°46’ north latitudes and between 75°16’ to 75°28’ east longitudes. The study area being a part of

Western Ghats of Karnataka receives an average annual rainfall around 3500 mm. Even though it consists of only one rain gauge station at Aivarnadu and bounded by quite a good number of rain gauge stations at Koila, Panja, and Puttur. The sub-catchment area is having an undulating topography distributed with hills over the elevated upland area, where streams originate. Streams descend along the valley slopes to the alluvial plains to join Gowri-HoLe and flow towards the outlet. Daily river-stage and discharge values are measured at Sarve Bridge, located near the sub-catchment outlet.

5.1.1 Hydrogeology

Figure 5.2 represents the Geological map of the study area including the rain-gauging network.

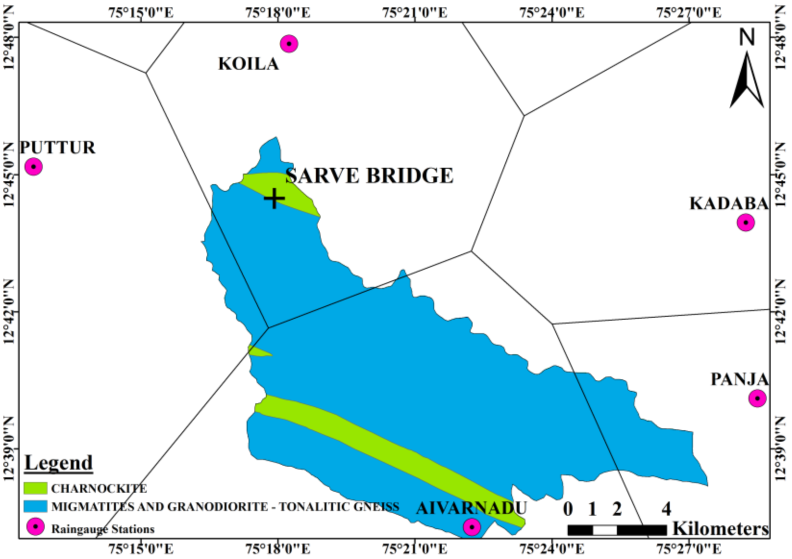


Figure 5.2 Geological map and rain gauge network of Gowri-HoLe Sub-catchment

Tonalitic Gneiss dominates the study area, which is one of the oldest rock formations of rock in India. Thick bands of Charnockite are also present in some parts of the study area. Both basement rocks are recognized to be of ancient Achaean age. Groundwater occurs in the unconfined condition of weathered zones of Gneiss and Charnockite ranging from 5 – 40 metres below ground level (mbgl) and 20 – 30 mbgl respectively. Detailed hydro-geological investigations such as pumping tests were conducted earlier by CGWB in the study area. Pumping test results and aquifer geology data give a clear insight into the condition of the aquifer and its recharge potential.

5.1.2 Soil Distribution

Factors such as geography, climate, soil classification, hydro-geology influence the variation of groundwater residence rate with surface water bodies. Different types of soils such as Fine soil, Fine Loamy, and Loamy-skeletal soils cover the top layer of the study area as shown in Figure 5.3.

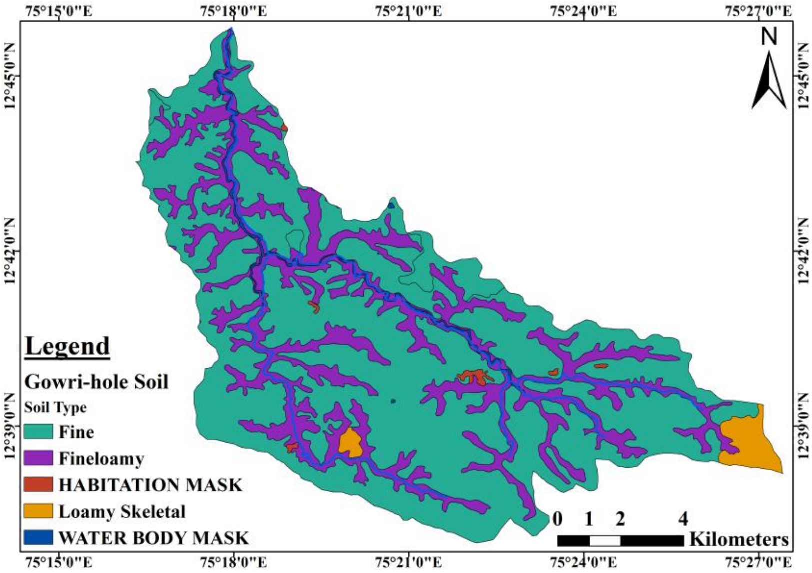


Figure 5.3 Soil Map

The fine soil is predominant in the upland slopes, whereas Fine Loamy soils are spread in the lower and intermediate slopes of the valley. Fine loamy soils are transported down the valley and deposited along the river banks and plains. They are most suitable for agriculture practice because of its very fertility. Loamy-skeletal soils are found at higher altitudes in Aivarnadu and Kalmadka reserve forest area where the temperature is low and rainfall intensity is high. They are covered mostly by forest vegetation suitable for soil conservation practices.

5.2 DATA COLLECTION

The hydro-geological data play a key role in understanding and characterizing the SW-GW systems of the catchment and their connectivity. Survey of India toposheets of 1:50000 were used for the delineation of sub-catchment boundary, river and stream features of the study area. Geological maps were obtained from the Geological Survey of India for defining aquifer boundaries. Daily rainfall data of rain gauge stations located at Aivarnadu, Koila, Panja and Puttur were gathered from Karnataka Public Works Department (KPWD). Daily river-stage and discharge data of Gowri-HoLe gauged at Sarve Bridge were collected from KPWD. Groundwater abstraction statistical data such as number of pumping wells, average daily pumping hours, wells in use, depth of wells, and pumping capacity of wells were downloaded from the website data.gov.in disseminated by the Ministry of Water Resources, Government of India. Monthly groundwater level observation data of two open wells were procured from Department of Mines and Geology, Karnataka. Whereas, seasonal groundwater level observation data of one dug well was collected from CGWB for the study. Digital Elevation Model (DEM) data of 1 arc second (approximately 30 m resolution) acquired by SRTM was downloaded from the official website of United States Geological Survey (USGS).

5.2.1 Aquifer Parameters of Gowri-HoLe sub-catchment

Recharge rate is estimated by using rainfall infiltration factor method as per the guidelines suggested by the Groundwater resource Estimation Committee of CGWB. The ranges of rainfall infiltration factor (CGWB 2009) and hydraulic conductivity values (Domenico and Schwartz 1990) are presented in Table 5.1.

Table 5.1 Rainfall Infiltration Factor and Hydraulic Conductivity Values for aquifer units of Gowri-HoLe sub-catchment

Sl. No.	Geological Units	Recharge Rate = Percentage of normal rainfall in the area (GEC guidelines)	Hydraulic Conductivity Values in m/day
1	Migmatites and Granodiorite - Tonalitic Gneiss	5 - 15	0.0006912 - 25.92
2	Charnockite	10 - 15	0.28512 - 4.4928

5.2.2 Riverbed Conductance

Riverbed conductance per unit length (m^2/day/m) determined for different segments of Gowri-HoLe is presented in Table 5.2.

Table 5.2 Riverbed conductance values of Gowri-HoLe Sub-catchment

River Segment	Riverbed conductance, C_{RIVER} (m^2/day/m)	Hydraulic conductivity, K (m/day)	Approximate Width of the river, W (m)	Assumed Thickness of riverbed, B (m)
1 (AB)	25	2.5	10	1
2 (CD)	20	2.5	8	1
3 (EF)	15	2.5	6	1
4 (GF)	25	2.5	10	1
5 (DF)	50	2.5	20	1
6 (BD)	75	2.5	30	1
7 (BH)	100	2.5	40	1

5.2.3 Groundwater draft

Distribution of open wells considered for groundwater pumping along with river segments of Gowri-HoLe sub-catchment is shown in Figure 5.4.

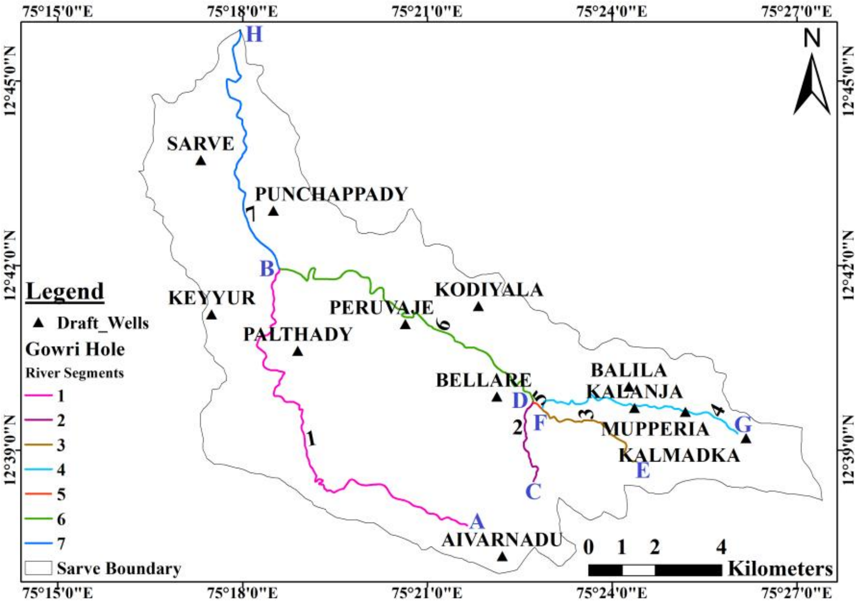


Figure 5.4 River Segments and Pumping wells of Gowri-HoLe sub-catchment

The estimation of groundwater draft is based on the information available (such as number of pumping wells, average daily pumping hours, wells in use, depth of wells, and pumping capacity of wells) in the website data.gov.in developed by Ministry of Water Resources, Government of India. Groundwater draft for the dug wells was determined using Water Power equation based on the above statistical data.

5.3 MODEL APPLICATION

In the current study, a regional groundwater model is downscaled for the assessment of stream-aquifer interactions of the Gowri-HoLe sub-catchment, using Top-Down approach.

5.3.1 Model Discretization

The study area was represented by a two-dimensional single-layered conceptual model grid consisting of 582 rows and 734 columns with 1,44,731 active cells. The size of each cell within the model domain was of approximate dimension 30 m x 30 m. Figure 5.5 represents the DEM data that was interpolated into the top elevation layer of the model grid.

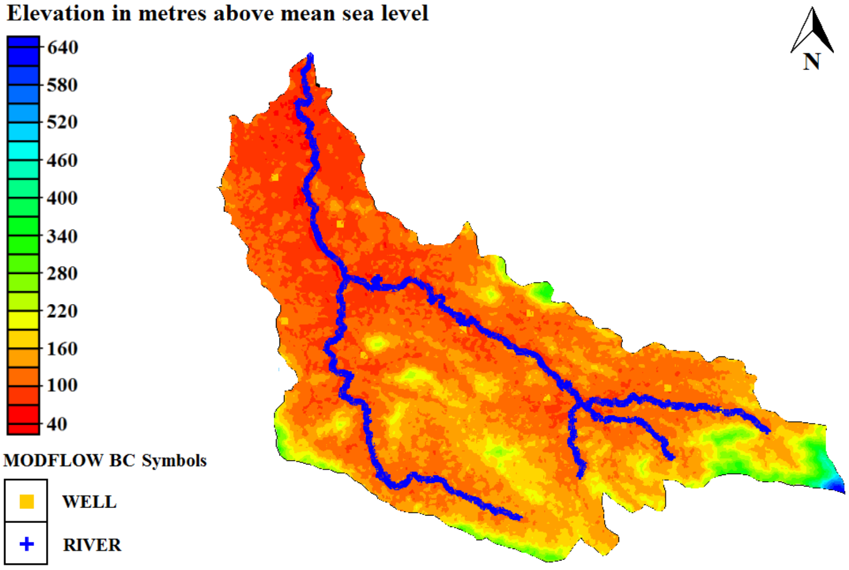


Figure 5.5 DEM data with Boundary Conditions for sub-catchment scale model

From aquifer characterization studies carried out by CGWB in the study area, it was identified that the thickness of the unconfined aquifer is varying from 20 to 40 m. The bottom elevation value for the single-layered model was assigned to be -30 m.

5.3.2 Initial and Boundary Conditions

Figure 5.5 also presents the model domain exhibiting the MODFLOW boundary conditions. The conceptual model was at first simulated under the steady-state condition for determining initial head conditions. Daily river-stage values and groundwater draft values were assigned for river arc features and wells respectively.

5.3.3 Model Calibration and Validation

Model calibration is often essential to estimate the aquifer flow characteristics. In the present study, the model was calibrated for transient analysis from June 2004 to May 2010 with a daily step input of all necessary hydro-geological data. Monthly observed groundwater head data available from two observation wells of Department of Mines and Geology, Government of Karnataka and seasonal data of one observation well of CGWB, Government of India were used for comparison of simulated and observed groundwater heads. During the calibration process, aquifer parameters such as hydraulic conductivity and recharge rate values were adjusted until computed and observed groundwater heads matched. The calibrated values of recharge rate and hydraulic conductivity values for different aquifer property zones are noted.

Automated Parameter Estimation (Automated PEST) analysis was performed to get better results by reducing the error in the simulated model. In the present study, the simulated model was validated with observed data for a period of 2 years from June 2010 to October 2012 under daily-step transient conditions. The details of observation wells utilized for calibration and validation process are presented in Table 5.3.

Table 5.3 Groundwater observation wells for calibration and validation

Sl. No.	Well Location	Geographical Co-ordinates	Elevation in m above MSL	Observation Period	Monitoring Agency
1	Sarve	12°44'32" N 75°17'52" E	69.4	Monthly	Department of Mines and Geology, Karnataka
2	Madavu	12°41'30" N 75°18'30" E	89	Quarterly	CGWB
3	Bellare	12°39'53" N 75°21'52" E	102.48	Monthly	Department of Mines and Geology, Karnataka

5.3.4 Simulation and Error Statistics

The simulation statistics for the sub-catchment scale model during calibration and validation period (mentioned inside the parenthesis) are presented in Table 5.4.

Table 5.4 Simulation Statistics of sub-catchment scale model

Well Location	Groundwater Head values in m above MSL	Minimum	Maximum	Mean	Standard Deviation
Madavu	Observed	78.37(79.59)	84.91(83.74)	81.33(82.09)	1.20(1.29)
	Computed	80.78(80.81)	83.28(83.45)	81.45(81.7)	0.74(0.8)
	% Difference	3.07(1.53)	-1.92(-0.34)	0.16(-0.47)	-
Bellare	Observed	90.25(91.17)	99.02(98.09)	94.34(95.06)	2.35(2.42)
	Computed	91.96(92.01)	100.01(100.5)	94.15(94.84)	2.39(2.58)
	% Difference	1.89(0.92)	1.00(2.46)	-0.20(-0.23)	-
Sarve	Observed	61.45(62.68)	69.55(69.23)	65.53(66.35)	2.05(2.19)
	Computed	63.31(65.31)	70.79(69.71)	66.10(66.43)	1.45(1.32)
	% Difference	3.03(4.19)	1.78(0.69)	0.87(0.13)	-

The statistics of the observation wells shows that the percentage difference in mean values is relatively less. Similar trend was observed for datasets even during the validation period (mentioned inside the parenthesis).

The simulated model was evaluated using the error summary for both calibration and validation period as shown in Table 5.5.

Table 5.5 Error Summary of simulated sub-catchment scale model

Error Summary	Calibration Period		Validation Period	
	Head (m)	Percentage Error (%)	Head (m)	Percentage Error (%)
Mean Absolute Error (MAE)	1.37	0.41	1.28	0.28
Root Mean Squared Error (RMSE)	1.79	0.56	1.53	0.53

From the error summary, it can be concluded that errors of the simulated model in both the calibration and validation period are within acceptable limits.

CHAPTER 6

RESULTS AND DISCUSSION

In the present study, a conceptual model is developed for SW-GW interactions using MODFLOW. The scale of the study area is adapted using Top-Down Approach. As a case study, two typical classified catchments are considered:

1. Nethravathi river basin for regional scale studies,
2. Gowri-HoLe sub-catchment (a tributary of Nethravathi River) for intermediate scale studies

In both the cases, the model is calibrated and validated using observed groundwater level data. The results are discussed in the following sections.

6.1 REGIONAL SCALE MODELING

For regional scale modeling, Nethravathi catchment, a west-flowing river is considered. The details of the river basin are discussed in detail in the study area section.

A groundwater model is built as a pre-requisite to examine the occurrence of SW-GW interactions for the Nethravathi basin using potentiometric maps and flow budgets. The regional scale model is simulated under steady state condition for calibration period of 2004 to 2009 and validation period of 2010 to 2011.

6.1.1 Calibration of the regional scale model in the year 2004

a) Spatial distribution of Groundwater heads:

In the present study, regional groundwater heads are calibrated and validated for the monsoon months of June, July, August and September. Spatial distributions of computed groundwater heads and calibration target bars for groundwater observation level data of 15 wells in the calibration year 2004 are shown in Figure 6.1.

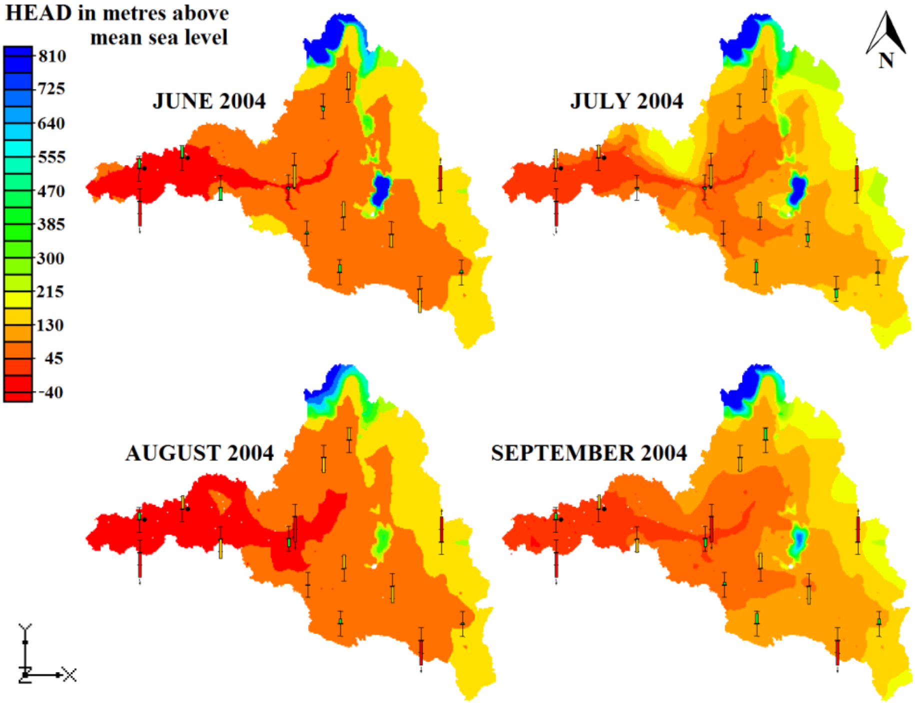


Figure 6.1 Computed groundwater heads for the calibration year 2004

The coloured bar in the calibration targets represents the residual error. If the residual error is <10%, the colour bar is drawn in green. If the residual error is more than 10% but less than 20%, then bar is drawn in yellow. If the error is greater than 20%, then bar is drawn in red. The calibration target is in good agreement for most of the wells. It demonstrates the adequacy level of model calibration.

The groundwater levels were observed to slightly increase in the downstream and decrease in metabasalt aquifer portions in the upstream of the basin during June to July 2004. From July to August 2004, decrease in groundwater levels was observed in both downstream part and upstream part of metabasalt aquifer portions in the basin. However, the groundwater levels were noticed to recover in the September month throughout the basin. The fluctuations in the groundwater heads indicated the significant influence of baseflow on the river flow in July and September months.

The spatial pattern of the groundwater levels were noticed to vary dynamically in the months of July and September 2004. In the study, the groundwater flow movement in the unconfined space of the catchment area appeared to follow the direction of surface water flow in the basin.

b) *Comparison of observed and computed Groundwater heads*:

The observed and computed values of groundwater heads for 15 wells, calibrated for the months of June, July, August, September 2004 are presented in the Figure 6.2.

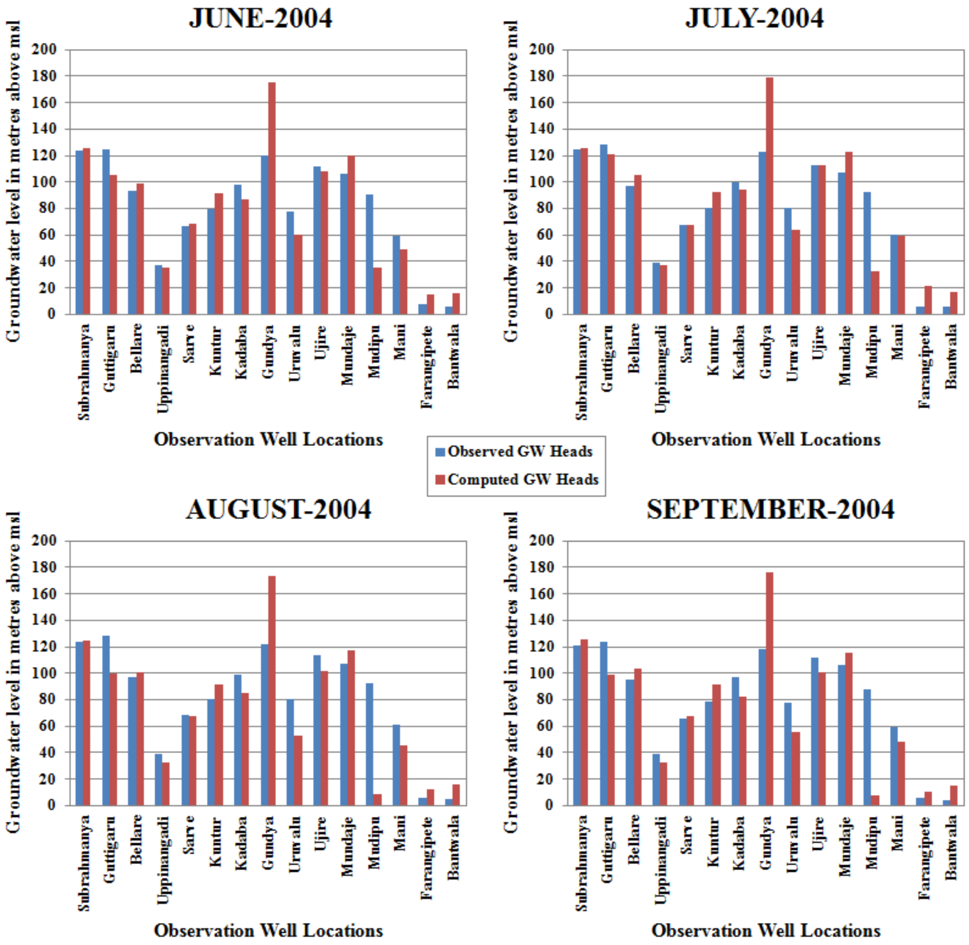


Figure 6.2 Observed v/s Computed groundwater heads in the year 2004

From the Figure 6.2, it is observed that in most of the wells, the observed and computed groundwater heads are reasonably matching. However, the following observations are made. In the month of June 2004, at Gundya, the observation head is around 120 m while the computed head is 175 m. At Mudipu, the observed head is 90 m whereas the computed head is 35 m. In the month of August 2004, at Gundya, the observed head is around 122 m as against the computed head of 172 m. And in

Mudipu, the observed head is about 90 m while the computed head is around 10 m. Similar trends were observed in the months of July and September 2004 respectively.

During calibration year 2004, there is significant over-estimation of groundwater heads in Gundya and under-estimation of groundwater heads in Mudipu. The top elevation value interpolated for the location of observation well at Gundya using DEM data was considerably more compared to the field elevation data and whereas it was less in the case of well at Mudipu. The study revealed that the dissimilarity of elevation values being the reason for the inconsistency in computed groundwater levels for the 2 wells resulting in over-estimation and under-estimation respectively.

Under-estimation of groundwater heads is also observed at Guttigaru and Uruvalu in August and September 2004. The aquifer parameter values were observed to be simplified for the aquifer characteristics of the basin leading to minor difference in the estimated groundwater heads.

Figure 6.3 shows the results of best fit for observed and computed values of all 15 observation wells utilized for the calibration year 2004.

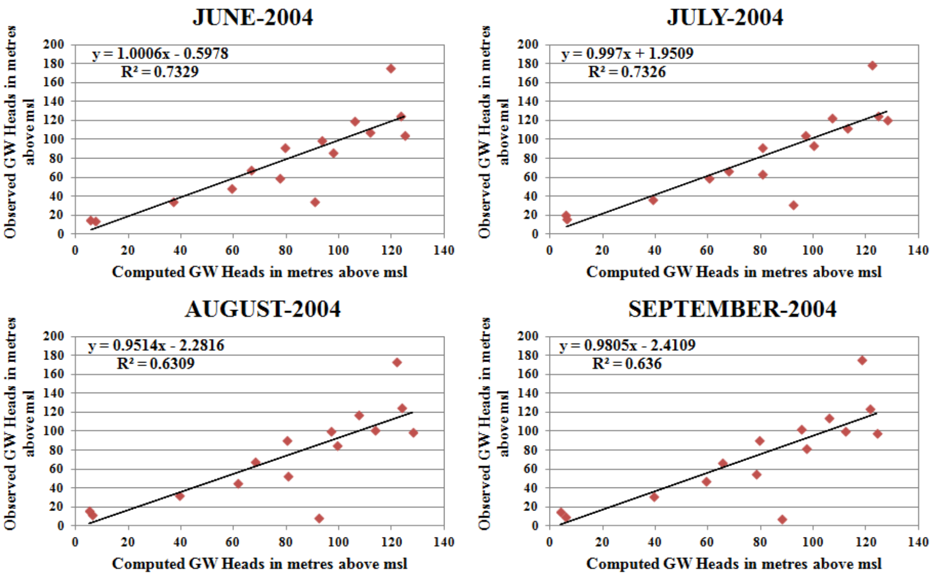


Figure 6.3 Scatter plots for the calibration year 2004

From the above Figure 6.3, it is observed that, the correlation co-efficient is close to 0.7 on an average in the calibration year 2004 and it can be acceptable. For all 4 months, only 2 note-worthy outlier points are observed. This illustrates that the calibration of regional groundwater model is reasonably well suited for the studies related to SW-GW interactions.

c) *Groundwater flux*:

The groundwater exchange with the surface water is analyzed from the flow budget values obtained from the simulated model for the year 2004 as shown in Table 6.1.

