GSFLOW Modeling of the Souhegan River watershed, New Hampshire

DISSERTATION

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By

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Abstract

Over several decades, hydrologists have worked to develop an integrated view of processes and parameters important in controlling the behavior of water through the land-based portion of the hydrologic cycle. With the development of GSFLOW, a coupled groundwater/surface water model, the USGS has created a capable system for modeling important hydrologic processes at a watershed scale (Markstrom et al., 2008). GSFLOW combines a land-surface model (Precipitation-Runoff Modeling System or PRMS; Leavsley et al., 1983) and MODFLOW. GSFLOW provides the capability for simulating coupled groundwater/surface-water flow by considering overland flow, saturated and unsaturated flow, and flow routing through streams and lakes. The study area for the GSFLOW application is the Souhegan River watershed, New Hampshire. The purpose of running GSFLOW on this basin is to better understand groundwater and surface water interactions, and particularly the conditions that promote flooding. The specific objectives of the study then are i) to develop PRMS, MODFLOW-2005, and GSFLOW models for Souhegan River watershed, ii) to calibrate the model through a trial and error adjustment of model parameters, iii) to analyze the adequacy of existing and easily available data in creating the model, and iv) to understand the conditions that give rise to flooding.
There are three calibration steps. First, the calibration of PRMS was carried out manually by trial-and-error adjustments to the values of various parameter files. Typically, only one parameter was changed for each model run to make clear how changes in value affected the calibration. The $R^2$ statistic for the best-fit line is 0.79. Second, MODFLOW-2005 was calibrated as steady state, while comparing simulated and observed hydraulic heads. Third, the calibration of GSFLOW was performed last, after the calibration of PRMS and MODFLOW. A simple plot of measured versus observed discharges (not shown) provides an $R^2$ value of 0.83. After calibration of GSFLOW model, validation is performed as the next step in order to demonstrate the predictive ability of the code and to build confidence in its suitability for applications.
Dedication

This document is dedicated to my loving family, my role model Woosik Kim; my strongest supporter Chunhee Choy; and my lovely sister, Ahyoung Kim. My parents, Woosik Kim and Chunhee Choy, have always cared for me and have always told me “I love you son or I believe you, so do not give up”. Also, I dedicate my dissertation to Ahyoung Kim. Although we had many ‘issues’ growing up as siblings, I do NOT doubt that she is the best sister in the whole world.

I would also like to dedicate this dissertation to another family, the Naylor’s. They have treated me as a family member since 2005 when I arrived here in the United States as a foreign exchange student. Because of them, I had exciting holidays and other joyful memories through my years here. I cannot express in words my great thanks to the Naylor’s. I’m going to miss them.

I also dedicate this work to my friends, whom motivated me each and every day at 8:00am. Thanks to this morning study group, I was able to manage my time wisely, and I finish my dissertation in a timely manner.

Lastly, I would like to dedicate this work to my grandmother, who passed away before I started my master’s degree. She was a humble and generous woman, who always taught me to become a noble man. She always worried about me, because I was the only one of her grandsons living abroad. Her will even requested that I should not be told of
her death because I might lose my focus on studying abroad. After her death, I promised myself that I would finish this dissertation for her.
Acknowledgments

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I also thank to Dr. Ganming Liu, who was long suffering in teaching me about the computer codes and my research. Without his kind support, it would have been impossible to work in developing the model of the Souhegan River Watershed. Lastly, I acknowledge the great help from Dr. Sangsuk Lee. He helped with preparation of figures and guidance in the preparation of the dissertation, and provided helpful advice about my future goals.
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Fields of Study

Major Field: Environmental Science
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CHAPTER 1: Introduction

Over several decades, hydrologists have worked to develop an integrated view of processes and parameters important in controlling the behavior of water through the land-based portion of the hydrologic cycle. Not surprisingly, hydrological models capable of simulating key processes, for example, subsurface flow, surface runoff, soil zone flow have become essential for quantitative predictions of watershed responses to precipitation events and the study of important science questions.

Historically, the earliest approaches to watershed-scale modeling used an empirical, lumped system formulation to rainfall-runoff modeling. With these models processes are sometimes described by differential equations but more commonly with empirical, algebraic equations. The Stanford Watershed Model (Crawford and Linsley, 1966) was perhaps the best known of these types of models. Since this code was developed, there have been literally hundreds of similar models. Notable follow-on models included HSPF (Hydrological Simulation Program—FORTRAN; Bicknell et al., 1997) and SWAT (Soil and Water Assessment Tool; Arnold et al., 1998). Development has continued to the present time on SWAT with, for example, an ARCGIS system for problem setup, and capabilities for both sediment and contaminant transport.