Table 6.1 Flow budget values for the calibration year 2004

Time	Flow Budget Values					
	Inflow in 10^6 m^3/day			Outflow in 10^6 m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
June 2004	4.87	8.19	13.06	9.89	3.17	13.06
July 2004	3.68	15.58	19.26	15.98	3.28	19.26
Aug 2004	5.72	3.47	9.19	6.19	3.00	9.19
Sep 2004	5.57	4.20	9.77	6.75	3.02	9.77

It is observed from the Table 6.1 that the domination of aquifer discharge is more in terms of contributing to the river flow during monsoons compared to river leakage and rainfall recharge.

6.1.2 Calibration of the regional scale model in the year 2005

a) Spatial distribution of Groundwater heads:

Spatial distributions of computed groundwater heads and calibration target bars for the calibration year 2005 are shown in Figure 6.4.

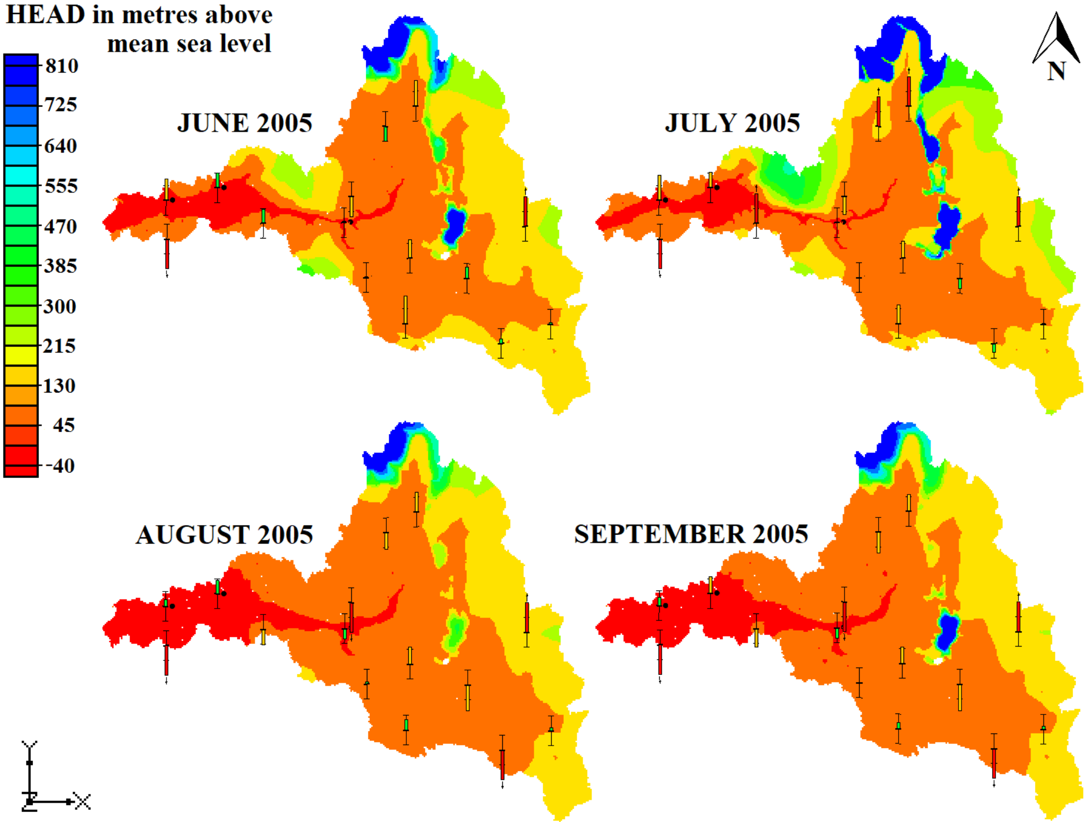


Figure 6.4 Computed groundwater heads for the calibration year 2005

The satisfactory agreement of calibration target for most of the wells displays the competence level of model calibration for observation level data of 15 wells.

From June to July 2005, slight increase in groundwater levels was observed in both the downstream areas and metabasalt aquifer units in the upstream portion of the basin. During July to August 2005, groundwater levels were observed to decrease throughout the catchment area. In the month of September, significant increase was observed in groundwater levels of the metabasalt aquifer units in upstream of the basin. The fluctuations in the groundwater heads revealed the effect of rainfall in July and baseflow in September over the catchment area. The spatial pattern of the groundwater heads was noticed to vary reasonably between the months of June and September 2005.

b) Comparison of observed and computed Groundwater heads:

The observed and computed groundwater heads of 15 observation wells calibrated for the months of June, July, August, September 2005 are presented in the Figure 6.5.

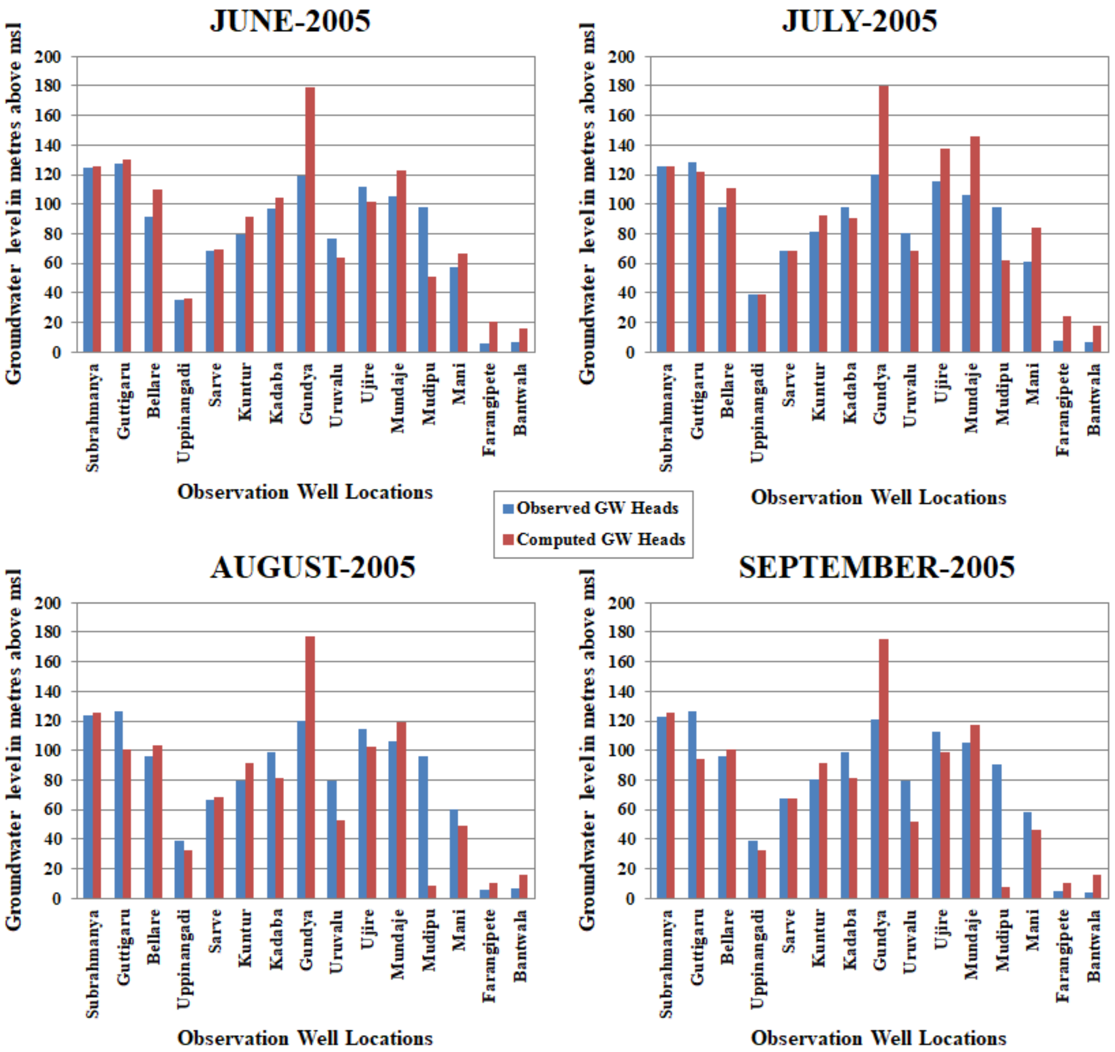


Figure 6.5 Observed v/s Computed groundwater heads in the year 2005

In the study, observed and computed groundwater heads reasonably matched for the majority of the wells. However, the following interpretations are conceded. In the month of June 2005, the observed head is around 120 m while the computed head is 178 m at Gundya. For the well located at Mudipu, the observed head is 95 m while the computed head is 50 m. In the month of August 2005, at Gundya, the observation head is around 120 m as against the computed head of 175 m. And in Mudipu, the observed head is about 90 m whereas the computed head is about 10 m. Identical trend is observed for wells at Gundya and Mudipu in the month of July and September 2005 respectively. For all the four months of calibration period, groundwater heads are over-estimated in Gundya and under-estimated in Mudipu. The dissimilar elevation values from DEM and field data for well location proved to be the cause for the discrepancy in computed groundwater levels. Under-estimation of groundwater heads is also observed at Guttigaru and Uruvalu in the months of August and September 2005.

Figure 6.6 shows the best fit of observed and computed groundwater levels for 15 observation wells for the calibration year 2005.

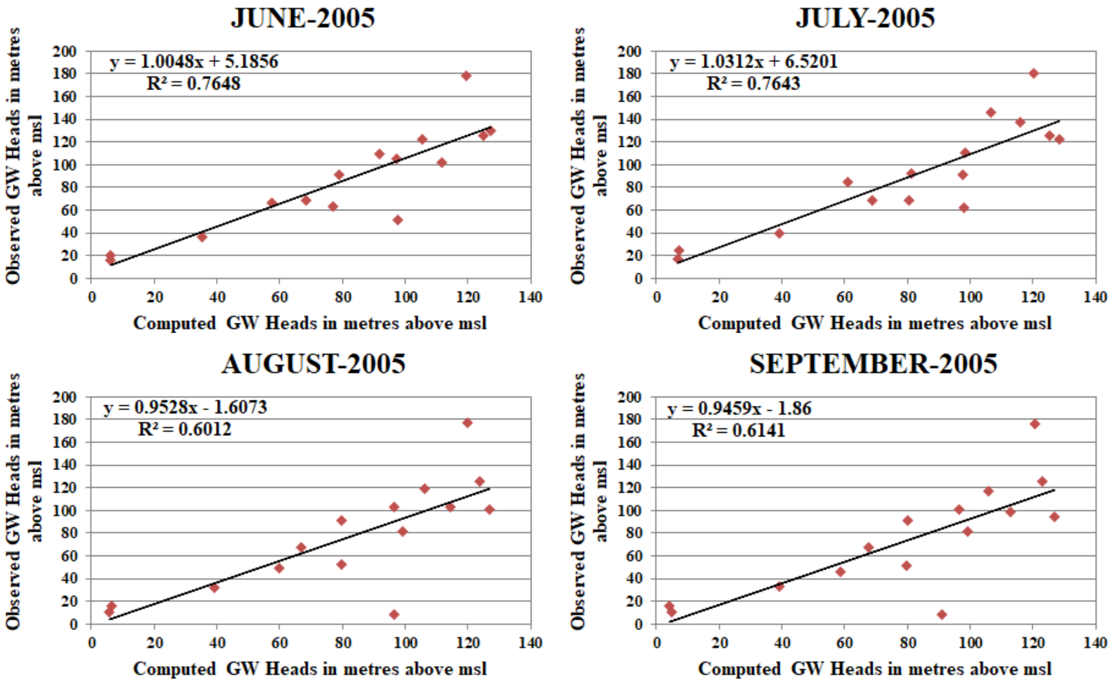


Figure 6.6 Scatter plots for the calibration year 2005

The correlation co-efficient is close to 0.7 on an average in the calibration year 2005 which is adequate. For all 4 months, 2 outliers are observed. This shows that the calibration of regional scale model is practically well suited for the SW-GW interaction studies.

c) Groundwater flux:

The groundwater exchange with the surface water is assessed from the flow budget values obtained from the simulated model for the year 2005 as shown in Table 6.2.

Table 6.2. Flow budget values for the calibration year 2005

Time	Flow Budget Values					
	Inflow in 10^6 m^3/day			Outflow in m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
June 2005	3.69	16.63	20.33	16.82	3.51	20.33
July 2005	3.09	30.09	33.18	29.71	3.47	33.18
Aug 2005	5.28	5.39	10.67	7.68	2.99	10.67
Sep 2005	5.71	4.07	9.77	6.60	3.17	9.77

It is observed from the Table 6.2 that the domination of aquifer discharge in the contribution to the river flows in the months of June, August and September 2005. Whereas rainfall recharge dominates the contribution to the groundwater storage in the month of July 2005.

6.1.3 Calibration of the regional scale model in the year 2006

a) Spatial distribution of Groundwater heads:

Spatial distributions of computed groundwater heads and calibration target bars for the calibration year 2006 are shown in Figure 6.7.

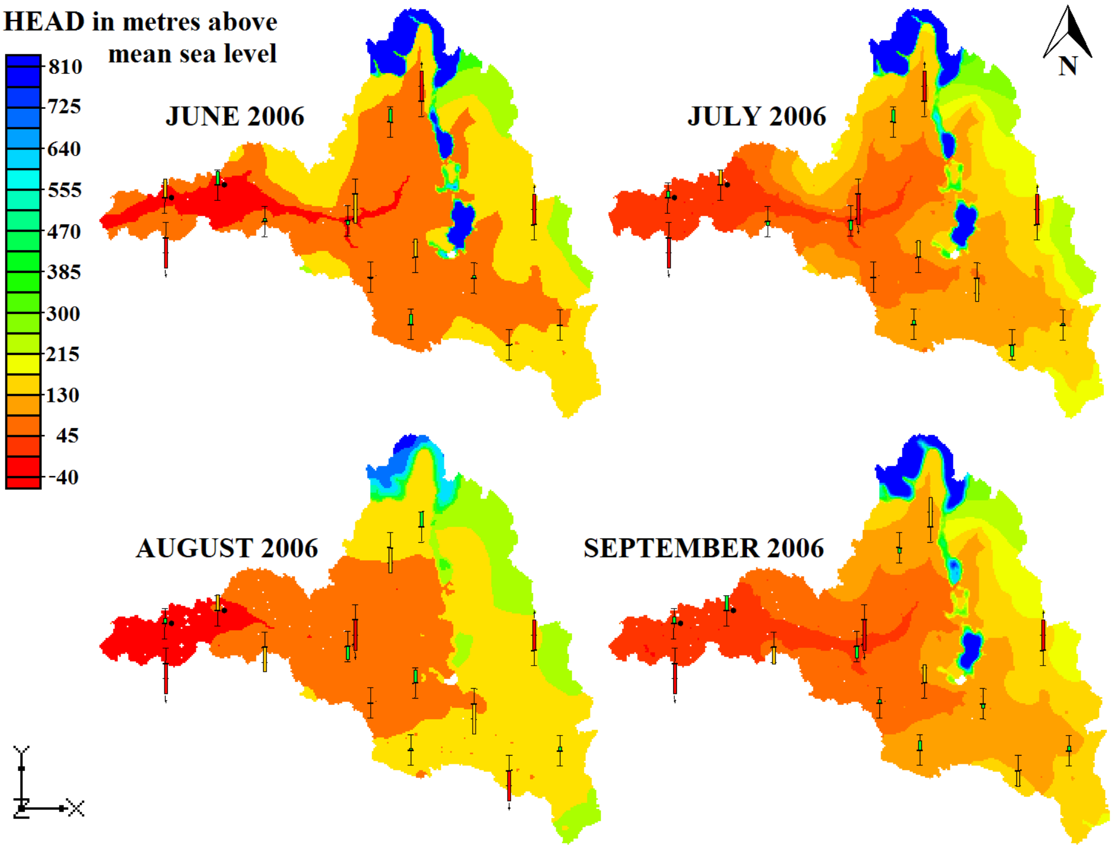


Figure 6.7 Computed groundwater heads for the calibration year 2006

The calibration target is found to be agreeing consistently accurate for most of the observation wells. It exhibits the satisfactoriness of model calibration for observed groundwater level data.

From June upto July 2006, gradual increase of groundwater levels was observed in the downstream portions of the basin. The groundwater levels were noticed to steadily decrease in both downstream and metabasalt aquifer areas of the basin during July to August 2006. However, the groundwater levels were observed to improve in the month of September 2006 in the basin. The fluctuations in the groundwater heads recognized the potential contribution of rainfall and groundwater on the river flow in the months of July, August and September. Dynamic variation was noticed in the spatial pattern of the groundwater heads during July and September 2006.

b) Comparison of observed and computed Groundwater heads:

The observed and computed groundwater head values of 15 observation wells that are used for calibration in June, July, August, September months of 2006 are presented in the Figure 6.8.

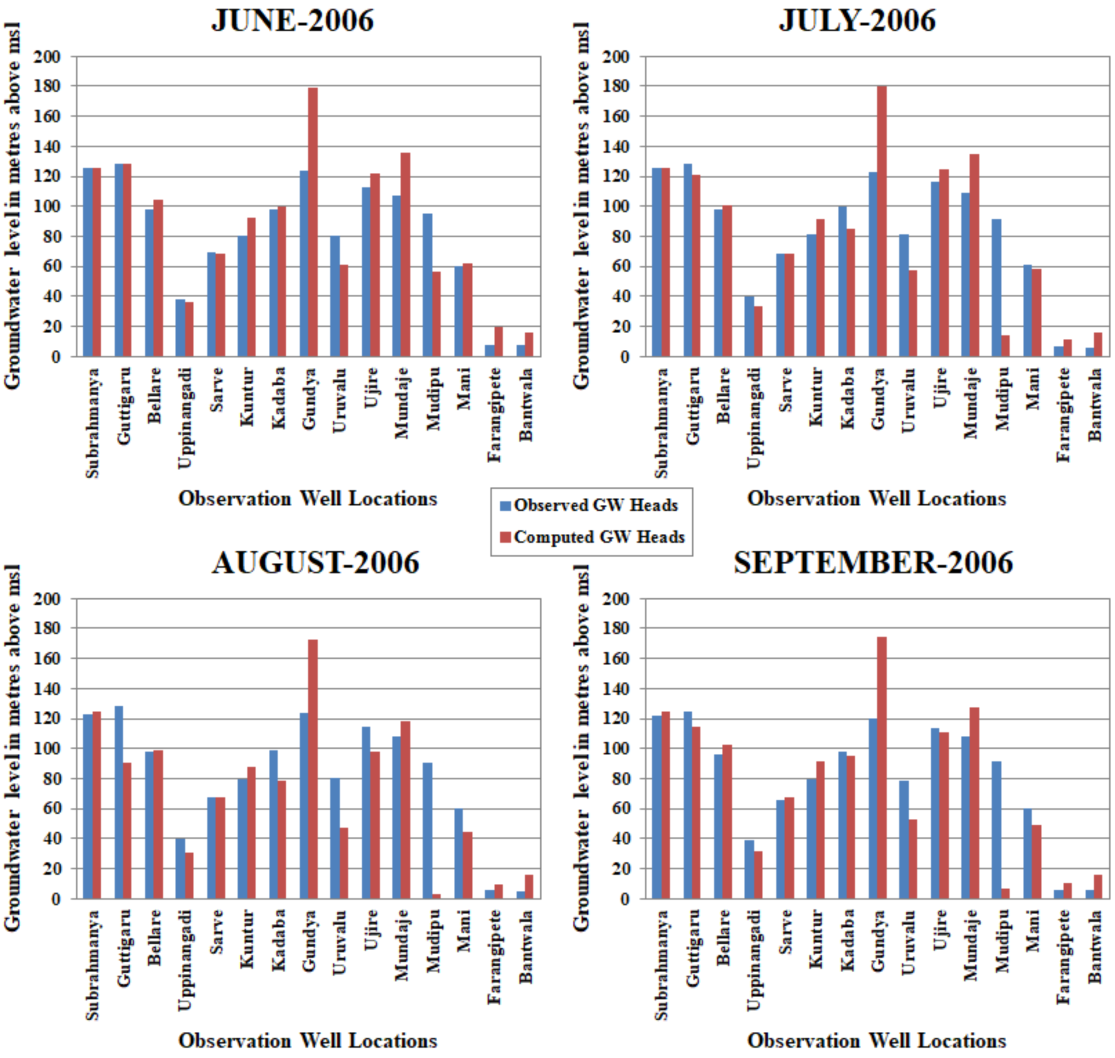


Figure 6.8 Observed v/s Computed groundwater heads in the year 2006

From the Figure 6.8, it is observed that the observed and computed groundwater heads are reasonably matching for most of the wells except at Gundya and Mudipu. Accordingly, the following observations are made. In the month of June 2006, at

Gundya, the observation head is 125 m while the computed head is around 178 m. At Mudipu, the observed head is 95 m while the computed head is 55 m. In the month of August 2006, at Gundya, the observed head is around 125 m as against the computed head of 170 m. And in Mudipu, the observed head is about 90 m whereas the computed head is about 10 m. Similar trends are observed in the months of July and September 2006 respectively. There is considerable over-estimation of groundwater heads in Gundya and under-estimation of groundwater heads in Mudipu in all the four months of calibration year 2006.

Figure 6.9 shows the best fit for observed and computed groundwater heads of all 15 observation wells in the calibration year 2006.

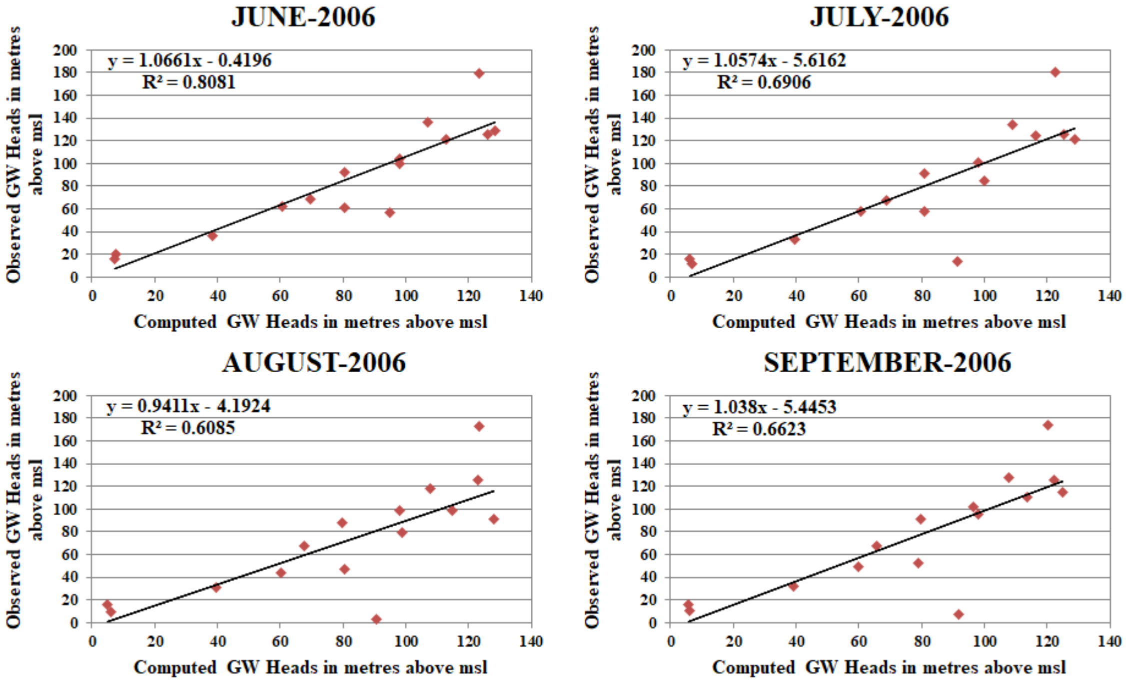


Figure 6.9 Scatter plots for the calibration year 2006

From the above Figure 6.9, it is observed that, the model correlation is acceptable with co-efficient values close to 0.7 and 0.8 on an average in the calibration year 2006. For all 4 months, 2 outliers are observed. In the calibration year 2006, only 2 or 3 outlier points are observed. This shows that the calibration of regional groundwater model is reasonably well applicable for analyzing SW-GW interactions.

c) Groundwater flux:

The groundwater exchange with the surface water is evaluated from the flow budget values obtained from the simulated model for the year 2006 as shown in Table 6.3.

Table 6.3. Flow budget values for the calibration year 2006

Time	Flow Budget Values					
	Inflow in 10^6 m^3/day			Outflow in 10^6 m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
June 2006	3.34	20.72	24.06	20.47	3.59	24.06
July 2006	3.89	16.01	19.90	16.41	3.50	19.90
Aug 2006	6.66	1.51	8.17	5.06	3.11	8.17
Sep 2006	4.95	7.53	12.49	9.30	3.19	12.49

It is observed from the Table 6.3 that the aquifer discharge is more dominating in contribution to the river flow in July and September 2006. Rainfall recharge and river leakage found to influence the flow in June and August months respectively.

6.1.4 Calibration of the regional scale model in the year 2007

a) *Spatial distribution of Groundwater heads*:

Spatial distributions of computed groundwater heads and calibration target bars for the calibration year 2007 are shown in Figure 6.10.

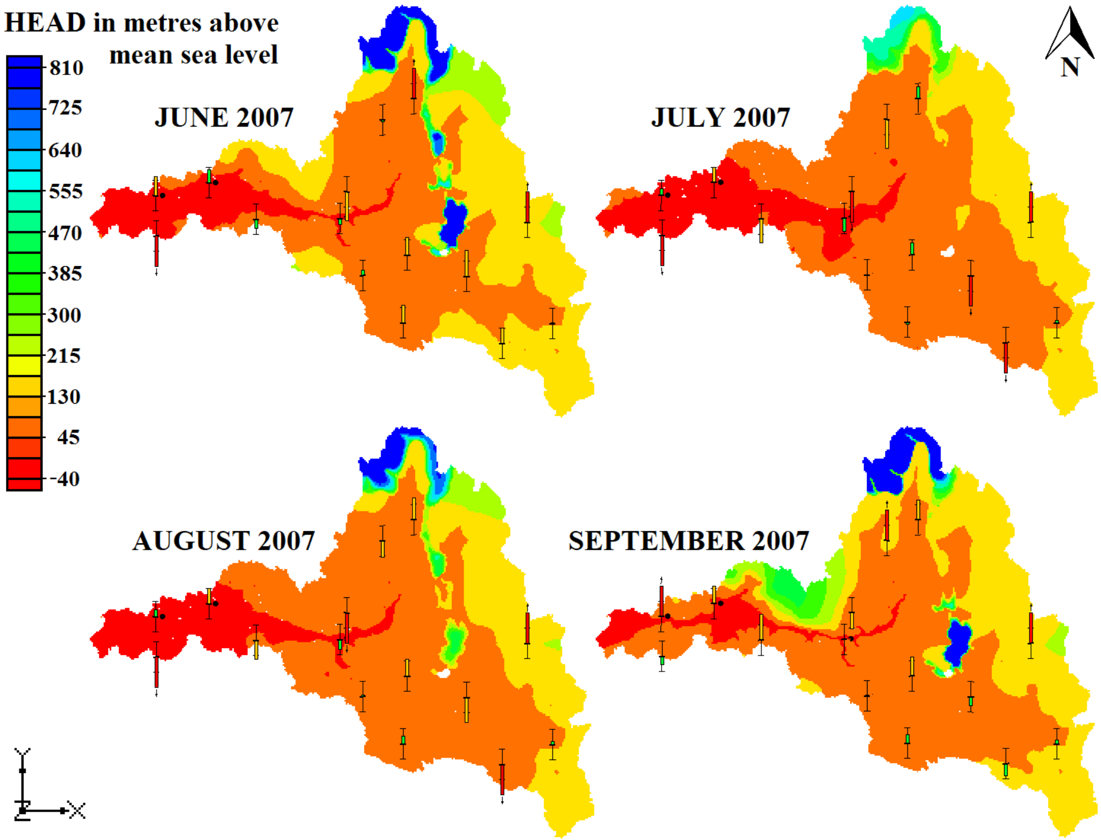


Figure 6.10 Computed groundwater heads for the calibration year 2007

The calibration target is in good agreement for most of the observation wells exhibiting the adequacy level of model calibration for groundwater heads.

The groundwater levels were observed to considerably decrease in both the downstream and metabasalt aquifer portions in the upstream of the basin during June to July 2007. From July upto September 2007, groundwater levels were noticed to progressively increase in both downstream and upstream areas of the basin. The fluctuations in the groundwater heads signified the impact of baseflow on the river flow in June, August and September months. The spatial pattern of the groundwater heads was noticed to vary moderately between the months of June and September 2007.

b) Comparison of observed and computed Groundwater heads:

The observed and computed values of groundwater heads for 15 observation wells, which are calibrated for June, July, August, September months of 2007 are presented in the Figure 6.11.

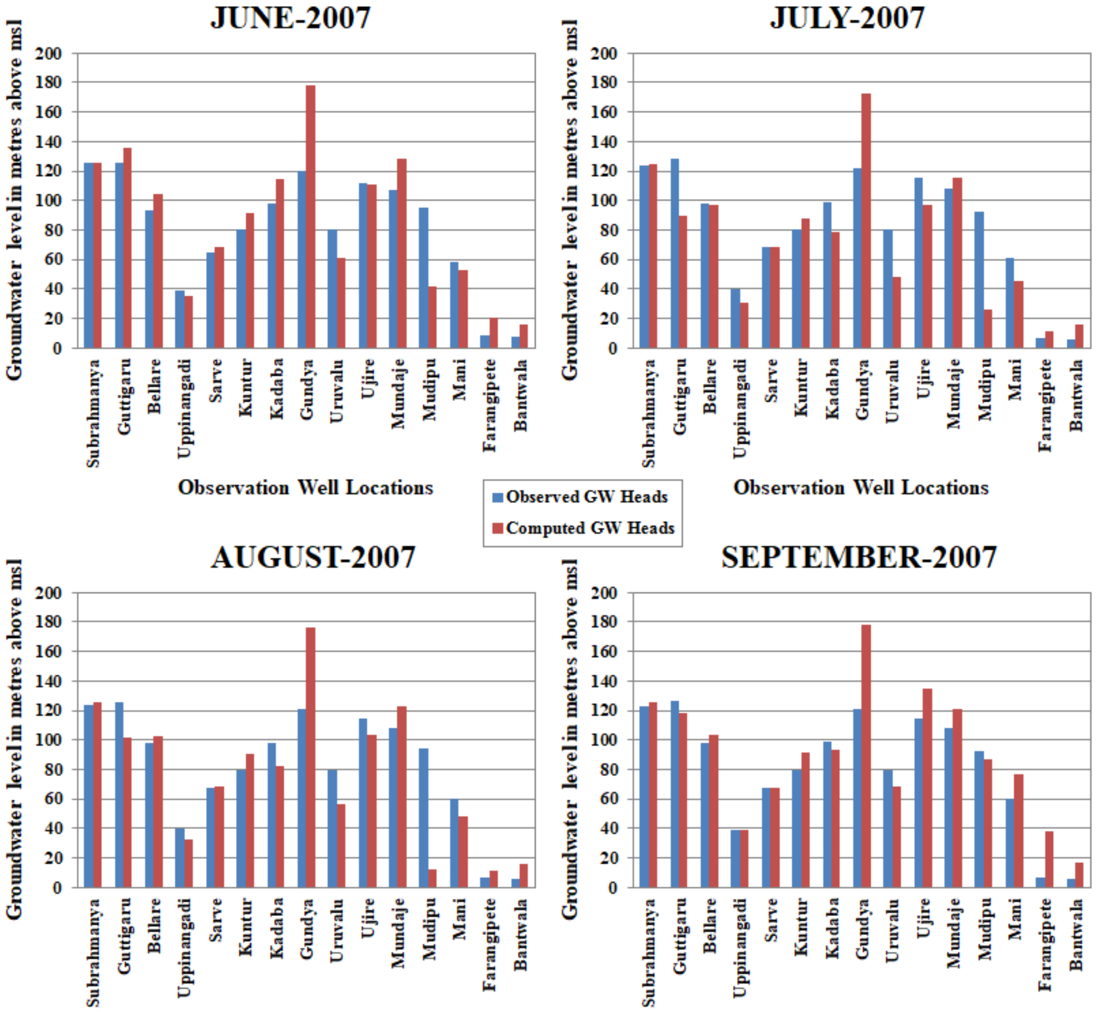


Figure 6.11 Observed v/s Computed groundwater heads in the year 2007

From the Figure 6.11, satisfactory matching of observed and computed groundwater heads is observed in majority of the wells. The following analysis is made subsequently. In the month of June 2007, the observation head is 120 m while the computed head is around 175 m at Gundya. Similar trends are observed for the well located at Gundya in the months of July, August and September 2007. In the month of June 2007, at Mudipu, the observed head is 92 m whereas the computed head is 42 m. In the month of July 2007, at Mudipu, the observation head is around 90 m as against the computed head of 25 m. For August 2007, the observed head is about 90 m while the computed head is about 10 m. There is considerable over-estimation of groundwater heads in Gundya for all the four months during calibration period and under-estimation of groundwater heads in Mudipu for June, July and August 2007.

Figure 6.12 shows the results of best fit for observed and computed values of all 15 observation wells utilized for the calibration year 2007.

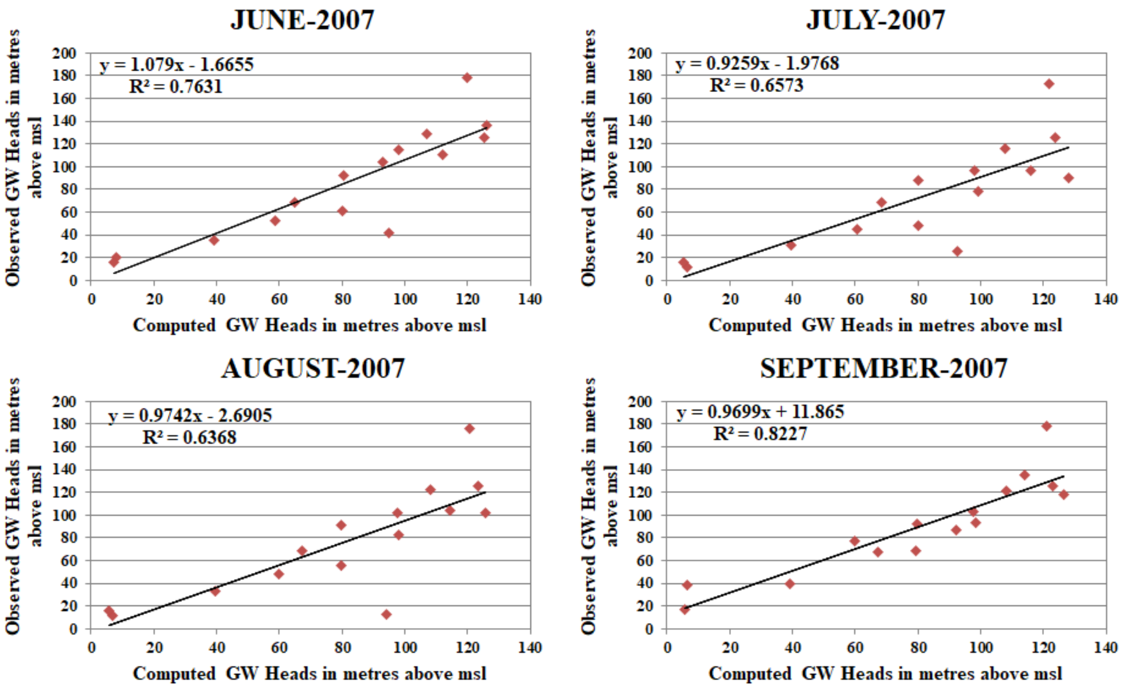


Figure 6.12 Scatter plots for the calibration year 2007

From the above Figure 6.12, it is observed that, the value of correlation co-efficient is close to 0.7 and 0.8 on an average in the calibration year 2007. 2 outlier points are observed in June, July and August 2007 and 1 outlier in September. This indicates that the calibration of regional groundwater model is fairly well suited for assessing SW-GW interactions.

c) *Groundwater flux*:

The groundwater exchange with the surface water is analyzed from the flow budget values obtained from the simulated model for the year 2007 as shown in Table 6.4.

Table 6.4. Flow budget values for the calibration year 2007

Time	Flow Budget Values					
	Inflow in 10^6 m^3/day			Outflow in 10^6 m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
June 2007	3.57	18.31	21.88	18.28	3.61	21.88
July 2007	6.84	1.47	8.31	5.10	3.22	8.31
Aug 2007	5.40	5.55	10.96	7.60	3.36	10.96
Sep 2007	3.92	21.65	25.57	21.72	3.85	25.57

It is observed from the Table 6.4 that the aquifer discharge dominates the contribution into the river flow in July, August and September 2007. Rainfall recharge noticed to enhance the flow in June 2007.

6.1.5 Calibration of the regional scale model in the year 2008

a) Spatial distribution of Groundwater heads:

Spatial distributions of computed groundwater heads and calibration target bars for the calibration year 2008 are shown in Figure 6.13.

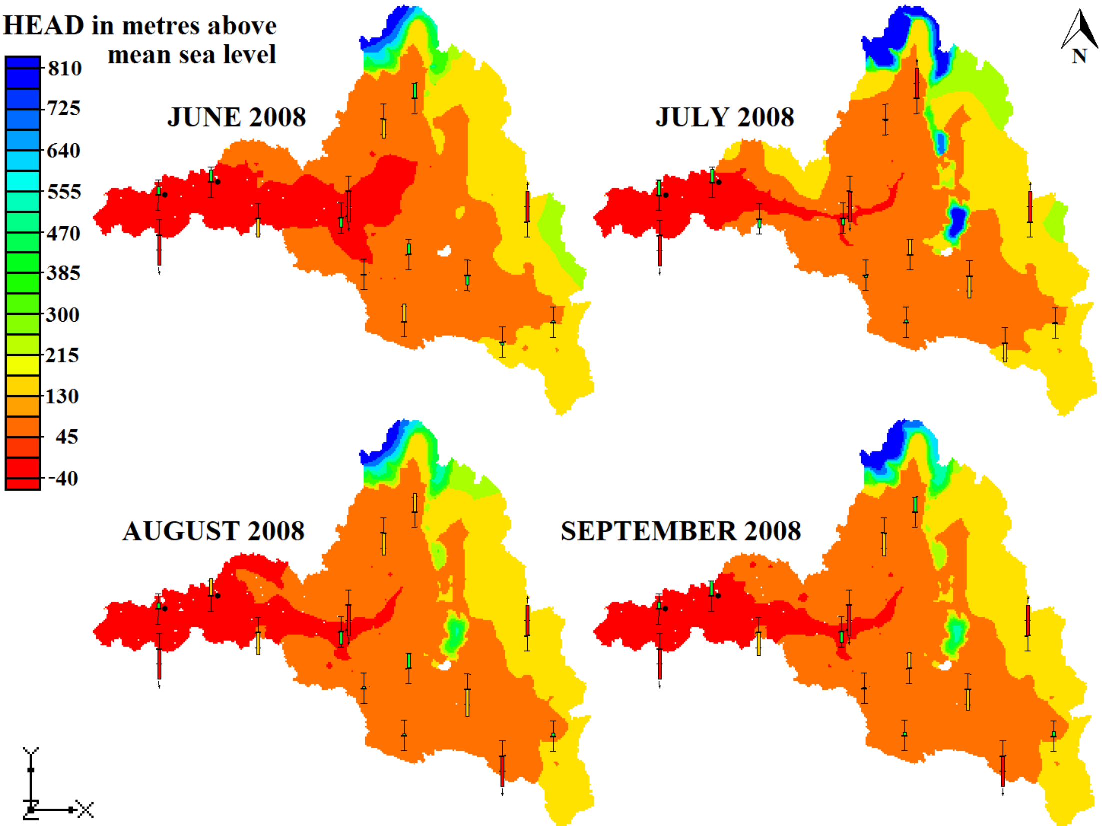


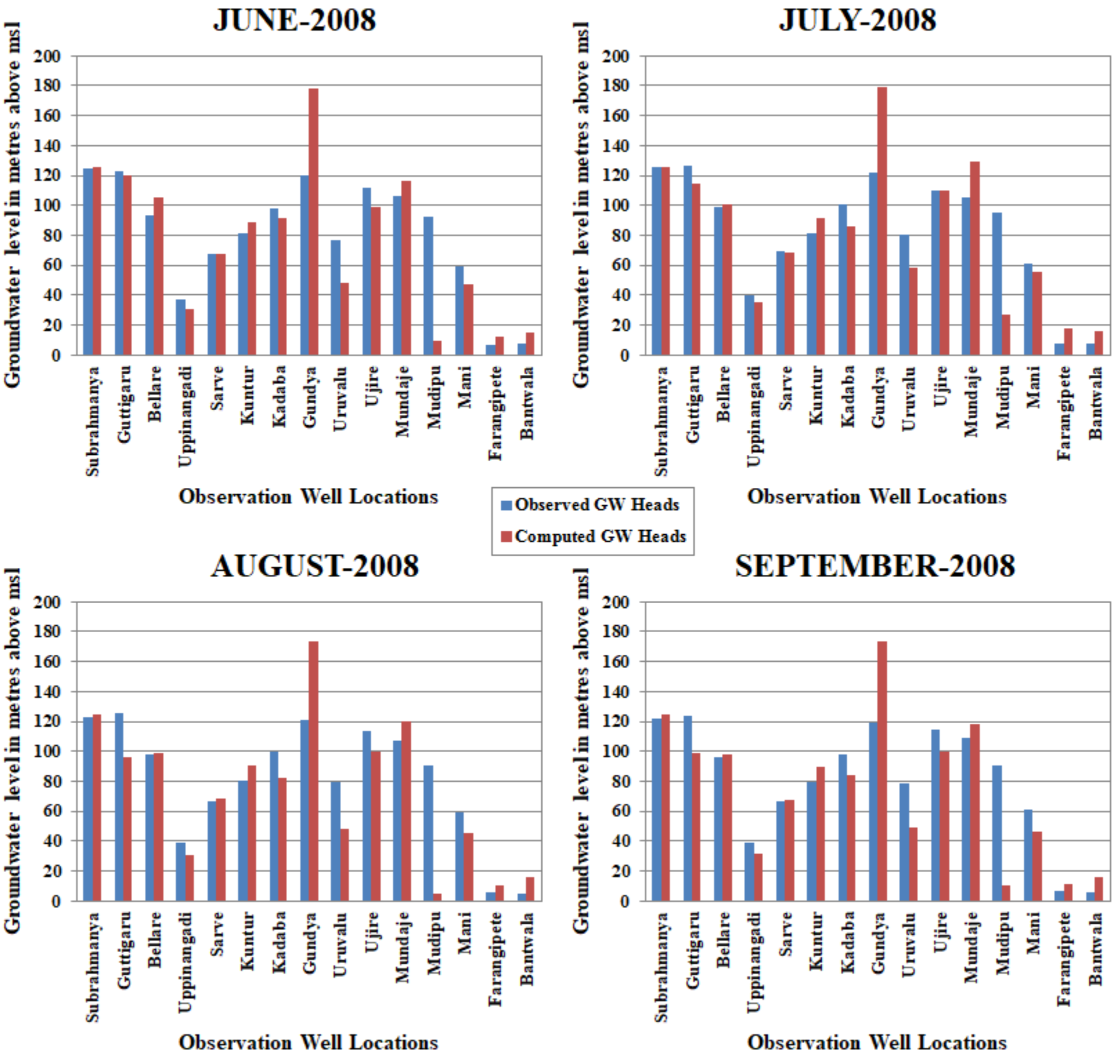
Figure 6.13 Computed groundwater heads for the calibration year 2008

The calibration target is in fair agreement for most of the groundwater observation wells. This describes the adequacy level of model calibration for observed groundwater heads.

From June to July 2008, the groundwater levels were noticeably increased in both the downstream and metabasalt aquifer portions in the upstream of the basin. However, groundwater levels were observed to slightly decrease in both downstream and metabasalt aquifer portions in upstream areas of the basin during July to August 2008. Slight enhancement in groundwater levels was noticed in the September month throughout the catchment. The fluctuations in the groundwater heads stated the prospective of baseflow and rainfall on the river flow in the month of June and September. The spatial distribution of the groundwater heads vary relatively in the months of June and September 2008.

b) Comparison of observed and computed Groundwater heads:

The observed and computed values of groundwater heads for the observation wells calibrated during June, July, August, September months of 2008 are presented in the Figure 6.14.



JUNE-2008

JULY-2008

AUGUST-2008

SEPTEMBER-2008

Figure 6.14 Observed v/s Computed groundwater heads in the year 2008

In the Figure 6.14, good match is observed for most of the wells between the observed and computed groundwater heads. In addition, the following points are distinguished.

In the month of June 2008, at Gundya, the observation head is 120 m while the computed head is around 178 m. At Mudipu, the observed head is 90 m while the computed head is 12 m. In the month of August 2008, at Gundya, the observed head is around 122 m as against the computed head of 175 m. And in Mudipu, the observed head is about 90 m whereas the computed head is about 10 m. Similar trends are observed in the months of July and September 2008 respectively. There is considerable over-estimation of groundwater heads in Gundya and under-estimation of groundwater heads in Mudipu in all the four months of calibration year 2008.

Figure 6.15 shows the results of best fit for observed and computed values of all 15 observation wells utilized for the calibration year 2008.

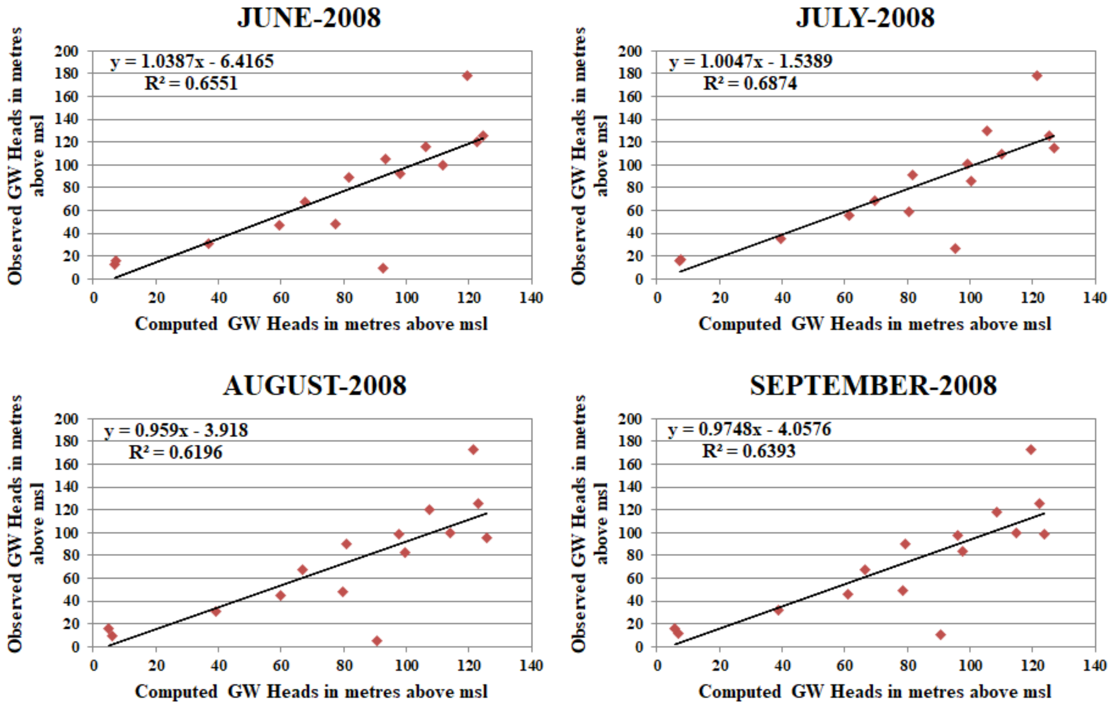


Figure 6.15 Scatter plots for the calibration year 2008

From the above Figure 6.15, it is observed that, the correlation co-efficient is close to 0.7 in all the four months and thus it is acceptable. In the calibration year 2008, 2 noteworthy outlier points are observed. This shows that the calibration of regional groundwater model is practically well suitable for the examining the SW-GW interactions.

c) Groundwater flux:

The groundwater exchange with the surface water is assessed from the flow budget values obtained from the simulated model for the year 2008 as shown in Table 6.5.

Table 6.5. Flow budget values for the calibration year 2008

Time	Flow Budget Values					
	Inflow in 10^6 m^3/day			Outflow in 10^6 m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
June 2008	5.36	5.77	11.13	7.77	3.36	11.13
July 2008	4.19	12.33	16.52	12.91	3.61	16.52
Aug 2008	6.15	2.88	9.03	5.81	3.22	9.03
Sep 2008	6.09	2.98	9.07	5.76	3.31	9.07

It is observed from the Table 6.5 that the aquifer discharge dominates the contribution into the river flow in the initial months June and July 2008. River leakage found to dominate the flow during later months August and September of 2008 respectively.

6.1.6 Calibration of the regional scale model in the year 2009

a) Spatial distribution of Groundwater heads:

Spatial distributions of computed groundwater heads and calibration target bars for the calibration year 2009 are shown in Figure 6.16.

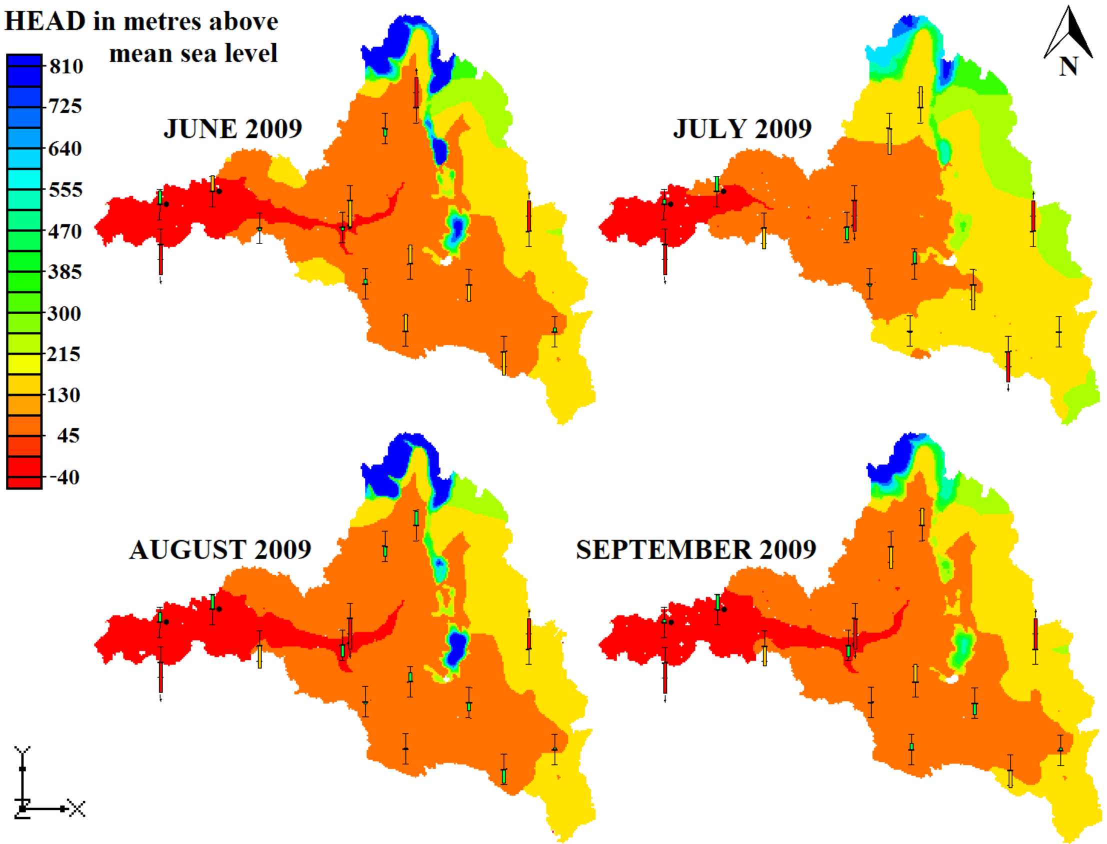


Figure 6.16 Computed groundwater heads for the calibration year 2009

The calibration target has satisfactorily agreed for majority of the observation wells considered in the study. This portrays the adequacy level of model calibration for observed groundwater heads.

Significant increase in the groundwater levels was observed in the downstream and decrease in metabasalt aquifer portions of the basin from June to July 2009. During July to August 2009, decrease in groundwater levels was observed in downstream portion and increase in metabasalt aquifer areas of the catchment. However in the September month, the groundwater levels were noticed to decline only within the metabasalt aquifer systems. The fluctuations in the groundwater heads indicated the influence of rainfall over the upstream part of the catchment in June and August and baseflow in July. The spatial distribution of the groundwater heads quite vary in the months of June and August 2009.

b) Comparison of observed and computed Groundwater heads:

The observed and computed groundwater heads calibrated for 15 observation wells in the months of June, July, August, September 2009 are presented in the Figure 6.17.

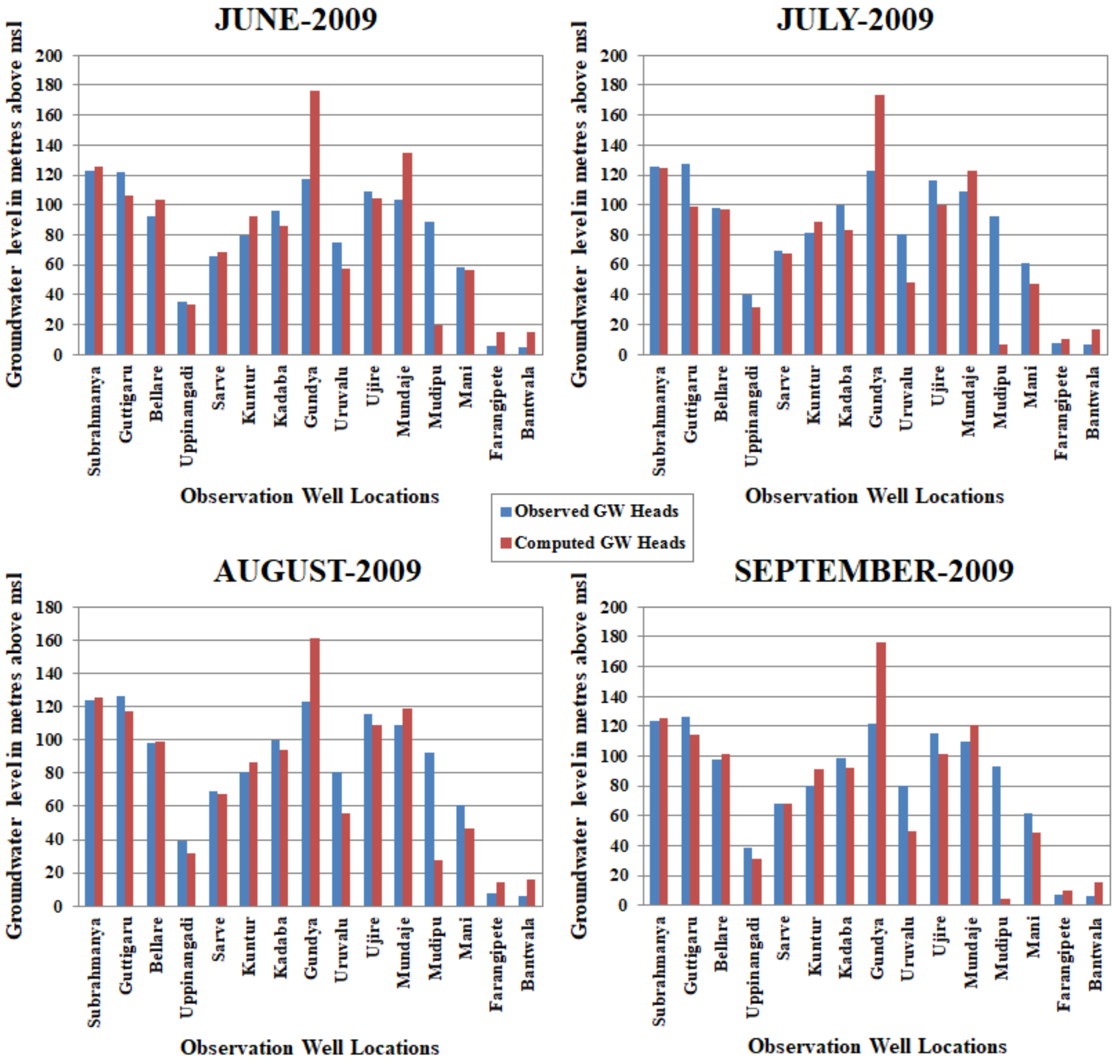


Figure 6.17 Observed v/s Computed groundwater heads in the year 2009

It is observed from the Figure 6.17 that in most of the wells, the observed and computed groundwater heads are matching satisfactorily. Besides, following points are pointed out. In the month of June 2009, the observation head is 120 m while the computed head is around 175 m at Gundya. At Mudipu, the observed head is 90 m while the computed head is 20 m. In the month of July 2009, at Gundya, the observed head is around 120 m as against the computed head of 170 m. And in Mudipu, the observed head is about 90 m whereas the computed head is about 10 m. Similar trends are observed in the months of August and September respectively. In all the four months of calibration year 2009, there is a significant over-estimation of groundwater heads in Gundya and under-estimation of groundwater heads in Mudipu.

Figure 6.18 shows the results of best fit for observed and computed values of all 15 observation wells utilized for the calibration year 2009.

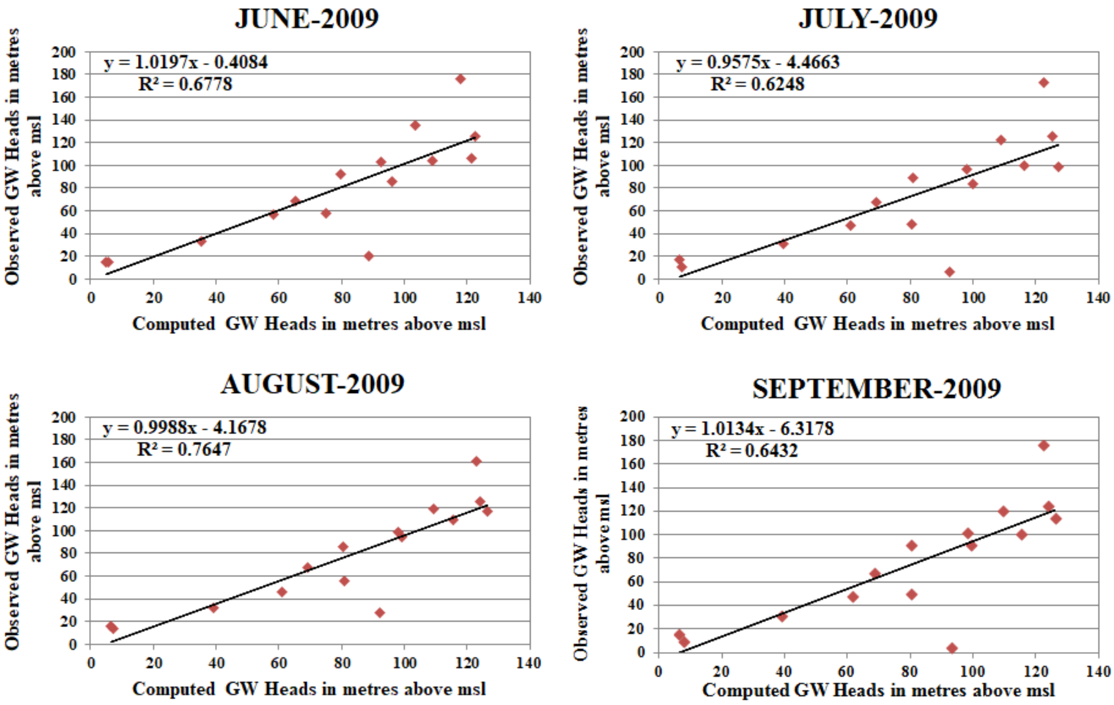


Figure 6.18 Scatter plots for the calibration year 2009

From Figure 6.18, it is observed that the correlation co-efficient on an average is close to 0.7 in the calibration year 2009, which is considered to be adequate. In all the four months, 2 outlier points are observed. This shows that the calibration of regional groundwater model is reasonably well suited to investigate SW-GW interactions.

c) *Groundwater flux*:

The groundwater exchange with the surface water is determined from the flow budget values obtained from the simulated model for the year 2009 as shown in Table 6.6.

Table 6.6. Flow budget values for the calibration year 2009

Time	Flow Budget Values					
	Inflow in 10^6 m^3/day			Outflow in 10^6 m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
June 2009	4.47	11.62	16.09	12.51	3.58	16.09
July 2009	6.14	3.26	9.39	6.08	3.32	9.39
Aug 2009	6.04	11.59	17.63	13.91	3.73	17.63
Sep 2009	5.05	6.38	11.43	8.11	3.32	11.43

From the Table 6.6, domination of aquifer discharge is observed contributing into the river flow in June, August and September 2009. River leakage is noticed to dominate in the flow in July 2009.

6.1.7 Validation of the regional scale model in the year 2010

a) Spatial distribution of Groundwater heads:

The calibrated model is validated for the months of June, July, August and September of 2010 and 2011. The computed groundwater heads for the validation year 2010 and validation targets are presented in Figure 6.19.

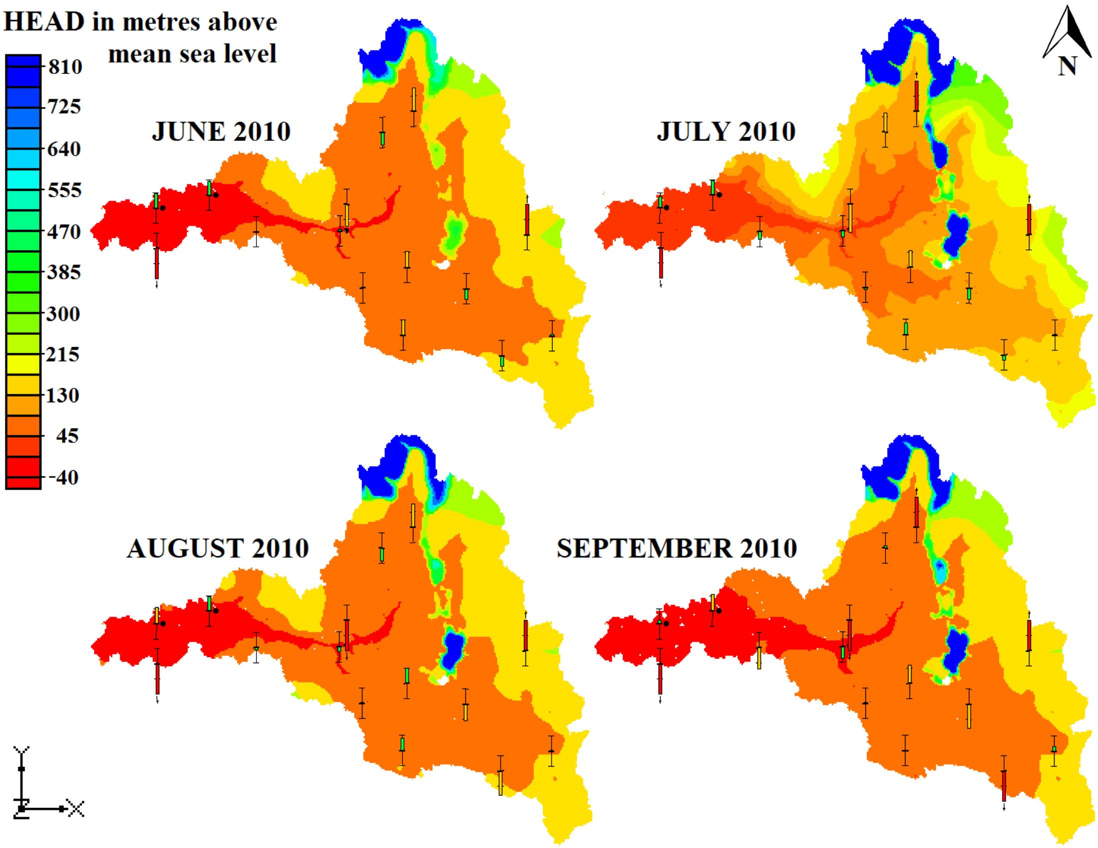


Figure 6.19 Computed groundwater heads for the validation year 2010

The validation target is in good agreement for most of the observation wells considered. This demonstrates the adequacy level of validation for the observation wells selected during validation year 2010.

During June to July 2010, the groundwater levels were observed to slightly increase in both the downstream and metabasalt aquifer portions in the upstream of the basin. Little decrease in groundwater levels was noticed both in downstream and metabasalt aquifer areas of the catchment from July to August. Further in the September month, the groundwater levels are observed to decline in the downstream portion of the basin. The fluctuations in the groundwater heads indicated the influence of rainfall over the catchment in July, August and September. The spatial pattern of the groundwater heads reasonably vary between the months of June and September 2010.

b) Comparison of observed and computed values of Groundwater heads:

The observed and computed values of groundwater heads of 15 wells, which are validated for June, July, August, September 2010 are presented in the Figure 6.20.

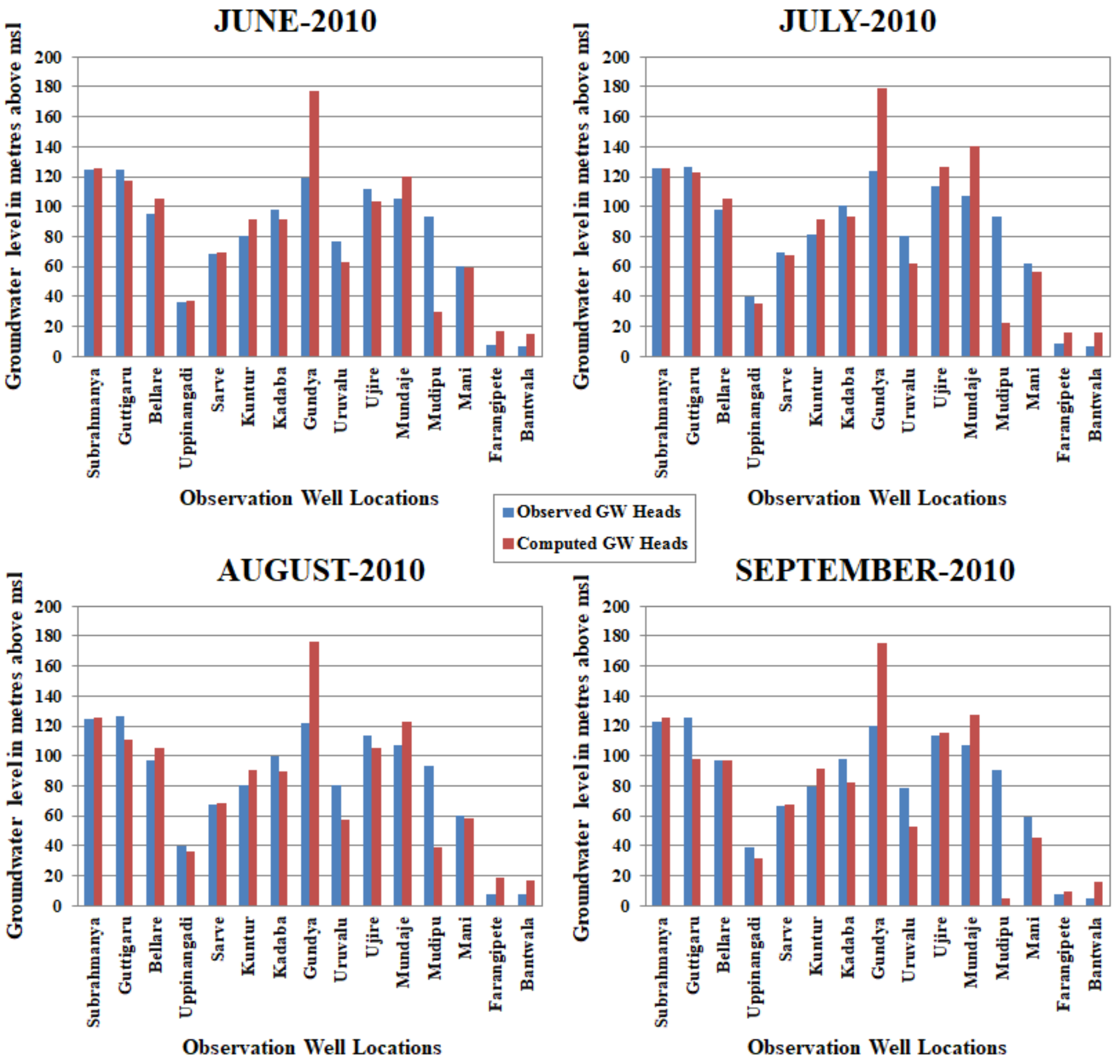


Figure 6.20 Observed v/s Computed groundwater heads in the year 2010

It is observed from the Figure 6.20 that in most of the wells, the observed and computed groundwater heads are matching satisfactorily. Besides, following points are distinguished. In the month of June 2010, the observation head is 120 m while the computed head is around 175 m at Gundya. Similar trends are observed for the well located at Gundya in the months of July, August and September 2010. For the well location at Mudipu, the observed head is around 90 m for all four months, whereas the computed head is 30 m, 20 m, 40 m and 10 m in the months of June, July, August and September 2010 respectively. There is notable over-estimation of groundwater heads in Gundya and under-estimation of groundwater heads in Mudipu during validation year 2010.

Figure 6.21 shows the results of best fit for observed and computed values of all 15 observation wells utilized for the validation year 2010.

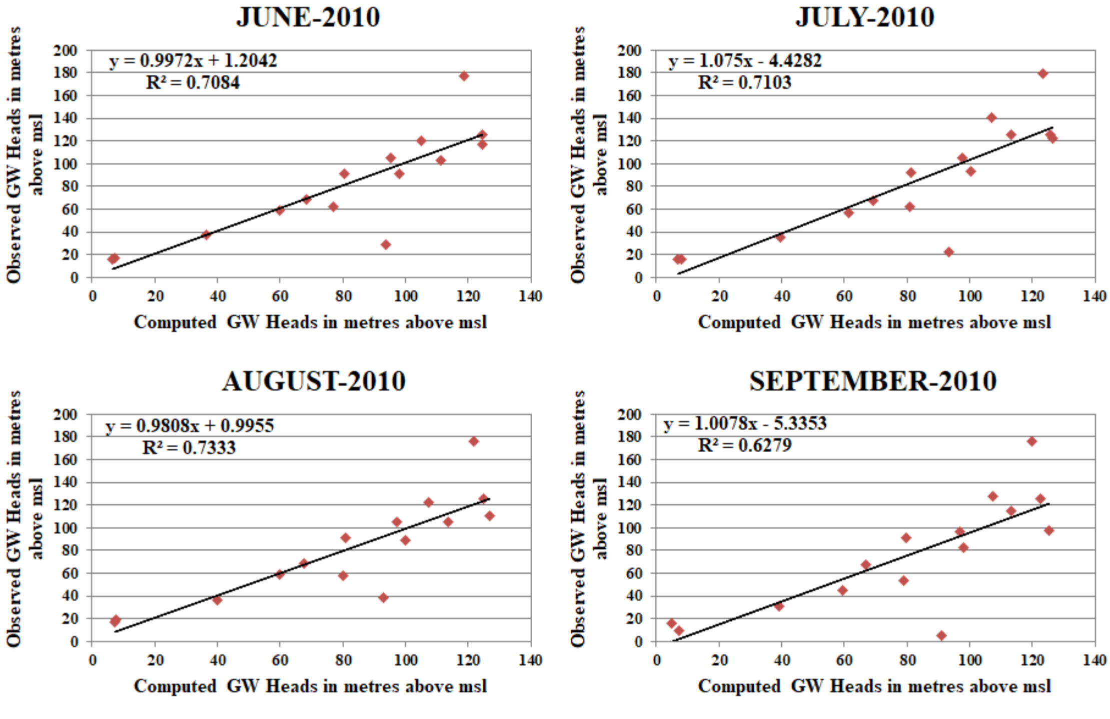


Figure 6.21 Scatter plots for the validation year 2010

From the above Figure 6.21, it is observed that, the correlation co-efficient on an average is close to 0.7 during validation year 2010 and it is acceptable. In all four months, only 2 outlier points are observed. This demonstrates that the validation of regional groundwater model is satisfactory and practically suitable for SW-GW interactions studies.

c) Groundwater flux:

The groundwater exchange with the surface water is assessed from the flow budget values obtained during the validation year 2010 is shown in Table 6.7.

Table 6.7. Flow budget values during validation year 2010

Time	Flow Budget Values					
	Inflow in 10^6 m^3/day			Outflow in 10^6 m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
June 2010	4.48	10.30	14.78	11.17	3.61	14.78
July 2010	3.55	18.44	21.99	18.38	3.61	21.99
Aug 2010	4.65	9.95	14.60	10.99	3.61	14.60
Sep 2010	5.31	7.67	12.98	9.74	3.24	12.98

From the Table 6.7, it is observed that the aquifer discharge dominate the contribution into the river flow in the validation year 2010. Rainfall recharge noticed to enhance the flow in July 2010.

6.1.8 Validation of the regional scale model in the year 2011

a) Spatial distribution of Groundwater heads:

The computed groundwater heads for the validation year 2011 and validation targets are presented in Figure 6.22.

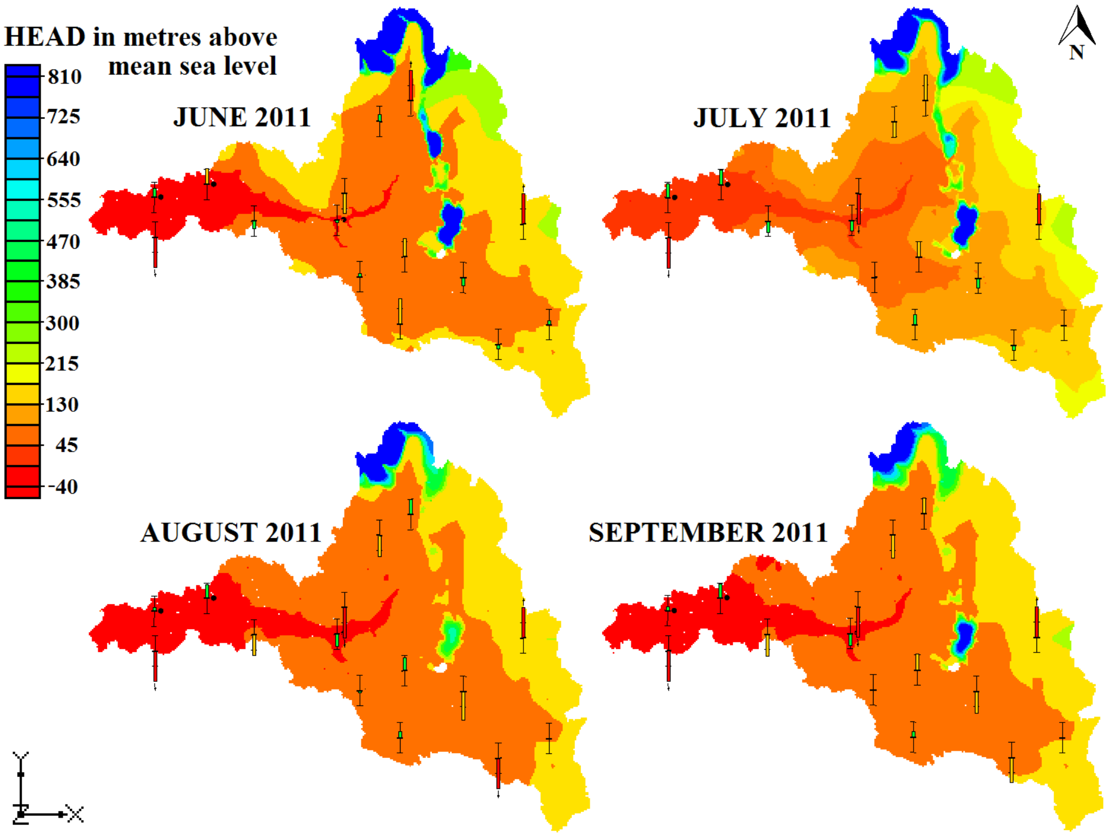


Figure 6.22 Computed groundwater heads for the validation year 2011

The good agreement of validation target for most of the wells displays the adequacy level of model validation for observation level data of 15 wells. This also exhibits the applicability of the simulated model for the investigation of SW-GW interactions within the catchment area.

Slight increase of groundwater levels was observed in the downstream and decrease in metabasalt aquifer portions in the upstream of the basin from June to July 2011. However during July to August 2011, the groundwater levels were noticed to gradually decrease in both the downstream and metabasalt aquifer areas. Further in the September month, the groundwater levels recovered in metabasalt aquifer units in the upstream of the basin. The fluctuations in the groundwater heads revealed the influence of rainfall in June and September and baseflow in June over the basin. The spatial pattern of the groundwater heads considerably vary between the months of June and September 2011.

b) Comparison of observed and computed values of Groundwater heads:

The observed and computed values of groundwater heads of 15 observation wells utilized for validation in the months of June, July, August, September in 2011 are presented in the Figure 6.23.

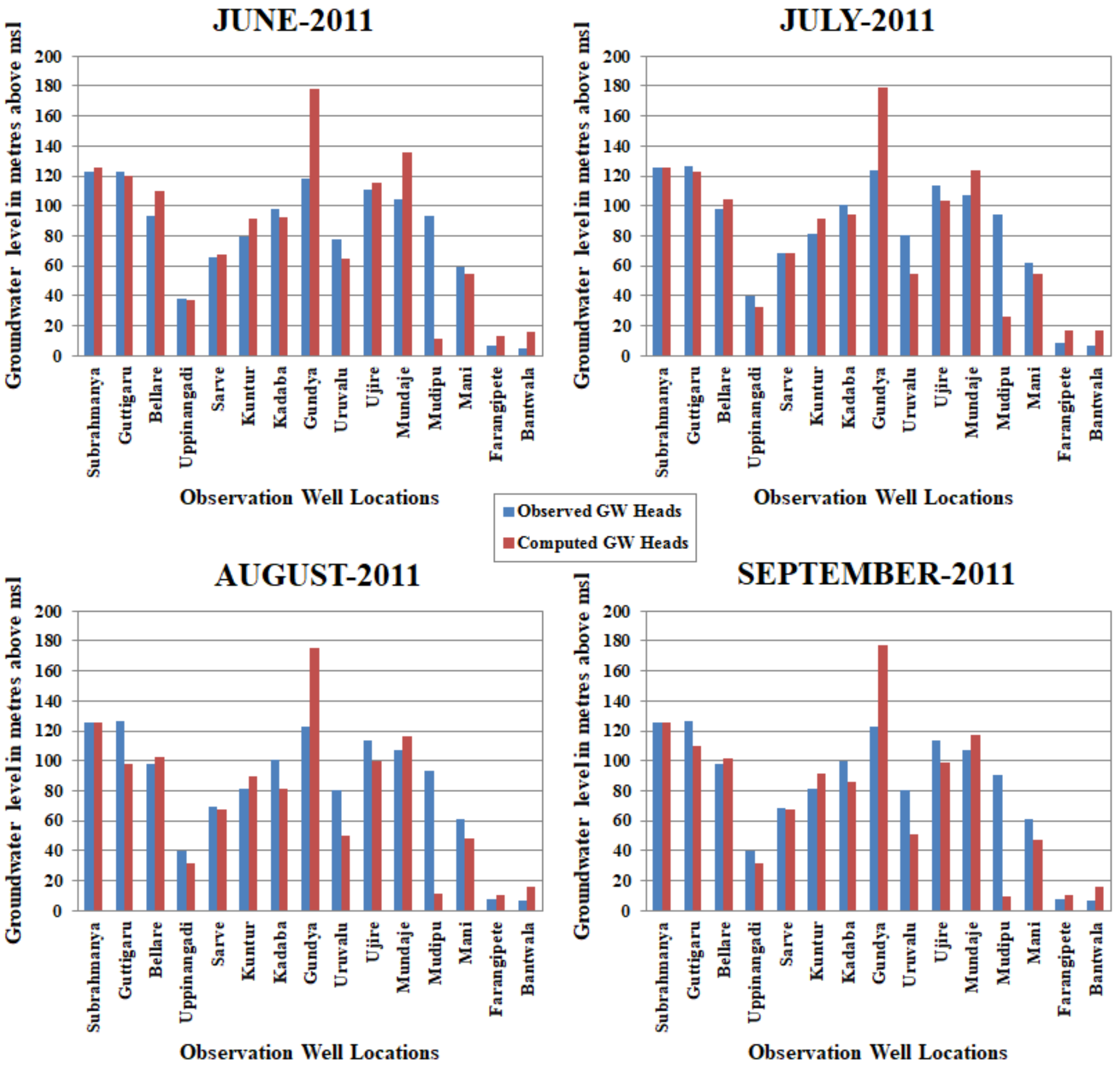


Figure 6.23 Observed v/s Computed groundwater heads in the year 2011

In the month of June 2011, the observed head is around 120 m while the computed head is 178 m at Gundya. For the well located at Mudipu, the observed head is 90 m while the computed head is 10 m. In the month of August 2011, at Gundya, the observation head is around 122 m as against the computed head of 175 m. And in Mudipu, the observed head is about 90 m whereas the computed head is about 10 m. Identical trend is observed for wells at Gundya and Mudipu in the month of July and September 2011 respectively. For all the four months of validation period, groundwater heads are over-estimated in Gundya and under-estimated in Mudipu.

Figure 6.24 shows the best fit for observed and computed values of all 15 observation wells utilized for the validation year 2011.

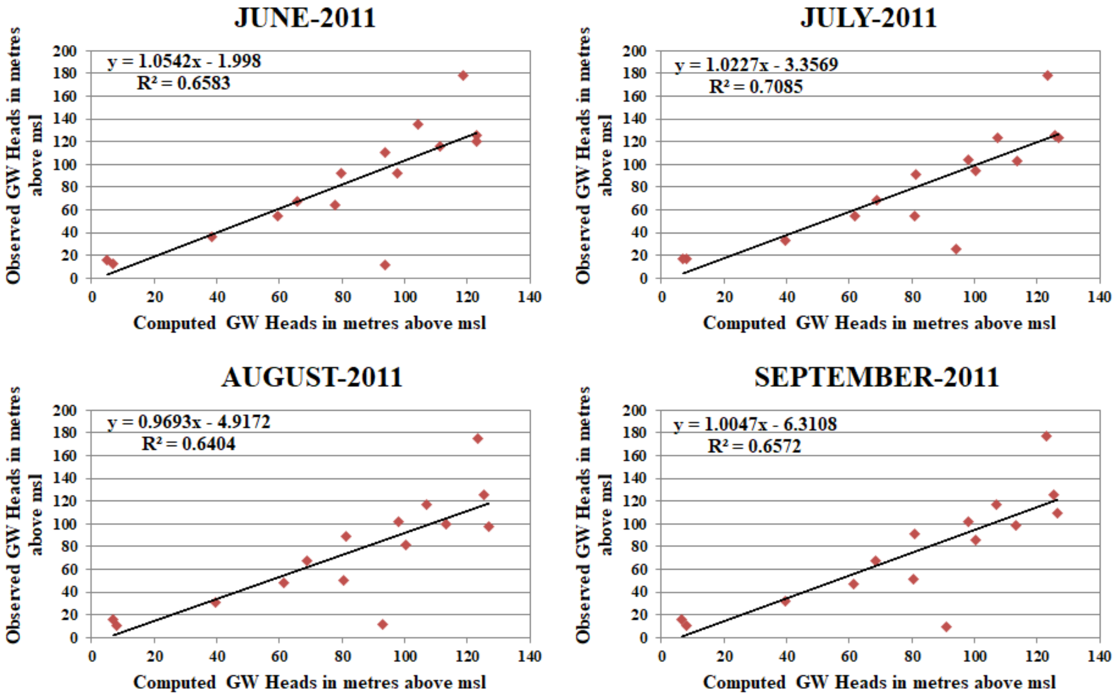


Figure 6.24 Scatter plots for the validation year 2011

From the above Figure 6.24, it is observed that, the correlation co-efficient on an average is close to 0.7 during the validation year 2011, which is satisfactory. In all the four months, only 2 noteworthy outlier points are observed. This describes that the calibration of regional groundwater model is reasonable and well suited to carry out the studies related to SW-GW interactions.

c) Groundwater flux:

The groundwater exchange with the surface water is assessed from the flow budget values obtained during the validation year 2011 is shown in Table 6.8.

Table 6.8. Flow budget values during validation year 2011

Time	Flow Budget Values					
	Inflow in in 10^6 m^3/day			Outflow in 10^6 m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
June 2011	3.76	16.33	20.09	16.53	3.56	20.09
July 2011	4.23	10.71	14.93	11.33	3.61	14.93
Aug 2011	6.04	3.24	9.28	5.94	3.34	9.28
Sep 2011	5.18	5.85	11.02	7.73	3.30	11.02

From the Table 6.8, aquifer discharge is observed to dominate by contributing into the river flow in June, July and September 2011. River leakage found to dominate in the flow in August 2011.

6.1.9 Selection of relevant sub-catchment from the regional scale model to assess SW-GW interactions based on Top-Down Approach

The groundwater observation wells at Sarve and Bellare village of Gowri-HoLe sub-catchment showed better agreement of simulation in the regional scale model of Nethravathi River Basin. In addition, the variation of groundwater levels in these wells were found to be significantly dynamic during both calibration and validation period substantiating the SW-GW flux from the flow budget values also. The above-mentioned results establish an opportunity to consider Gowri-HoLe Sub-catchment for the next level assessment i.e., in the finer scale of the Nethravathi River Basin. Henceforth, the applicability of the simulated model for the investigation of SW-GW interactions within the Gowri-HoLe Sub-catchment is suitable.

6.2 SUB-CATCHMENT SCALE MODELING

For intermediate scale modeling, Gowri-HoLe sub-catchment, a tributary of Nethravathi river is considered. In the present study, a transient model is developed for investigating the SW-GW interactions and analyzing theirs spatio-temporal variations within the river regime. The sub-catchment scale model is calibrated from June 2004 to May 2010 and validated from June 2010 to September 2012 using groundwater level data of 2 monthly and 1 seasonal observation wells.

6.2.1 Calibration of the sub-catchment scale model from June 2004 - May 2010

a) Spatial distribution of Groundwater heads from June 2004 - May 2005:

In the study, preliminary investigations of river-aquifer interactions are carried out for the sub-catchment scale by analyzing groundwater head fluctuations.

Spatial distributions of computed groundwater heads for 3 observation wells in the calibration period June 2004 - May 2005 are shown in Figure 6.25.

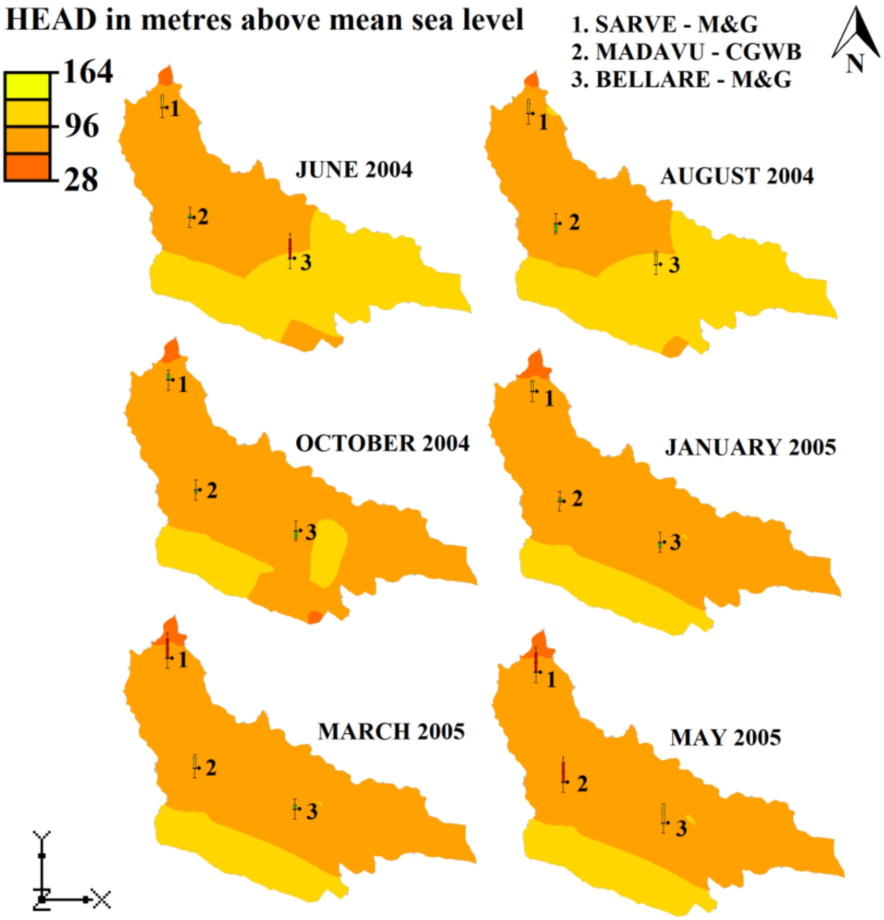


Figure 6.25 Computed groundwater heads from June 2004 - May 2005

From June to August 2004, slight increase in groundwater heads was noticed in the upstream area. The groundwater heads declined significantly during August 2004 to May 2005.

However, in the month of October 2004, the groundwater heads were observed to be at higher elevation near well no. 3 compared to the neighbouring areas. Hence, it can be stated that the nearby river segment would be under the influence of baseflow contribution due to higher groundwater levels.

b) Groundwater flux from June 2004 - May 2005:

In the present study, river-aquifer flow exchange is assessed from the flow-budget values for the calibration period June 2004 - May 2005 as shown in Table 6.9.

Table 6.9. Flow budget values from June 2004 - May 2005

Time	Flow Budget Values					
	Inflow in m^3/day			Outflow in m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
Jun-04	117985.0	389434.4	507419.4	240626.2	266793.7	507419.9
Jul-04	121875.9	362640.7	484516.6	217726.4	266793.7	484520.1
Aug-04	93875.9	558983.8	652859.8	386065.7	266793.7	652859.4
Sep-04	224325.7	84601.4	308927.1	42134.5	266793.7	308928.3
Oct-04	188425.6	140353.2	328778.8	61986.6	266793.7	328780.3
Nov-04	258934.4	42282.7	301217.1	34420.5	266793.7	301214.2
Dec-04	263980.3	0.0	263980.3	48964.0	215016.2	263980.2
Jan-05	286510.4	0.0	286510.4	46521.1	239989.6	286510.8
Feb-05	292911.7	0.0	292911.7	46296.9	246615.2	292912.1
Mar-05	292911.7	0.0	292911.7	46296.9	246615.2	292912.1
Apr-05	262548.6	41646.2	304194.8	57579.6	246615.2	304194.8
May-05	274453.9	25999.1	300453.0	53839.9	246615.2	300455.2

In the Table 6.9, aquifer discharge was found to increase due to rise of groundwater table above the riverbed elevations during June to August 2004. Later from August 2004 to May 2005, river leakage was noticed to increase due to decline in groundwater table. Aquifer discharge was recognized to be remarkably high in October 2004 compared to neighbouring months.

The volumetric change of the parameters, river leakage and aquifer discharge proved to be the significant evidence for the river-aquifer flow exchange.

c) Spatial distribution of Groundwater heads from June 2005 - May 2006:

Spatial distributions of computed groundwater heads for 3 observation wells in the calibration period June 2005 - May 2006 are shown in Figure 6.26.

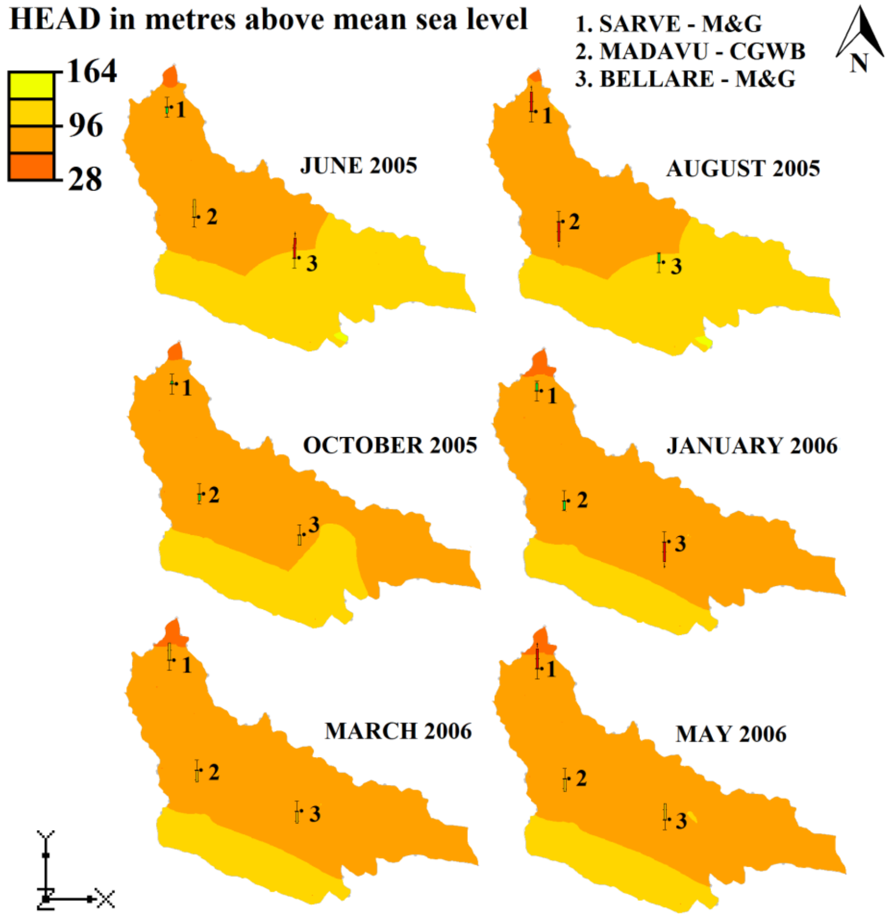


Figure 6.26 Computed groundwater heads from June 2005 - May 2006

Small increase in groundwater heads was observed from the month of June 2005 to August 2005 in the upstream. However, during August 2005 to May 2006, the groundwater heads were noticed to decline notably. In the month of October 2005, groundwater heads were identified to be at higher elevation near well no. 3 compared to the neighbouring areas. It is certain that the nearby river segment would be under the influence of aquifer contribution due to higher groundwater levels.

d) Groundwater flux from June 2005 - May 2006:

In the present study, river-aquifer flow exchange is assessed from the flow-budget values for the calibration period June 2005 - May 2006 as shown in Table 6.10.

Table 6.10. Flow budget values from June 2005 - May 2006

Time	Flow Budget Values					
	Inflow in m^3/day			Outflow in m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
Jun-05	96776.0	403923.6	500699.6	254084.8	246615.2	500700.1
Jul-05	72976.8	552270.8	625247.6	378632.4	246615.2	625247.6
Aug-05	91182.8	450983.9	542166.7	295552.0	246615.2	542167.2
Sep-05	132585.6	255176.1	387761.7	141149.5	246615.2	387764.7
Oct-05	193119.1	141184.8	334303.9	87691.2	246615.2	334306.5
Nov-05	223612.5	97347.1	320959.6	74345.3	246615.2	320960.6
Dec-05	281276.5	17865.5	299142.0	52527.0	246615.2	299142.2
Jan-06	296451.0	0.0	296451.0	47690.6	248760.7	296451.3
Feb-06	296978.9	0.0	296978.9	47649.4	249329.9	296979.2
Mar-06	294175.3	2172.9	296348.1	47019.4	249329.9	296349.3
Apr-06	275480.2	26916.5	302396.7	53068.4	249329.9	302398.3
May-06	269573.2	35594.1	305167.3	55838.9	249329.9	305168.8

In the Table 6.10, aquifer discharge was found to increase slightly from June to August 2005. Later, river leakage was observed to increase during August 2005 to May 2006.

e) Spatial distribution of Groundwater heads from June 2006 - May 2007:

Spatial distributions of computed groundwater heads for 3 observation wells in the calibration period June 2006 - May 2007 are shown in Figure 6.27.

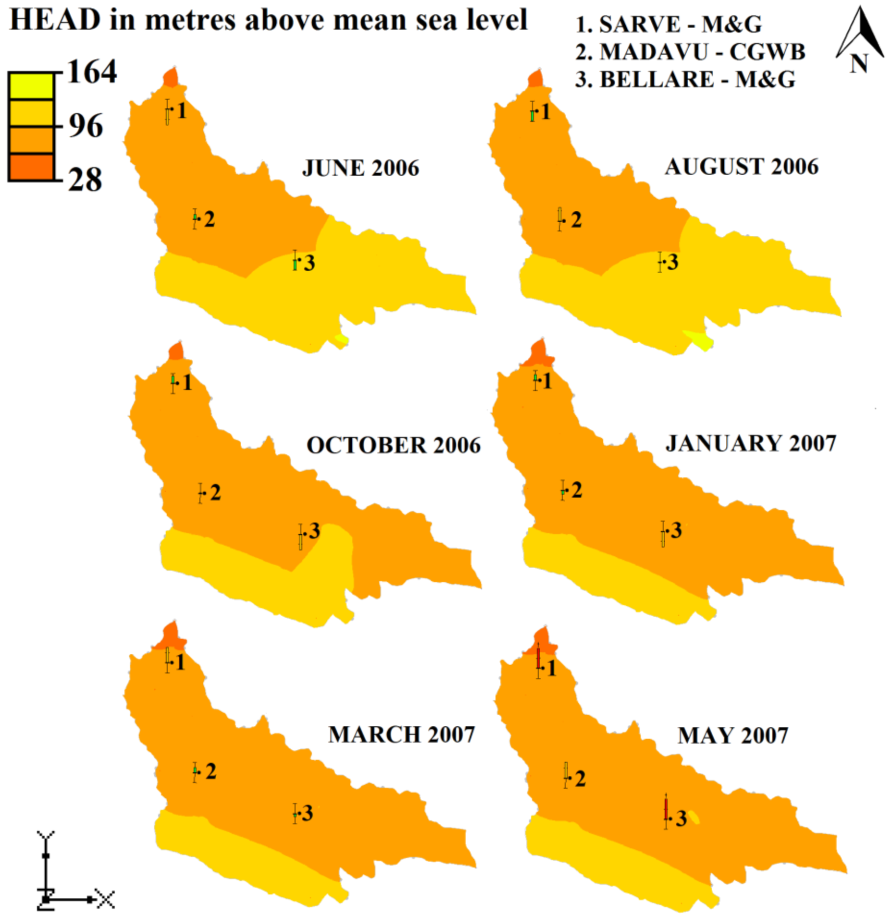


Figure 6.27 Computed groundwater heads from June 2006 - May 2007

From the month of June to August 2006, mild increase in groundwater heads was noticed in the upstream portion. The groundwater heads declined considerably from August 2006 to May 2007. Groundwater head was recognized to be at higher elevation near well no. 3 compared to the neighbouring areas in the month of October 2006. Thus, it can be mentioned that the nearby river segment would be under the influence of baseflow contribution due to increased groundwater levels.

f) Groundwater flux from June 2006 - May 2007:

In the present study, river-aquifer flow exchange is assessed from the flow-budget values for the calibration period June 2006 - May 2007 as shown in Table 6.11.

Table 6.11. Flow budget values from June 2006 - May 2007

Time	Flow Budget Values					
	Inflow in m^3/day			Outflow in m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
Jun-06	97113.2	407986.7	505099.9	255770.4	249329.9	505100.3
Jul-06	61927.9	673417.3	735345.2	486018.5	249329.9	735348.3
Aug-06	92644.8	423446.1	516090.9	266757.7	249329.9	516087.5
Sep-06	117484.0	297603.0	415087.0	165759.2	249329.9	415089.1
Oct-06	189770.4	155176.3	344946.7	95614.5	249329.9	344944.3
Nov-06	238769.1	82441.7	321210.8	71878.9	249329.9	321208.8
Dec-06	290139.3	9404.6	299543.9	50215.7	249329.9	299545.5
Jan-07	296762.4	0.0	296762.4	47433.4	249329.9	296763.3
Feb-07	295527.1	0.0	295527.1	46197.6	249329.9	295527.5
Mar-07	295527.1	0.0	295527.1	46197.6	249329.9	295527.5
Apr-07	280082.2	21232.9	301315.0	51987.1	249329.9	301316.9
May-07	264297.0	41379.0	305676.0	56343.9	249329.9	305673.7

From the Table 6.11, aquifer discharge was found to increase slightly during June to August 2006. Later from August 2006 to May 2007, river leakage was noticed to increase.

g) Spatial distribution of Groundwater heads from June 2007 - May 2008:

Spatial distributions of computed groundwater heads for 3 observation wells in the calibration period June 2007 - May 2008 are shown in Figure 6.28.

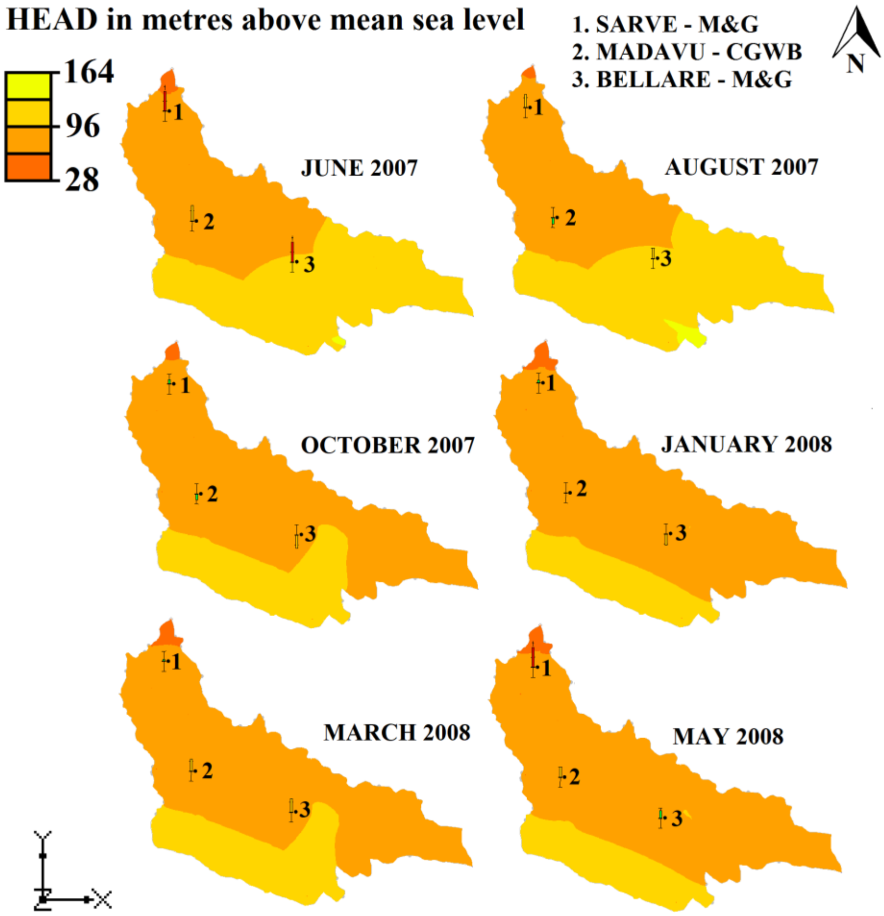


Figure 6.28 Computed groundwater heads from June 2007 - May 2008

Gradual increase in groundwater heads was observed from the month of June 2007 until August 2007 in the upstream part. However during August 2007 to May 2008, the groundwater heads declined significantly. Groundwater head was noticed to be at higher elevation near well no. 3 compared to the neighbouring areas in the month of October 2007. In the month of March 2008, the groundwater heads were again observed to increase due to unexpected rainfall over the sub-catchment. Thereby, it can be stated that the nearby river segment would be under the influence of baseflow contribution due to higher groundwater levels.

h) Groundwater flux from June 2007 - May 2008:

In the present study, river-aquifer flow exchange is assessed from the flow-budget values for the calibration period June 2007 - May 2008 as shown in Table 6.12.

Table 6.12. Flow budget values from June 2007 - May 2008

Time	Flow Budget Values					
	Inflow in m^3/day			Outflow in m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
Jun-07	98670.3	385727.3	484397.6	235070.0	249329.9	484399.9
Jul-07	56932.6	729307.4	786240.1	536910.5	249329.9	786240.4
Aug-07	71339.4	545389.6	616729.0	367397.8	249329.9	616727.6
Sep-07	101357.3	369880.0	471237.2	221906.5	249329.9	471236.4
Oct-07	192115.5	151835.8	343951.3	94621.2	249329.9	343951.0
Nov-07	263207.2	46859.5	310066.7	60737.2	249329.9	310067.0
Dec-07	296989.1	0.0	296989.1	47660.0	249329.9	296989.9
Jan-08	295527.0	0.0	295527.0	46197.6	249329.9	295527.5
Feb-08	293746.6	2294.1	296040.7	46710.3	249329.9	296040.1
Mar-08	200691.1	136093.8	336784.9	87457.4	249329.9	336787.2
Apr-08	284601.4	16656.3	301257.7	51927.7	249329.9	301257.5
May-08	284811.1	13731.4	298542.5	49213.2	249329.9	298543.0

In the Table 6.12, aquifer discharge was found to increase from June to August 2007. Later during August 2007 to May 2008, river leakage was noticed to increase. Aquifer discharge was recognized to be remarkably high in March 2008 compared to neighbouring months.

i) Spatial distribution of Groundwater heads from June 2008 - May 2009:

Spatial distributions of computed groundwater heads for 3 observation wells in the calibration period June 2008 - May 2009 are shown in Figure 6.29.

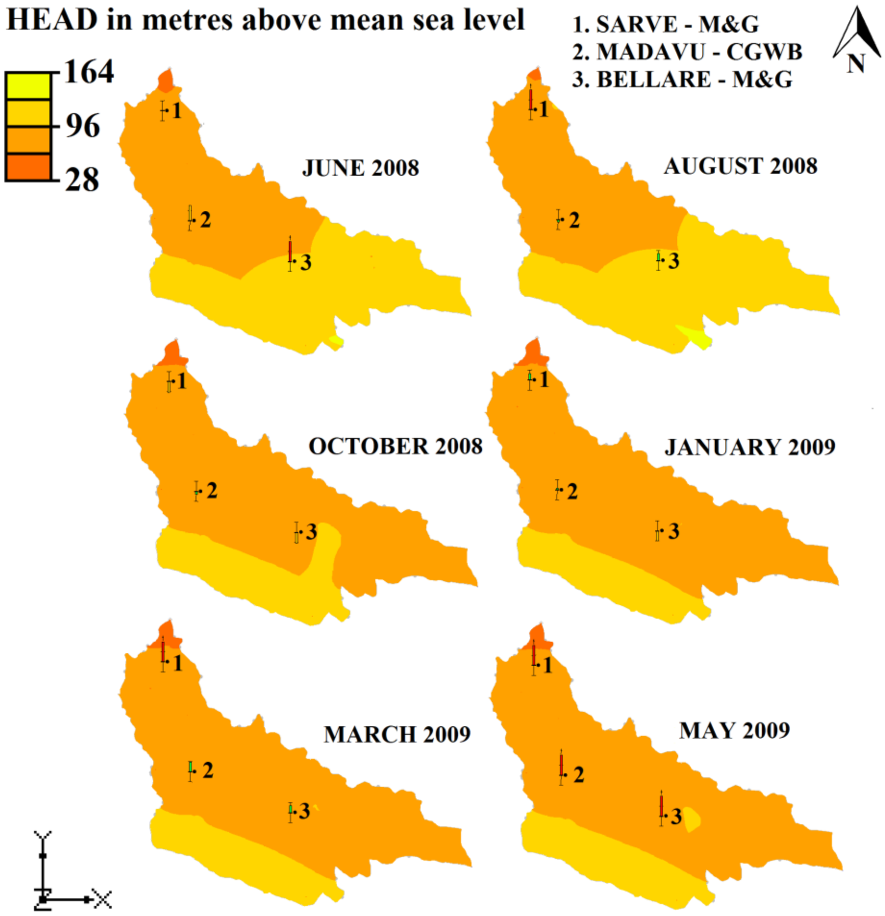


Figure 6.29 Computed groundwater heads from June 2008 - May 2009

From the month of June until August 2008, slight increase in groundwater heads was noticed in the upstream area. However, groundwater heads declined remarkably during August 2008 to May 2009. In the month of October 2008 and May 2009, groundwater head was recognized to be at higher elevation near well no. 3 compared to the neighbouring areas. It can be deduced that the nearby river segment would be under the influence of aquifer contribution due to higher groundwater levels.

j) *Groundwater flux from June 2008 - May 2009:*

In the present study, river-aquifer flow exchange is assessed from the flow-budget values for the calibration period June 2008 - May 2009 as shown in Table 6.13.

Table 6.13. Flow budget values from June 2008 - May 2009

Time	Flow Budget Values					
	Inflow in m^3/day			Outflow in m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
Jun-08	97246.7	399851.7	497098.4	247767.9	249329.9	497097.8
Jul-08	101301.2	370929.2	472230.3	222899.5	249329.9	472229.3
Aug-08	74150.1	550545.8	624696.0	375363.2	249329.9	624693.1
Sep-08	178901.2	169213.8	348114.9	98788.0	249329.9	348117.9
Oct-08	214755.3	115507.2	330262.5	80934.1	249329.9	330263.9
Nov-08	285066.9	16182.8	301249.7	51919.3	249329.9	301249.1
Dec-08	295695.9	1797.1	297492.9	48162.9	249329.9	297492.8
Jan-09	296829.3	0.0	296829.3	47499.5	249329.9	296829.4
Feb-09	295527.1	0.0	295527.1	46197.6	249329.9	295527.5
Mar-09	286246.8	12589.7	298836.5	49504.8	249329.9	298834.6
Apr-09	282622.5	16567.9	299190.3	49862.7	249329.9	299192.6
May-09	223588.1	107290.2	330878.3	81548.6	249329.9	330878.4

In the Table 6.13, aquifer discharge was found to increase from June to August 2008. Later during August 2008 to May 2009, river leakage was observed to increase. Aquifer discharge was recognized to be significantly high in May 2009 compared to neighbouring months.

k) Spatial distribution of Groundwater heads from June 2009 - May 2010:

Spatial distributions of computed groundwater heads for 3 observation wells in the calibration period June 2009 - May 2010 are shown in Figure 6.30.

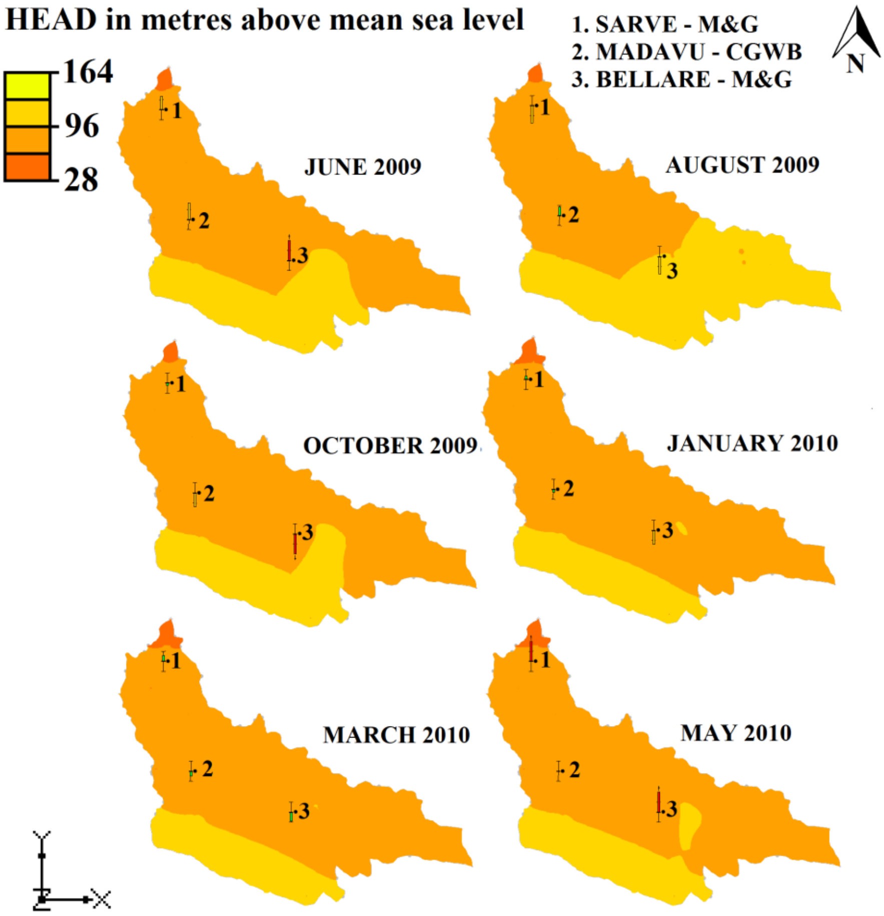


Figure 6.30 Computed groundwater heads from June 2009 - May 2010

During the month of June to August 2009, notable increase in groundwater heads was observed in the upstream. The groundwater heads declined significantly from August 2009 to May 2010. Groundwater head was noticed to be at higher elevation near well no. 3 compared to the neighbouring areas in the month of October 2009 and May 2010. Consequently, it can be described that the nearby river segment would be under the influence of aquifer contribution due to higher groundwater levels.

l) Groundwater flux from June 2009 - May 2010:

In the present study, river-aquifer flow exchange is assessed from the flow-budget values for the calibration period June 2009 - May 2010 as shown in Table 6.14.

Table 6.14. Flow budget values from June 2009 - May 2010

Time	Flow Budget Values					
	Inflow in m^3/day			Outflow in m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
Jun-09	181101.8	164882.2	345984.0	96656.3	249329.9	345986.2
Jul-09	57699.1	737695.0	795394.2	546062.6	249329.9	795392.4
Aug-09	112148.2	320646.9	432795.1	183467.2	249329.9	432797.1
Sep-09	105541.5	349175.7	454717.2	205389.0	249329.9	454718.9
Oct-09	195478.2	151083.3	346561.5	97234.5	249329.9	346564.3
Nov-09	243314.7	75684.8	318999.5	69669.7	249329.9	318999.6
Dec-09	287030.1	13679.0	300709.1	51377.7	249329.9	300707.6
Jan-10	261355.2	48798.5	310153.7	60823.3	249329.9	310153.2
Feb-10	294691.6	1344.6	296036.2	46707.2	249329.9	296037.0
Mar-10	289586.1	8235.7	297821.8	48490.8	249329.9	297820.6
Apr-10	262306.3	43507.8	305814.2	56485.2	249329.9	305815.0
May-10	226263.1	94844.8	321107.9	71777.0	249329.9	321106.8

In the Table 6.14, aquifer discharge was found to increase during June to August 2009. Later, river leakage was observed to increase from August 2009 to May 2010. Aquifer discharge was recognized to be considerably high in May 2010 compared to neighbouring months.

m) Comparison of observed and computed values of Groundwater heads:

The observed and computed values of groundwater heads calibrated for the period of June 2004 to May 2010 are presented in the Figure 6.31.

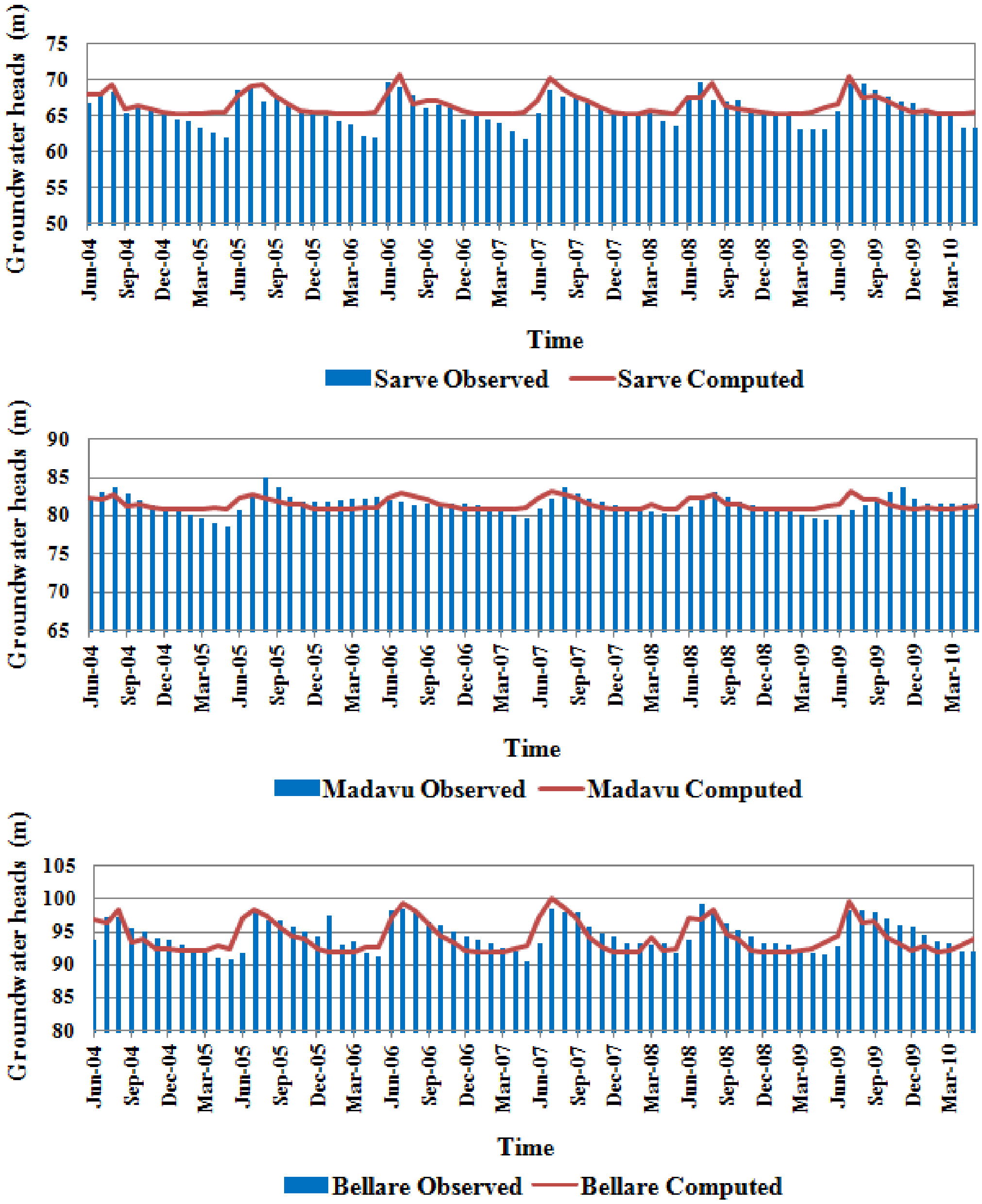


Figure 6.31 Computed vs Observed Groundwater Heads for calibration period

During the calibration period, the model computed groundwater heads satisfactorily matched with observed ones in monsoon months, but modestly over-estimated for summer months.

6.2.2 Validation of the sub-catchment scale model from June 2010 - May 2012

a) Spatial distribution of Groundwater heads from June 2010 - May 2011:

Spatial distributions of computed groundwater heads for 3 observation wells in the validation period June 2010 - May 2011 are shown in Figure 6.32.

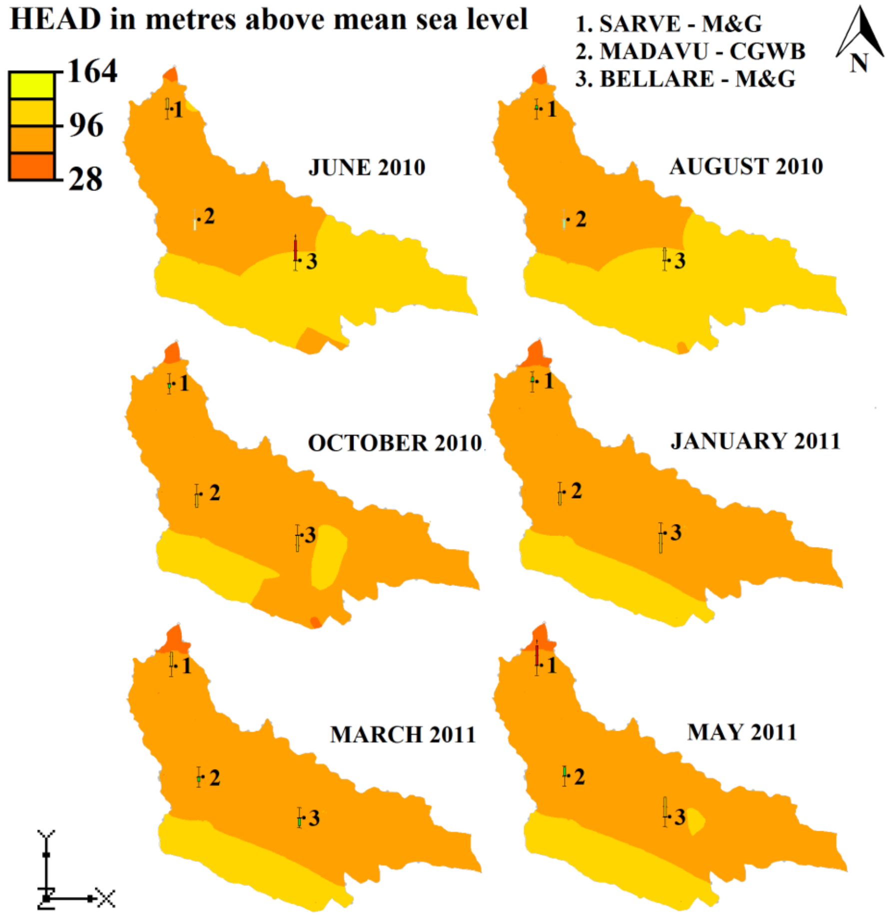


Figure 6.32 Computed groundwater heads from June 2010 - May 2011

From the month of June to August 2010, slight increase in groundwater heads was noticed in the upstream area. However, groundwater heads declined considerably during August 2010 to May 2011. In the month of October 2010 and May 2011, the groundwater heads were observed to be at higher elevation near well no. 3 compared to the neighbouring areas. Hence, it can be specified that the nearby river segment would be under the influence of aquifer contribution due to higher groundwater levels.

b) Groundwater flux from June 2010 - May 2011:

In the present study, river-aquifer flow exchange is assessed from the flow-budget values for the validation period June 2010 - May 2011 as shown in Table 6.15.

Table 6.15. Flow budget values from June 2010 - May 2011

Time	Flow Budget Values					
	Inflow in m^3/day			Outflow in m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
Jun-10	107868.9	523437.3	631306.3	329425.7	301880.2	631305.9
Jul-10	98200.4	525466.4	623666.7	321785.0	301880.2	623665.2
Aug-10	90130.3	564185.1	654315.3	352438.2	301880.2	654318.4
Sep-10	128224.9	336269.9	464494.8	162615.5	301880.2	464495.7
Oct-10	204916.1	163375.0	368291.0	66412.2	301880.2	368292.3
Nov-10	160428.8	236566.4	396995.2	95117.5	301880.2	396997.6
Dec-10	291237.1	6696.5	297933.6	48603.1	249329.9	297932.9
Jan-11	295885.0	327.6	296212.7	46883.1	249329.9	296212.9
Feb-11	294845.4	0.0	294845.4	45515.9	249329.9	294845.8
Mar-11	294729.0	0.0	294729.0	45399.5	249329.9	294729.4
Apr-11	255051.9	54135.2	309187.0	59854.6	249329.9	309184.4
May-11	233463.1	85704.7	319167.8	69838.0	249329.9	319167.8

In the Table 6.15, aquifer discharge was found to increase from June to August 2010. Later during August 2010 to May 2011, river leakage was observed to increase. Aquifer discharge was recognized to be noticeably high in November 2010 and May 2011 compared to neighbouring months.

c) Spatial distribution of Groundwater heads from June 2011 - May 2012:

Spatial distributions of computed groundwater heads for 3 observation wells in the validation period June 2011 - May 2012 are shown in Figure 6.33.

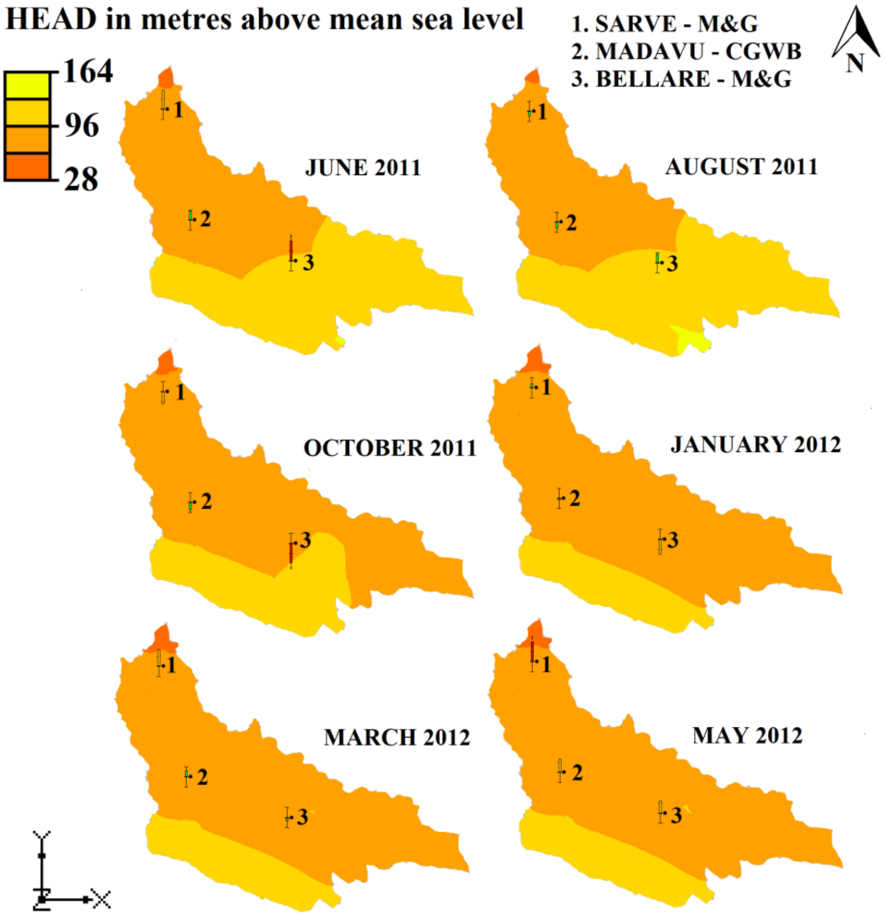


Figure 6.33 Computed groundwater heads from June 2011 - May 2012

Slight increase in groundwater heads was observed from the month of June to August 2011 in the upstream portion. The groundwater heads declined noticeably from August 2011 to May 2012. Groundwater head was identified to be at higher elevation near well no. 3 compared to the neighbouring areas in the month of October 2011. Consequently, it can be stated that the nearby river segment would be under the influence of baseflow contribution due to higher groundwater levels.

d) Groundwater flux from June 2011 - May 2012:

In the present study, river-aquifer flow exchange is assessed from the flow-budget values for the validation period June 2011 - May 2012 as shown in Table 6.16.

Table 6.16. Flow budget values from June 2011 - May 2012

Time	Flow Budget Values					
	Inflow in m^3/day			Outflow in m^3/day		
	River Leakage	Rainfall Recharge	Total Inflow	Aquifer Discharge	Well Draft	Total Outflow
Jun-11	98711.3	394116.8	492828.1	243499.1	249329.9	492829.0
Jul-11	54661.5	762550.7	817212.2	567883.5	249329.9	817213.4
Aug-11	67950.5	576853.7	644804.1	395473.8	249329.9	644803.7
Sep-11	96533.9	398307.0	494840.9	245509.1	249329.9	494839.0
Oct-11	178586.8	171816.2	350403.0	101071.7	249329.9	350401.5
Nov-11	230016.2	96272.8	326289.0	76959.8	249329.9	326289.7
Dec-11	287783.8	13205.3	300989.1	51660.6	249329.9	300990.4
Jan-12	293933.6	3317.1	297250.7	47922.9	249329.9	297252.7
Feb-12	294729.1	0.0	294729.1	45399.5	249329.9	294729.4
Mar-12	289768.0	6833.5	296601.5	47270.0	249329.9	296599.8
Apr-12	259127.0	50393.7	309520.7	60188.6	249329.9	309518.5
May-12	280380.6	19266.0	299646.6	50316.2	249329.9	299646.0

In the Table 6.16, aquifer discharge was found to increase during June to August 2011. Later, river leakage was noticed to increase from August 2011 to May 2012. Aquifer discharge was recognized to be moderately high in April 2012 compared to neighbouring months.

In the present study, the spatial distribution of groundwater heads during the validation period showed similar dynamics as that of the calibration period.

e) Comparison of observed and computed values of Groundwater heads:

The observed and computed values of groundwater heads validated for the period of June 2010 to September 2012 are presented in the Figure 6.34.

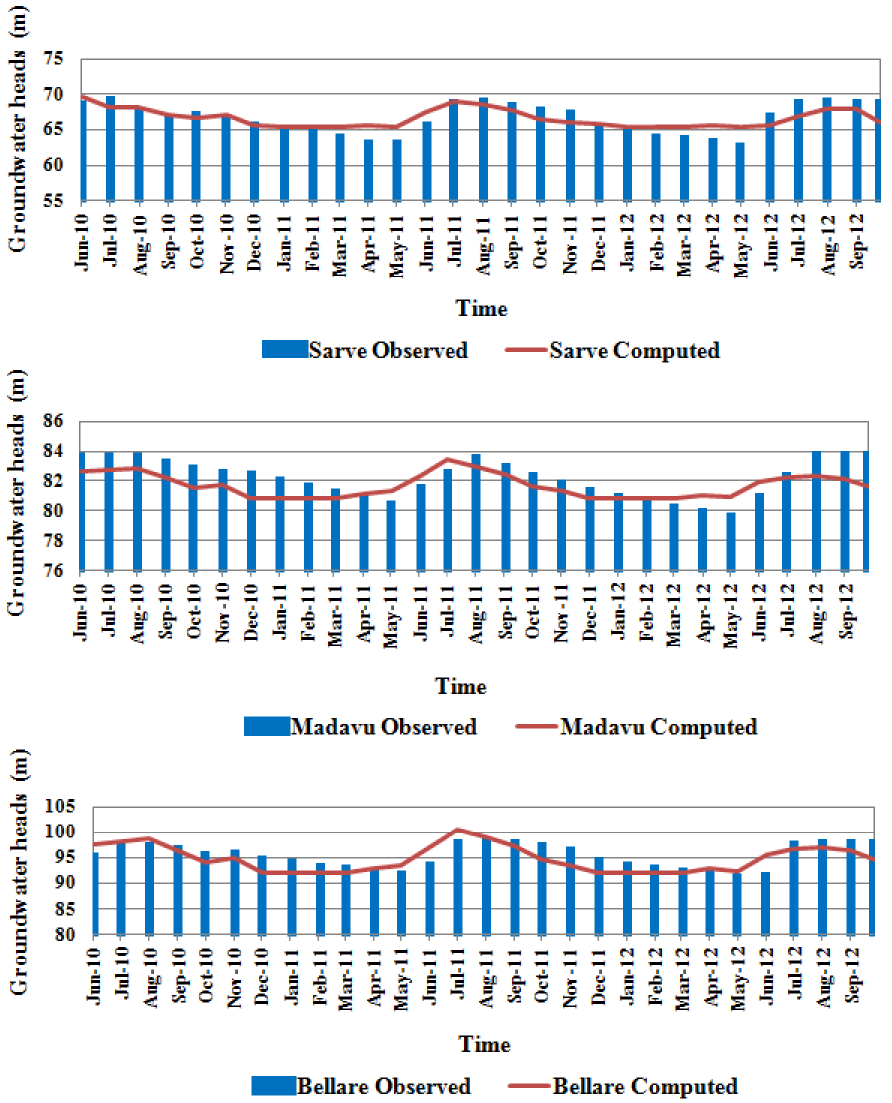


Figure 6.34 Computed vs Observed Groundwater Heads for validation period

During the validation period, model computed groundwater heads satisfactorily matched with observed ones during monsoon months, but slightly under-estimated during post-monsoon period and moderately over-estimated for summer months.

6.2.3 Temporal variation of river leakage and aquifer discharge

The interactions between surface water and groundwater in a riverflow regime for a sub-catchment are highly complex in a time-variant system. This has to be analyzed with a focus on interactive mechanism between surface and groundwater systems. In the present section, temporal variations of river-aquifer interactions of the sub-catchment are studied and the results are discussed in detail.

In the conceptual modeling approach, rainfall recharge and river leakage are input to the system whereas groundwater draft and aquifer discharge are output from the system. The temporal variation of the river leakage and aquifer discharge in the study area is shown in Figure 6.35.

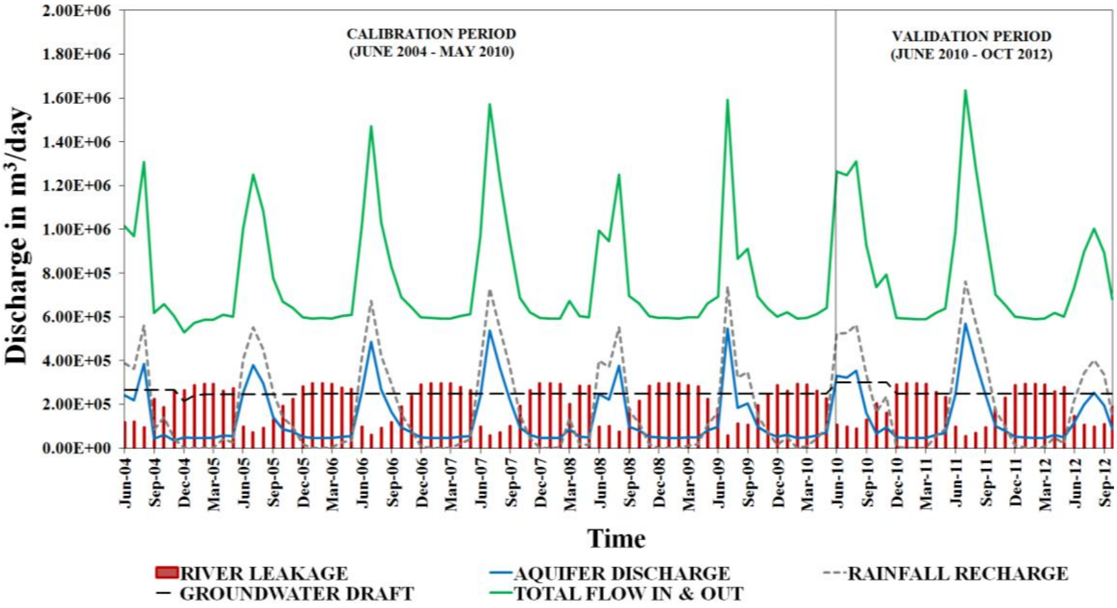


Figure 6.35 Temporal variation of river leakage and aquifer discharge

During the calibration period, in the initial monsoon months from June to July 2007, river leakage reduced from 98,670 m^3 (10.2%) to 56,932 m^3 (3.6%), since high-intensity rainfall converted into runoff due to early saturation of the water-bearing units. The decline in peak rainfall from August provided enough opportunity for flow over the riverbed to recharge the aquifer beneath. Hence, river leakage significantly increased from 71,340 m^3 (5.8%) in August to 2,96,989 m^3 (50%) in December. Consequently, groundwater resources were much utilized in the area for irrigational activities during the post-monsoon period. From December month of 2007, river leakage sustained to occur upto 2,84,811 m^3 (47.7%) until May 2008. With the increase in groundwater heads by the advent of monsoons in June 2007, aquifer discharge into the river flow increased from 2,35,070 m^3 (24.3%) in June to 5,36,910 m^3 (34.1%) in July. In the post-monsoon period due to the drop in groundwater heads, aquifer contribution into the river flow considerably decreased up to 46,197 m^3 (7.8%) in January 2008. Aquifer discharge continued to faintly exist in the summer period up to 49,213 m^3 (8.2%) until the end of May 2008.

For the validation period, in the year 2011, river leakage reduced from 98,711 m^3 (10%) to 54,661 m^3 (3.3%) from June to July. It drastically increased from 67,950 m^3 (5.3%) in August to 2,87,783 m^3 (47.8%) in December. River leakage slowly decreased to 2,80,380 m^3 (46.8%) in May 2012. River leakage found to be slightly under-estimated during post-monsoon and summer months. Aquifer discharge into the river flow increased from 2,43,500 m^3 (24.7%) in June 2011 to 5,67,883 m^3 (34.7%) in July 2011. In the post-monsoon, aquifer discharge noticeably decreased to 47,923 m^3 (8.1%) in January 2012, but existed to contribute up to 50,316 m^3 (8.4%) in May 2012. Aquifer discharge found to be modestly over-estimated during post-monsoon and summer months. The trend in temporal variation of interaction during the validation period June 2011 – May 2012 proved to match with that of the calibration period June 2007 – May 2008 successfully.

In the present study, temporal variation of river leakage is tabulated in terms of percentage with reference to total flow for calibration period June 2004 - May 2010 and validation period June 2010 - May 2012 as shown in Table 6.17.

Table 6.17. Percentage Temporal Variation of River Leakage

Time	Calibration						Validation		RL
Month	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	Average
Jun	11.6	9.7	9.6	10.2	9.8	26.2	8.5	10.0	11.9
Jul	12.6	5.8	4.2	3.6	10.7	3.6	7.9	3.3	6.5
Aug	7.2	8.4	9.0	5.8	5.9	13.0	6.9	5.3	7.7
Sep	36.3	17.1	14.2	10.8	25.7	11.6	13.8	9.8	17.4
Oct	28.7	28.9	27.5	27.9	32.5	28.2	27.8	25.5	28.4
Nov	43.0	34.8	37.2	42.4	47.3	38.1	20.2	35.2	37.3
Dec	50.0	47.0	48.4	50.0	49.7	47.7	48.9	47.8	48.7
Jan	50.0	50.0	50.0	50.0	50.0	42.1	49.9	49.4	48.9
Feb	50.0	50.0	50.0	49.6	50.0	49.8	50.0	50.0	49.9
Mar	50.0	49.6	50.0	29.8	47.9	48.6	50.0	48.8	46.8
Apr	43.2	45.5	46.5	47.2	47.2	42.9	41.2	41.9	44.5
May	45.7	44.2	43.2	47.7	33.8	35.2	36.6	46.8	41.6

In the present study, temporal variation of aquifer discharge is tabulated in terms of percentage with reference to total flow for calibration period June 2004 - May 2010 and validation period June 2010 - May 2012 as shown in Table 6.18.

Table 6.18. Percentage Temporal Variation of Aquifer Discharge

Time	Calibration						Validation		AD
Month	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	Average
Jun	23.7	25.4	25.3	24.3	24.9	14.0	26.1	24.7	23.5
Jul	22.5	30.3	33.0	34.1	23.6	34.3	25.8	34.7	29.8
Aug	29.6	27.3	25.8	29.8	30.0	21.2	26.9	30.7	27.7
Sep	6.8	18.2	20.0	23.5	14.2	22.6	17.5	24.8	18.5
Oct	9.4	13.1	13.9	13.8	12.3	14.0	9.0	14.4	12.5
Nov	5.7	11.6	11.2	9.8	8.6	10.9	12.0	11.8	10.2
Dec	9.3	8.8	8.4	8.0	8.1	8.5	8.2	8.6	8.5
Jan	8.1	8.0	8.0	7.8	8.0	9.8	7.9	8.1	8.2
Feb	7.9	8.0	7.8	7.9	7.8	7.9	7.7	7.7	7.8
Mar	7.9	7.9	7.8	13.0	8.3	8.1	7.7	8.0	8.6
Apr	9.5	8.8	8.6	8.6	8.3	9.2	9.7	9.7	9.1
May	9.0	9.1	9.2	8.2	12.3	11.2	10.9	8.4	9.8

6.2.4 Spatial variation of river leakage and aquifer discharge in calibration

In the present study, spatial variations of river leakage and aquifer discharge were analyzed for calibration period of June 2004 to May 2010.

The model results indicated the contribution of aquifer discharge into the river flow was persistent at the downstream confluence point throughout the simulation period. Some parts of river segments 1, 6 and 7 of the study area were noticed to be continuously under the influence of aquifer discharge. River segments 2, 3 and 4 were consistently dominated by river leakage areas.

a) Spatial variation of river-aquifer interactions from June 2004 - May 2005:

The spatial variation of river leakage and aquifer discharge over the study area for the calibration period from June 2004 - May 2005 is presented in Figure 6.36.

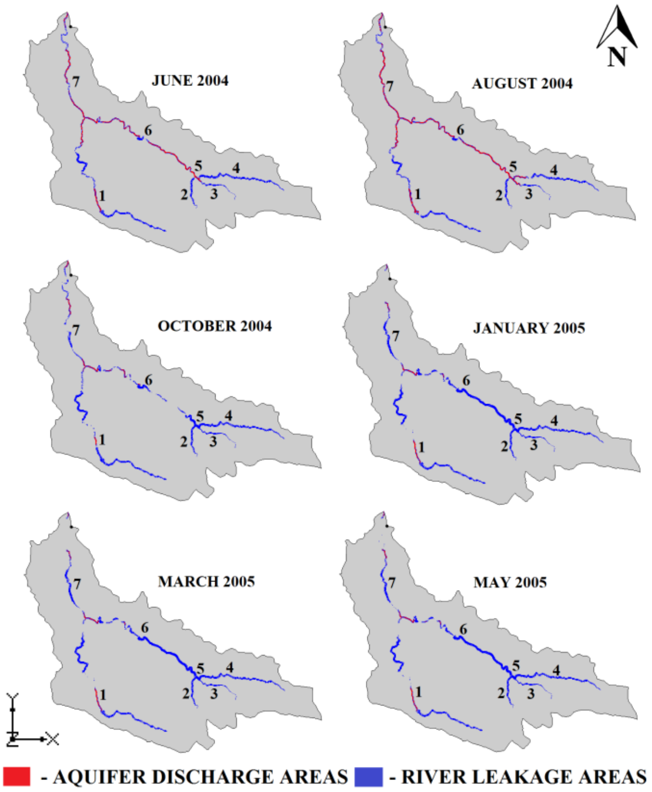


Figure 6.36 Spatial variation of interactions from June 2004 - May 2005

In the peak monsoon months of June to August 2004, aquifer discharge areas observed to majorly extend into the river segments 1, 5, 6 and 7 due to increased groundwater table caused by quick saturation. Whereas, river leakage areas were noticed at the river segments 2, 3 and 4 in this duration. With the descent of monsoons from August to October 2004, aquifer discharge found to cease at river segments 1, 6 and 7 due to the lowered groundwater table. From October 2004, it was observed that river leakage areas significantly increased until existent monsoon flows in the river diminished by the end of January 2005. During January to May 2005, the dominant river leakage areas resulted in fragmentation and drying of some parts of river segments 1, 6 and 7. Aquifer contribution areas sustained some parts of the low flow river segments from drying during the summer months of 2005.

b) Spatial variation of river-aquifer interactions from June 2005 - May 2006:

The spatial variation of river leakage and aquifer discharge over the study area for the calibration period from June 2005 - May 2006 is presented in Figure 6.37.

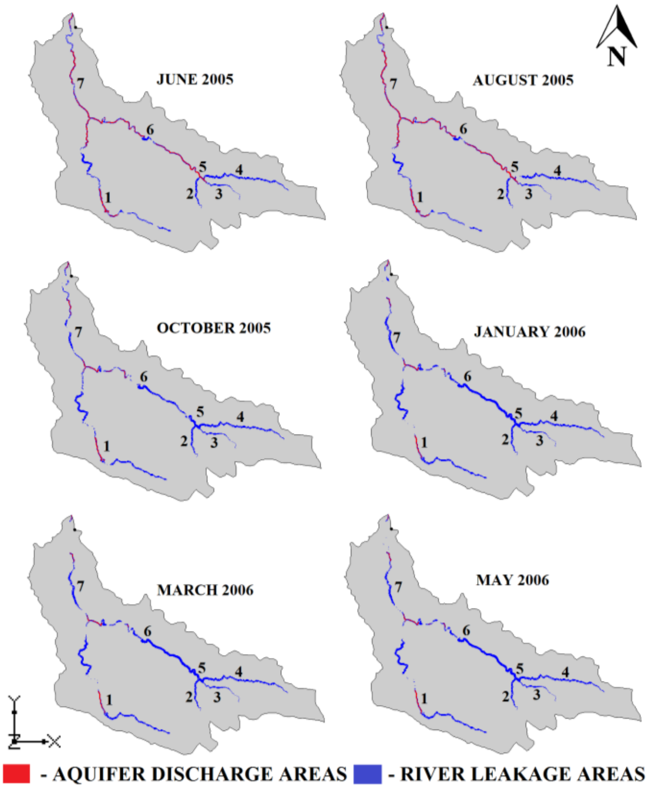


Figure 6.37 Spatial variation of interactions from June 2005 - May 2006

During the monsoon months of June to August 2005, aquifer discharge areas appeared to dominate the river segments 1, 5, 6 and 7 with increased groundwater table. While, river leakage areas were noticed in the river segments 2, 3 and 4. From August to

October 2005, influence of aquifer discharge on the river segments decreased with the decline in monsoon flows. It was noticed that from October 2005 to January 2006, river leakage areas considerably increased due to the lowered groundwater table. During January to May 2006, the prevailing river leakage areas resulted in drying up and fragmentation of some parts of river segments 1, 6 and 7. Aquifer discharge areas in some parts of the segments sustained low flow river from drying during the summer months until May 2006.

c) Spatial variation of river-aquifer interactions from June 2006 - May 2007:

The spatial variation of river leakage and aquifer discharge over the study area for the calibration period from June 2006 - May 2007 is presented in Figure 6.38.

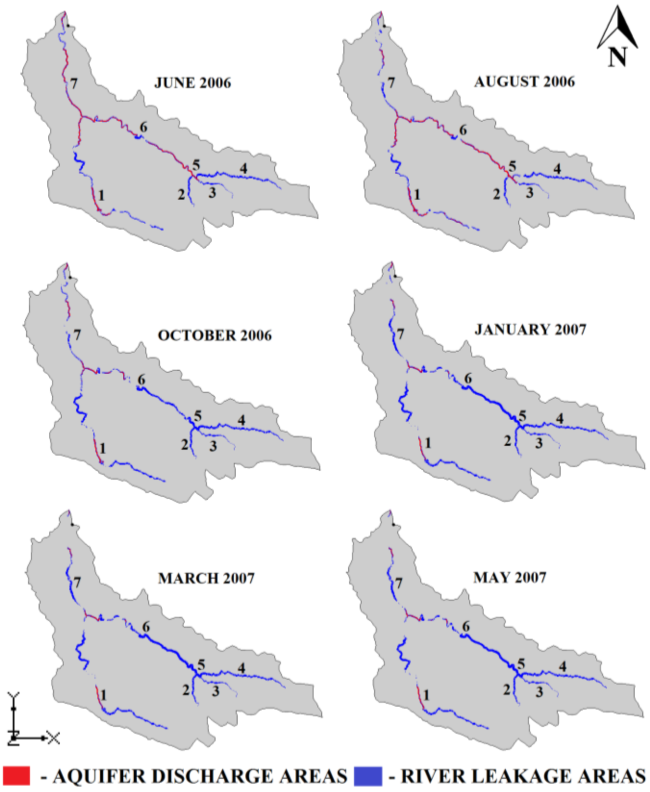


Figure 6.38 Spatial variation of interactions from June 2006 - May 2007

At peak monsoon months of June to August 2006, aquifer discharge areas were observed to expand into the river segments 1, 5, 6 and 7 due to high groundwater table. With that, river leakage areas were observed to dominate the upstream river segments 2, 3 and 4. During August to October 2006, river segments under the influence of aquifer discharge decreased due to decline in groundwater table. From October 2006, river leakage areas significantly increased with the end of existential monsoon flow by the end of January 2007. It was noticed from January that the river leakage resulted in fragmentation of river segments 1, 6 and 7 due to drying of some parts of the river reaches until May 2007. Aquifer contribution areas sustained the low flow river segments from drying in this duration.

d) *Spatial variation of river-aquifer interactions from June 2007 - May 2008:*

The spatial variation of river leakage and aquifer discharge over the study area for the calibration period from June 2007 - May 2008 is presented in Figure 6.39.

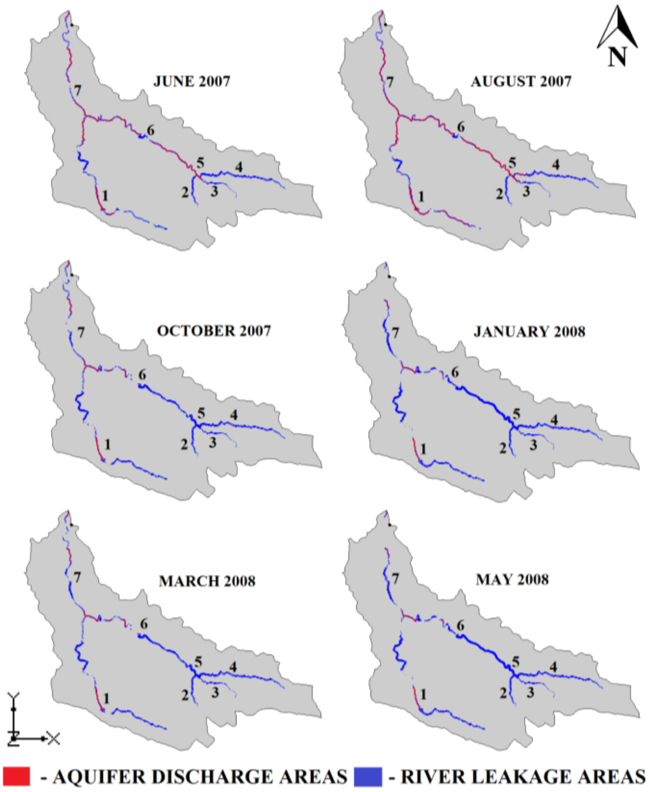


Figure 6.39 Spatial variation of interactions from June 2007 - May 2008

During peak monsoon months of June to August 2007, aquifer discharge areas appeared to majorly extend into the river segments 1, 5, 6 and 7 due to augmented groundwater table caused by quick saturation. Whereas, river leakage areas were noticed in the river segments 2, 3 and 4. During August to October 2007, river segments under the influence of aquifer discharge decreased due to the lowered groundwater table by the descent of monsoon flows. From October 2007, it was observed that river leakage areas notably increased until existent monsoon flows in the river diminished by the end of January. However from January 2008, the dominant river leakage areas resulted in fragmentation and drying of some parts of river segments 1, 6 and 7. Aquifer discharge areas sustained the low flow river segments from drying in summer months of 2008.

e) Spatial variation of river-aquifer interactions from June 2008 - May 2009:

The spatial variation of river leakage and aquifer discharge over the study area for the calibration period from June 2008 - May 2009 is presented in Figure 6.40.

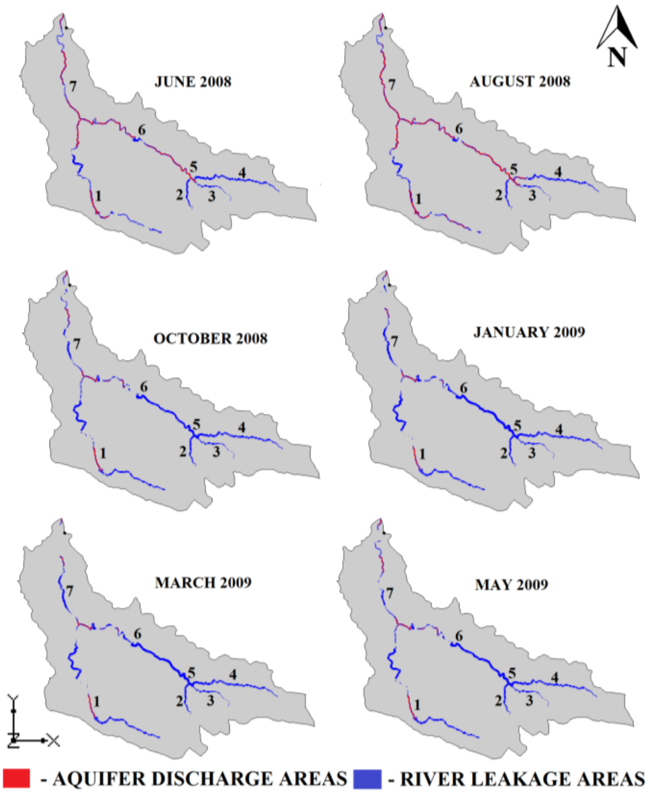


Figure 6.40 Spatial variation of interactions from June 2008 - May 2009

In peak monsoon months of June to August 2008, aquifer discharge areas were observed to dominate the river segments 1, 5, 6 and 7 with the increase in groundwater table. While in this duration, river leakage areas were noticed in the river segments 2, 3 and 4. From August to October 2008, the influence of aquifer discharge areas on river segments decreased with the descent of monsoon flows. Although from

October 2008, river leakage areas significantly increased due to the lowered groundwater table upto the month of January 2009. Since January, the dominant river leakage areas resulted in fragmentation and drying of some parts of river segments 1, 6 and 7 until the end of May 2009. In this duration, aquifer contribution at some parts of the segments sustained the low flow river from drying.

f) Spatial variation of river-aquifer interactions from June 2009 - May 2010:

The spatial variation of river leakage and aquifer discharge over the study area for the calibration period from June 2009 - May 2010 is presented in Figure 6.41.

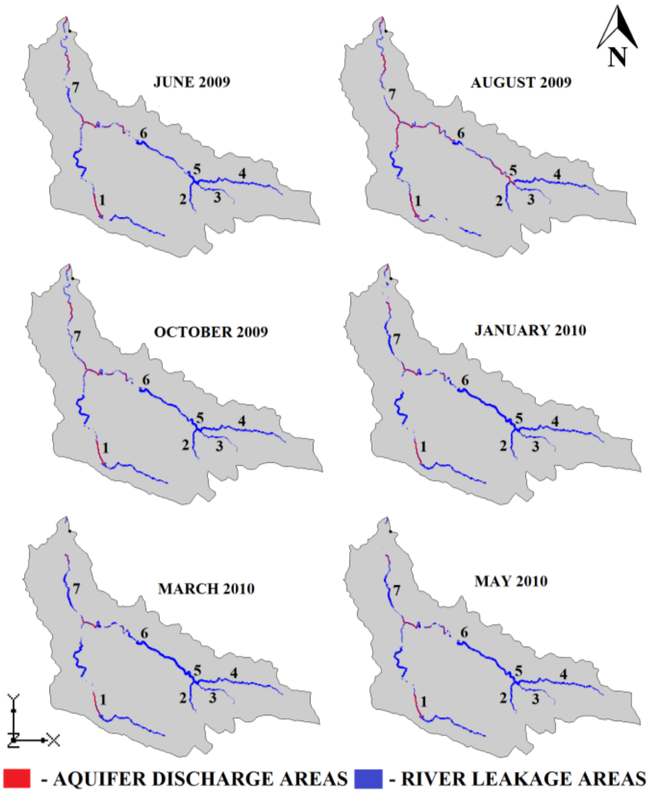


Figure 6.41 Spatial variation of interactions from June 2009 - May 2010

At peak monsoon months of June to August 2009, aquifer discharge areas noticed to mainly spread in the river segments 1, 5, 6 and 7 due to elevated groundwater table. Whereas, river leakage areas were observed in the river segments 2, 3 and 4. During August to October 2009, aquifer discharge areas decreased the influence on river segments due to the lowered groundwater table. However it was observed from October 2009 that the river leakage areas considerably increased until the end of

January 2010. Further from January upto May 2010, the existing river leakage areas resulted in fragmentation and drying of some parts of river segments 1, 6 and 7. Aquifer discharge areas sustained the low flow river segments from drying during the summer months.

6.2.5. Spatial variation of river leakage and aquifer discharge in validation

In the present study, spatial variations of river leakage and aquifer discharge were evaluated for validation period of June 2010 to May 2012.

a) Spatial variation of river-aquifer interactions from June 2010 - May 2011:

The spatial variation of river leakage and aquifer discharge over the study area for the validation period from June 2010 - May 2011 is presented in Figure 6.42.

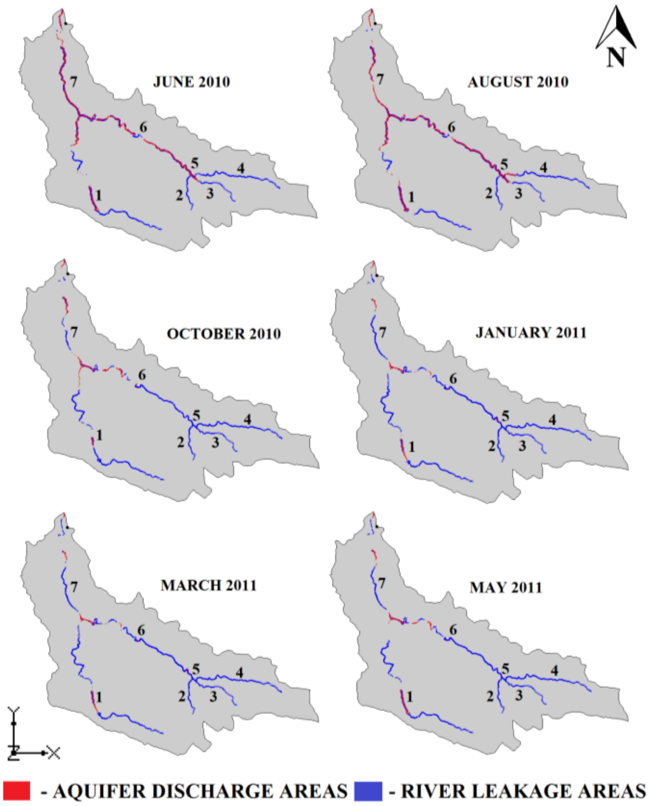


Figure 6.42 Spatial variation of interactions from June 2010 - May 2011

In peak monsoon months of June to August 2010, aquifer discharge areas appeared to majorly extend into the river segments 1, 5, 6 and 7 due to higher groundwater table. While, river leakage areas were noticed in the river segments 2, 3 and 4 in this period.

From August to October 2010, river segments under the influence of aquifer discharge decreased due to the lowered groundwater table. Since October, it was observed that river leakage areas significantly increased with the descent of existential monsoon flows upto January 2011. However during January to May 2011, the dominant river leakage areas resulted in fragmentation and drying of some parts of river segments 1, 6 and 7. Aquifer contribution areas sustained the low flow river segments from drying in the summer months.

b) Spatial variation of river-aquifer interactions from June 2011 - May 2012:

The spatial variation of river leakage and aquifer discharge over the study area for the validation period from June 2011 - May 2012 is presented in Figure 6.43.

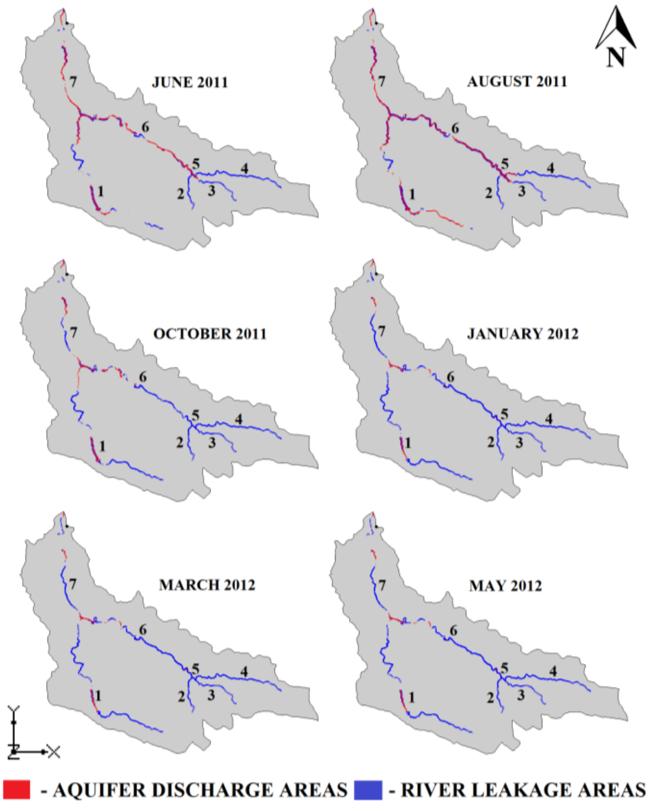


Figure 6.43 Spatial variation of interactions from June 2011 - May 2012

At peak monsoon months of June to August 2011, aquifer discharge areas were noticed to dominate the river segments 1, 5, 6 and 7 due to increased groundwater table. Whereas, river leakage areas were observed in the river segments 2, 3 and 4. During August to October 2011, the influence of aquifer discharge areas on river segments decreased due to the lowered groundwater table. From October 2011, it was observed that river leakage areas significantly increased until existent monsoon flows in the river diminished upto January 2012. Since January, the dominant river leakage areas resulted in fragmentation and drying of some parts of river segments 1, 6 and 7 until the end of May 2012. Aquifer contribution areas sustained some parts of the low flow river segments from drying during the summer months of 2012.

For the validation period June 2010 to May 2012, the dynamics in the spatial pattern of interaction proved to match with that of the calibration period June 2004 to May 2010.

6.2.6. Characterization of flow exchange in the river-segments of Gowri-HoLe

The study also focuses on the characterization of flow exchange in different river segments of Gowri-HoLe sub-catchment. The flow exchange between river-aquifer systems is assessed using sub-catchment scale model for the calibration period June 2004 - May 2010 and validation period June 2010 - May 2012.

The respective volume (m^3/day) of river leakage and aquifer discharge for different river segments for June 2004 - May 2005 are presented in the table 6.19. Positive values in the table represent the river leakage (RL) values and negative values represent the aquifer discharge (AD) values.

Table 6.19 River leakage and aquifer discharge values for June 2004 - May 2005

Time	River Segments						
	1 (AB)	2 (CD)	3 (EF)	4 (GF)	5 (DF)	6 (BD)	7 (BH)
Jun-04	-9578.6 AD	12935.1 RL	8910.5 RL	34860.8 RL	-8072.2 AD	-104429.9 AD	-57267.2 AD
Jul-04	435.4 RL	13076.9 RL	9977.9 RL	35630.8 RL	-6999.0 AD	-90053.2 AD	-57919.6 AD
Aug-04	-45846.3 AD	11817.9 RL	-517.4 AD	15720.2 RL	-12512.0 AD	-164768.6 AD	-96083.7 AD
Sep-04	64089.7 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	41026.8 RL	6869.9 RL
Oct-04	52467.4 RL	13759.7 RL	12564.5 RL	38149.0 RL	5622.1 RL	13825.4 RL	-9949.3 AD
Nov-04	75065.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	72047.2 RL	7196.8 RL
Dec-04	43995.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	84019.3 RL	16797.2 RL
Jan-05	44283.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	108816.6 RL	16684.7 RL
Feb-05	44339.2 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	115358.4 RL	16712.6 RL
Mar-05	44339.2 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	115358.4 RL	16712.6 RL
Apr-05	33569.8 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	91040.1 RL	10154.5 RL
May-05	38503.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	101839.9 RL	10066.1 RL

From Table 6.19, it was observed that Gowri-HoLe acts as a Gaining River during the monsoon period of 2004 due to aquifer discharge. It acts as a Losing River due to river leakage during post-monsoon and summer months of the year 2005. The upstream segments 2, 3 and 4 were found to be continuously exhibiting losing characteristics throughout the period. The segments 1, 5 and 6 portray gaining characteristics in the initial months of monsoon and losing characteristics for rest of the time considered.

The respective volume (m^3/day) of river leakage and aquifer discharge for different river segments for June 2005 - May 2006 are presented in the table 6.20.

Table 6.20 River leakage and aquifer discharge values for June 2005 - May 2006

Time	River Segments						
	1 (AB)	2 (CD)	3 (EF)	4 (GF)	5 (DF)	6 (BD)	7 (BH)
Jun-05	-58136.3 AD	12784.0 RL	7892.8 RL	34295.5 RL	-8806.0 AD	-86398.4 AD	-58940.5 AD
Jul-05	-100379.8 AD	11774.5 RL	767.7 RL	22049.9 RL	-12350.9 AD	-145135.9 AD	-82381.6 AD
Aug-05	-64477.2 AD	12582.4 RL	6170.7 RL	31761.0 RL	-9834.4 AD	-99872.2 AD	-80699.7 AD
Sep-05	-15897.4 AD	13503.7 RL	12365.5 RL	37772.1 RL	-1468.3 AD	-19497.8 AD	-35341.7 AD
Oct-05	9362.9 RL	13729.0 RL	12564.5 RL	38149.0 RL	5090.6 RL	30571.1 RL	-4039.5 AD
Nov-05	15187.8 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	50442.4 RL	13432.4 RL
Dec-05	38564.9 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	103311.6 RL	16668.4 RL
Jan-06	44364.6 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117329.9 RL	16861.3 RL
Feb-06	44405.8 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117908.0 RL	16811.3 RL
Mar-06	44361.0 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117723.8 RL	14866.5 RL
Apr-06	36311.2 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	99724.3 RL	16171.6 RL
May-06	36210.4 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	97974.4 RL	9344.9 RL

From Table 6.20, it was noticed that Gowri-HoLe acts as a Gaining River during the monsoon period of 2005 due to aquifer discharge. It acts as a Losing River due to river leakage during post-monsoon and summer months of the year 2006. The upstream segments 2, 3 and 4 were found to be constantly illustrating losing characteristics throughout the period. The segments 1, 5 and 6 show gaining characteristics in the initial months of monsoon and losing characteristics for rest of the time considered.

The respective volume (m^3/day) of river leakage and aquifer discharge for different river segments for June 2006 - May 2007 are presented in the table 6.21.

Table 6.21 River leakage and aquifer discharge values for June 2006 - May 2007

Time	River Segments						
	1 (AB)	2 (CD)	3 (EF)	4 (GF)	5 (DF)	6 (BD)	7 (BH)
Jun-06	-58467.9 AD	12841.4 RL	8472.9 RL	34838.4 RL	-8436.2 AD	-85550.3 AD	-62355.9 AD
Jul-06	-129215.0 AD	11016.6 RL	-3920.0 AD	12447.6 RL	-13895.2 AD	-181104.0 AD	-119420.8 AD
Aug-06	-81062.7 AD	12181.9 RL	3556.1 RL	26960.2 RL	-11269.1 AD	-116456.7 AD	-8022.7 AD
Sep-06	-33607.6 AD	13247.1 RL	11285.7 RL	36634.9 RL	-5150.8 AD	-47856.1 AD	-22828.7 AD
Oct-06	8432.1 RL	13746.1 RL	12564.5 RL	38149.0 RL	5439.9 RL	33059.4 RL	-17235.2 AD
Nov-06	23698.5 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	71838.8 RL	1148.3 RL
Dec-06	41394.4 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	111641.6 RL	16683.2 RL
Jan-07	44426.7 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117942.2 RL	16755.5 RL
Feb-07	44440.4 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117964.3 RL	16720.1 RL
Mar-07	44440.4 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117964.3 RL	16720.1 RL
Apr-07	38385.8 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	104936.8 RL	14567.8 RL
May-07	33997.6 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	91899.6 RL	11851.4 RL

From Table 6.21, it was deduced that Gowri-HoLe acts as a Gaining River during the monsoon period of 2006 due to aquifer discharge. It acts as a Losing River due to river leakage during post-monsoon and summer months of the year 2007. The upstream segments 2, 3 and 4 were found to be constantly demonstrating losing characteristics throughout the period. The segments 1, 5 and 6 indicate gaining characteristics in the initial months of monsoon and losing characteristics for rest of the time considered.

The respective volume (m^3/day) of river leakage and aquifer discharge for different river segments for June 2007 - May 2008 are presented in the table 6.22.

Table 6.22 River leakage and aquifer discharge values for June 2007 - May 2008

Time	River Segments						
	1 (AB)	2 (CD)	3 (EF)	4 (GF)	5 (DF)	6 (BD)	7 (BH)
Jun-07	-57294.2 AD	12853.0 RL	8598.3 RL	34927.4 RL	-8354.9 AD	-83054.9 AD	-44074.6 AD
Jul-07	-153027.7 AD	10074.0 RL	-9193.6 AD	638.7 RL	-15349.7 AD	-210308.1 AD	-102811.8 AD
Aug-07	-104963.8 AD	11641.9 RL	-31.3 AD	20816.5 RL	-12653.4 AD	-149745.3 AD	-61123.1 AD
Sep-07	-53507.8 AD	12856.9 RL	8444.1 RL	34797.3 RL	-8411.5 AD	-79807.4 AD	-34921.2 AD
Oct-07	9012.5 RL	13752.5 RL	12564.5 RL	38149.0 RL	5530.5 RL	34469.5 RL	-15984.3 AD
Nov-07	33481.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	93027.4 RL	5756.7 RL
Dec-07	44360.6 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117833.3 RL	16930.6 RL
Jan-08	44440.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117964.2 RL	16720.2 RL
Feb-08	44354.2 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	116828.2 RL	15649.3 RL
Mar-08	7705.7 RL	13766.3 RL	12564.5 RL	38149.0 RL	5678.8 RL	37442.2 RL	-2073.1 AD
Apr-08	40542.9 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	108321.8 RL	13604.2 RL
May-08	42093.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	108164.9 RL	15135.3 RL

From Table 6.22, it was identified that Gowri-HoLe acts as a Gaining River during the monsoon period of 2007 due to aquifer discharge. It acts as a Losing River due to river leakage during post-monsoon and summer months of the year 2008. The upstream segments 2, 3 and 4 were found to be continuously signifying losing characteristics throughout the period. The segments 1, 5 and 6 specify gaining

characteristics in the initial months of monsoon and losing characteristics for rest of the time considered.

The respective volume (m^3/day) of river leakage and aquifer discharge for different river segments for June 2008 - May 2009 are presented in the table 6.23.

Table 6.23 River leakage and aquifer discharge values for June 2008 - May 2009

Time	River Segments						
	1 (AB)	2 (CD)	3 (EF)	4 (GF)	5 (DF)	6 (BD)	7 (BH)
Jun-08	-59620.6 AD	12918.7 RL	9296.2 RL	35395.6 RL	-7847.8 AD	-84288.5 AD	-56374.9 AD
Jul-08	-52528.1 AD	12963.8 RL	9513.2 RL	35509.5 RL	-7569.3 AD	-75945.6 AD	-43542.1 AD
Aug-08	-94144.9 AD	11787.7 RL	131.6 RL	20036.3 RL	-12405.4 AD	-140259.5 AD	-86359.2 AD
Sep-08	3899.3 RL	13718.7 RL	12564.5 RL	38149.0 RL	4807.8 RL	22436.6 RL	-15462.9 AD
Oct-08	15727.5 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	50455.7 RL	-2566.5 AD
Nov-08	39885.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	107796.9 RL	15260.8 RL
Dec-08	44165.6 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117594.7 RL	15568.1 RL
Jan-09	44424.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117938.2 RL	16762.6 RL
Feb-09	44440.4 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	117964.4 RL	16720.1 RL
Mar-09	41113.0 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	109904.9 RL	15519.5 RL
Apr-09	41665.1 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	107568.8 RL	13321.1 RL
May-09	21818.7 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	64842.6 RL	-14826.3 AD

From Table 6.23, it was analyzed that Gowri-HoLe acts as a Gaining River during the monsoon period of 2008 due to aquifer discharge. It acts as a Losing River due to river leakage during post-monsoon and summer months of the year 2009. The upstream segments 2, 3 and 4 were found to be relentlessly expressing losing characteristics throughout the period. The segments 1, 5 and 6 proclaim gaining

characteristics in the initial months of monsoon and losing characteristics for rest of the time considered.

The respective volume (m^3/day) of river leakage and aquifer discharge for different river segments for June 2009 - May 2010 are presented in the table 6.24.

Table 6.24 River leakage and aquifer discharge values for June 2009 - May 2010

Time	River Segments						
	1 (AB)	2 (CD)	3 (EF)	4 (GF)	5 (DF)	6 (BD)	7 (BH)
Jun-09	6756.6 RL	13715.9 RL	12564.5 RL	38149.0 RL	4664.2 RL	24632.0 RL	-16037.0 AD
Jul-09	-141408.4 AD	10315.8 RL	-9178.8 AD	-1346.7 AD	-15105.9 AD	-199711.2 AD	-131928.6 AD
Aug-09	-35992.8 AD	13234.1 RL	11227.6 RL	36589.8 RL	-5268.5 AD	-51281.0 AD	-39828.2 AD
Sep-09	-45246.9 AD	13043.2 RL	10028.3 RL	35786.3 RL	-6976.0 AD	-66597.3 AD	-39885.5 AD
Oct-09	13453.4 RL	13760.4 RL	12564.5 RL	38149.0 RL	5623.3 RL	39461.3 RL	-24768.5 AD
Nov-09	27858.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	78722.8 RL	-3140.7 AD
Dec-09	40909.5 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	110172.4 RL	14365.8 RL
Jan-10	32157.6 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	89776.8 RL	8392.9 RL
Feb-10	44385.3 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	116670.9 RL	16723.7 RL
Mar-10	41852.7 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	112497.7 RL	16540.3 RL
Apr-10	32349.2 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	88059.4 RL	15208.0 RL
May-10	18328.2 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	56422.4 RL	9530.8 RL

From Table 6.24, it was recognized that Gowri-HoLe acts as a Gaining River during the monsoon period of 2009 due to aquifer discharge. It acts as a Losing River due to river leakage during post-monsoon and summer months of the year 2010. The upstream segments 2, 3 and 4 were found to be constantly portraying losing characteristics throughout the period. The segments 1, 5 and 6 demonstrate gaining

characteristics in the initial months of monsoon and losing characteristics for rest of the time considered.

The respective volume (m^3/day) of river leakage and aquifer discharge for different river segments for June 2010 - May 2011 are presented in the table 6.25.

Table 6.25 River leakage and aquifer discharge values for June 2010 - May 2011

Time	River Segments						
	1 (AB)	2 (CD)	3 (EF)	4 (GF)	5 (DF)	6 (BD)	7 (BH)
Jun-10	-34747.7 AD	12550.9 RL	6310.9 RL	31989.0 RL	-9886.7 AD	-116311.7 AD	-111461.7 AD
Jul-10	-49441.1 AD	12150.6 RL	3667.1 RL	27130.8 RL	-11333.4 AD	-134857.3 AD	-70901.4 AD
Aug-10	-62087.4 AD	11632.0 RL	-306.7 AD	19519.7 RL	-12724.4 AD	-154561.7 AD	-63779.8 AD
Sep-10	-488.2 AD	13264.4 RL	11427.4 RL	36728.7 RL	-4946.0 AD	-57964.1 AD	-32413.0 AD
Oct-10	48980.4 RL	13766.3 RL	12564.5 RL	38149.0 RL	5675.3 RL	35514.2 RL	-16146.1 AD
Nov-10	33208.3 RL	13620.7 RL	12564.5 RL	38145.4 RL	1802.0 RL	-2741.2 AD	-31288.7 AD
Dec-10	43712.6 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	113231.1 RL	15485.6 RL
Jan-11	45509.6 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	116803.5 RL	16484.2 RL
Feb-11	45598.8 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	116877.9 RL	16648.1 RL
Mar-11	45599.4 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	116879.0 RL	16646.4 RL
Apr-11	32290.9 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	84790.3 RL	7911.5 RL
May-11	21624.6 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	63662.9 RL	8133.0 RL

From Table 6.25, it was observed that Gowri-HoLe acts as a Gaining River during the monsoon period of 2010 due to aquifer discharge. It acts as a Losing River due to river leakage during post-monsoon and summer months of the year 2011. The upstream segments 2, 3 and 4 were found to be repetitively showcasing losing characteristics throughout the period. The segments 1, 5 and 6 show gaining

characteristics in the initial months of monsoon and losing characteristics for rest of the time considered.

The respective volume (m^3/day) of river leakage and aquifer discharge for different river segments for June 2011 - May 2012 are presented in the table 6.25.

Table 6.26 River leakage and aquifer discharge values for June 2011 - May 2012

Time	River Segments						
	1 (AB)	2 (CD)	3 (EF)	4 (GF)	5 (DF)	6 (BD)	7 (BH)
Jun-11	-55504.8 AD	12904.3 RL	9048.7 RL	35257.2 RL	-8021.8 AD	-82295.2 AD	-56176.4 AD
Jul-11	-170855.0 AD	9472.6 RL	-11040.0 AD	-1336.0 AD	-15981.3 AD	-229113.5 AD	-94369.0 AD
Aug-11	-115452.8 AD	11443.2 RL	-802.1 AD	20147.0 RL	-13045.2 AD	-162552.4 AD	-67261.2 AD
Sep-11	-61253.6 AD	12870.1 RL	9050.1 RL	35274.9 RL	-8098.1 AD	-88112.1 AD	-48706.8 AD
Oct-11	1777.2 RL	13729.6 RL	12564.5 RL	38149.0 RL	5124.1 RL	20682.7 RL	-14512.3 AD
Nov-11	19290.8 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	63229.2 RL	331.7 RL
Dec-11	44670.0 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	114619.1 RL	6629.8 RL
Jan-12	45450.6 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	116468.1 RL	13887.3 RL
Feb-12	45599.4 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	116879.1 RL	16646.3 RL
Mar-12	43446.8 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	112347.1 RL	16499.5 RL
Apr-12	35770.1 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	91632.1 RL	1331.5 RL
May-12	40740.0 RL	13766.3 RL	12564.5 RL	38149.0 RL	5724.5 RL	105003.1 RL	14116.6 RL

From Table 6.26, it was identified that Gowri-HoLe acts as a Gaining River during the monsoon period of 2011 due to aquifer discharge. It acts as a Losing River due to river leakage during post-monsoon and summer months of the year 2012. The upstream segments 2, 3 and 4 were found to be constantly describing losing characteristics throughout the period. The segments 1, 5 and 6 exhibit gaining

characteristics in the initial months of monsoon and losing characteristics for rest of the time considered.

6.3 COMPARISON OF DRIVING FORCES INFLUENCING THE REGIONAL AND SUB-CATCHMENT SCALE INTERACTIONS

In the present study, the driving forces were calculated for both regional scale and sub-catchment scale model. Recharge rate was estimated by using rainfall infiltration factor method as per the guidelines suggested by Groundwater resource Estimation Committee (CGWB, 2009). Hydraulic conductivity values were considered from representative values for various geological formations (Domenico and Schwartz, 1990).

6.3.1 Driving Forces of regional scale interactions

During the calibration, the driving force values were adjusted until the model is simulated with a good match between computed and observed groundwater heads. The calibrated values of the rainfall recharge factor and hydraulic conductivity values for the regional scale model of Nethravathi basin are shown in the Table 6.27:

Table 6.27 Calibrated values of Rainfall Recharge Factor and Hydraulic Conductivity for the Regional scale model of Nethravathi basin

Sl. No.	Geological units	Recharge Rate (m/day) = Percentage of normal rainfall in the area (GEC guidelines)	Hydraulic Conductivity Values (m/day)
1	Migmatites and Granodiorite - Tonalitic Gneiss	5% - 15%	12.96
2	Charnockite	10% - 15%	2.39
3	Laterite	4% - 10%	864.02
4	Metabasalt including thin Iron stone	4% - 10%	0.02
5	Basal Oligomictic Conglomerate (Neralakatte)	10% - 15%	259.24
6	Alluvium/Beach sand, Alluvial soil	20% - 25%	8.65

6.3.2 Driving Forces of sub-catchment scale interactions

The calibrated values of the rainfall recharge factor and hydraulic conductivity values for the sub-catchment scale model of Gowri-HoLe are shown in the Table 6.28:

Table 6.28 Calibrated values of Rainfall Recharge Factor and Hydraulic Conductivity for the Sub-catchment scale model of Gowri-HoLe

Sl. No.	Geological units	Recharge Rate (m/day) = Percentage of normal rainfall in the area (GEC guidelines)	Hydraulic Conductivity Values (m/day)
1	Migmatites and Granodiorite - Tonalitic Gneiss	12.5%	0.0006912 – 25.92
2	Charnockite	12.5%	0.28512 – 4.4928

From the present study, it is evident that the hydraulic conductivity values for the respective geological units remained constant during the calibration of regional-scale model. Whereas, rainfall recharge factor kept unchanged during the calibration of sub-catchment scale model. Consequently, the study identified that recharge rate is the driving factor influencing the interactions at regional scale and hydraulic conductivity is the driving factor of sub-catchment scale interactions.

6.3.3 Parameter estimation for the regional scale of Nethravathi basin

In the present study, aquifer parameters were estimated by CGWB (2012) under groundwater exploration programme for the exploratory wells located inside the Nethravathi river basin. The transmissivity values ranged from 3 - 476 m^2/day for the unconfined aquifer system with depth varying around 30 metres for the catchment. The representative values of hydraulic conductivity were found to be satisfactorily matching with the values estimated from the exploratory wells of CGWB in the Nethravathi basin.

6.3.4 Parameter estimation for the sub-catchment area using pumping test

In the present study, pumping test was conducted for the unconfined aquifer system of the Gowri-HoLe sub-catchment. From the field study, aquifer parameters such as transmissivity, specific storage, and specific yield were estimated for the unconfined depth of the aquifer varying around 30 metres. In the present study, Theis (1935) method, Nueman (1974) method and Tartakovsky and Nueman (2007) methods are used for the analysis which are applicable for unconfined aquifer system.

The aquifer parameters estimated from the pumping test observations by using the AQTESOLV software are presented in the Table 6.29:

Table 6.29 Aquifer parameters using pumping test analysis

Well	Theis(1935) method		Nueman (1974) method		Tartakovsky and Nueman (2007) method	
	Transmissivity (m^2/day)	Specific storage	Transmissivity (m^2/day)	Specific yield	Transmissivity (m^2/day)	Specific yield
Bellare	574.4	2.379	589.4	0.5	452	0.09706

The value of hydraulic conductivity estimated from the analysis satisfactorily matched with the standard representative values used for the calibration of sub-catchment scale model.

CHAPTER 7

CONCLUSIONS

7.1 SUMMARY

The SW-GW interaction plays an important role in overall understanding of river-aquifer system. In the present study, these aspects are studied. A steady-state regional scale model is built to examine the SW-GW interactions for Nethravathi River basin for a calibration period of 2004 - 2009 and validation period of 2010 - 2011. Groundwater flux with the surface water systems is determined using flow budget calculations.

Consequently, a transient-state intermediate scale model is simulated for the Gowri-HoLe sub-catchment to estimate river-aquifer interactions for calibration period of June 2004 - May 2010 and validation period of June 2010 - May 2012. In the present study, due to the limited availability of the data, the groundwater model was simulated for a duration of 8 years i.e., from 2004 to 2012. In this time-line, 75% of the data period was utilized for calibration i.e., from June 2004 - May 2010 whereas 25% of the data period was utilized for validation i.e., from June 2010 - October 2012. The spatial and temporal variability of interaction processes such as river leakage and aquifer discharge are analyzed over the sub-catchment. The characteristics of flow exchange in different river segments of Gowri-HoLe are evaluated. The scale-based processes are conceptualized using MODFLOW for both the scales to be represented as driving forces using various modules. The comparison of driving forces of regional and sub-catchment scale interactions with each other indicated the significance of the scale-based processes.

7.2 CONCLUSIONS

It can be concluded from the study that:

1. The simulated regional groundwater model is in good agreement with most of the wells reasonably matching the observed and computed groundwater heads. It shows that the simulation of regional groundwater model is reasonable and is well suitable for the studies related to SW-GW interactions.
2. In the regional scale model, the groundwater levels are observed to slightly increase in the downstream and decrease in the Metabasalt aquifer portions of the basin during June - July. From the month of July to August, decrease in groundwater levels is observed in both downstream and metabasalt aquifer units in the basin. However, groundwater is noticed to recover throughout the basin in the September month.
3. From regional scale modeling, the groundwater level fluctuations revealed the influence of rainfall and baseflow over the basin. Aquifer discharge is observed to dominate contributing into the river from June - July. Whereas, river leakage dominates during August - September.
4. In the sub-catchment scale model, groundwater heads gradually increase from June - August with the arrival of monsoons and decline significantly from September upto the month of May. Groundwater swelling is noticed near Well No. 3 of Bellare village in the month of October.
5. In Gowri-HoLe sub-catchment, river leakage decrease from 10 – 11 % in June to 4 – 5 % in July with the commencement of peak monsoon flows. It steadily increase from 7 – 8 % in August and continue to occur up to 41 – 42 % until the end of May. Aquifer discharge increase from 24 – 25 % in June to 30 – 32 % in July due to quick saturation during monsoon. From August, aquifer contribution into the river significantly decreases upto 9 – 10 % in May.
6. The contribution of aquifer discharge into the river is observed to be consistent at confluence point “B” of the Gowri-HoLe sub-catchment. Some parts of river segments 1, 6 and 7 are noticed under the influence of aquifer discharge.

River segments 2, 3 and 4 are dominated by river leakage areas throughout the year.

7. Gowri-HoLe acts as a Gaining River during monsoons due to aquifer discharge. And, it acts as Losing River due to river leakage throughout post-monsoon and summer months.
8. Recharge rate is identified as the driving factor influencing the interactions at regional scale and hydraulic conductivity is the driving factor of sub-catchment scale interactions.

7.3 SCOPE FOR FUTURE RESEARCH

1. The 2-Dimensional conceptual model grid can be upgraded to 3-Dimensional grid with sufficient information of the sub-surface strata, which can be obtained by using methods such as Electrical Resistivity Tomography (ERT) and Ground Penetrating Radars (GPRs).
2. The cell size/resolution of the finite-difference model can be enhanced using Digital Elevation Model data with better resolution available in the recent times.
3. Private wells, other than public wells in the study area can be identified for monitoring groundwater level fluctuations with the help of local people to improve the accuracy of the prediction.

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