Hydrologists have also pursued a different strategy for watershed modeling, which is based on solution of coupled differential equations capable of rigorously
describing overland flow, unsaturated/saturated flow, and stream flow in a physically realistic way. The blueprint for such physically-based hydrologic response models has also existed for a long time (Freeze and Harland, 1969). However, it has taken decades to move from the blueprint to working models. It took time for the necessary theoretical/mathematical frameworks to develop and appropriate computational power to become available. Over the last 20 years, there has been exceptional progress in developing models of this type for example, Cheng and Anderson, (1993), Yu and Schwartz (1998). The USGS (United States Geological Survey) has also been active in enhancing water-cycle capabilities in their well-known aquifer simulation program MODFLOW (see McDonald and Harbaugh, 2003 for history) through the addition of lake packages (e.g., Merritt and Konikow, 2000), a stream package, and a stream-flow routing package (Prudic, 1989).

Finally, with the development of GSFLOW, a coupled groundwater/surface water model, the USGS has created a capable system for modeling important hydrologic processes at a watershed scale (Markstrom et al., 2008). GSFLOW combines a land-surface model (Precipitation-Runoff Modeling System or PRMS; Leavsley et al., 1983) and MODFLOW. GSFLOW provides the capability for simulating coupled groundwater/surface-water flow by considering overland flow, saturated and unsaturated flow, and flow routing through streams and lakes. This open source code is well supported by the USGS with a detailed user’s guide, worked examples, and a graphical user interface to facilitate problem setup.
Also worth mentioning are two other well developed modeling systems, which are capable of hydrologic simulations. ParFlow was developed by the Department of Energy, in order to assist with contaminant cleanup at numerous governmental and industrial facilities. ParFlow is a three-dimensional and variably saturated groundwater flow code that is parallelized for faster execution (Kollet and Maxwell, 2006). It also has also been coupled with a land surface model (CLM) to facilitate applications problems of water cycling. The code suffers from problems, including an inadequate treatment of flow on slopes, a difficult user interface, and lack of support.

HydroGeoSphere (HGS) is a state-of-the-art hydrologic model and can be used to simulate the entire terrestrial portion of the hydrologic cycle (Therrien and Sudicky, 1996; Brunner and Simmons, 2012). It was developed primarily by researchers at the University of Waterloo. This is undoubtedly the most capable hydrologic modeling system of those presented. It has been applied to a variety of practical problems up to a continental scale (see for example, publications at the website: (http://www.aquanty.com/). However, it also suffers from problems that make it difficult to use. For example, the code is not well supported with worked examples, and the HGS manual is weak.

Work is continuing to expand the capabilities of these kinds of codes. The obvious next step is to connect the land-based hydrologic models to climate models to encompass the entire hydrologic cycle. At the present time, existing climate models commonly treat the land-based components through simple compartmentalized approaches. Moreover, surface water and groundwater interactions are typically neglected because of model limitations and computing constraints (Vaccaro, 1992;
Middelkoop et al., 2001; Scibek et al., 2007; Jyrkama and Skyes, 2007; Tague and Grant, 2009; Allen et al., 2010). Research is at an early stage coupling ParFlow or HGS to meso-scale climate models (Maxwell and Kollet, 2008; Ferguson and Maxwell, 2010; Sulis et al., 2011).

1.1 Purpose and Scope

The focus of the study here is the GSFLOW code developed by the USGS. My goals are to understand the strengths and weaknesses of the code and whether it is practical from a data perspective to use it to examine questions involving rainfall-runoff in relatively large and watersheds. The study area for the GSFLOW application is the Souhegan River watershed, New Hampshire. The purpose of running GSFLOW on this basin is to understand better of the groundwater and surface water interactions, and particularly the conditions that promote flooding. The specific objectives of the study then are (i) to developing PRMS, MODFLOW-2005, and GSFLOW models for Souhegan River watershed, (ii) to calibrate the model through a trial and error adjustment of model parameters, (iii) to analyze the adequacy of existing and easily available data in creating the model, and (iv) to understand the conditions that give rise to flooding.

One of the main challenges in applying a water cycle model like GSFLOW is the extensive requirement for data of all kinds, necessary to characterize land surface and subsurface hydrologic processes. However, as is typical for models of this type, GSFLOW not only requires different information and parameters, but also details of its variation in two or three dimensions. Typical data needs include spatial/temporal
information on precipitation, land-surface cover, channel networks and subsurface data like patterns of hydrogeologic layering and hydraulic conductivity distributions.

1.2 Overview of Souhegan River watershed

The Souhegan River watershed is located in southern New Hampshire in the northeastern United States.

Figure 1.1 Base Map of Souhegan River watershed
The climate of southern New Hampshire is humid continental with warm, humid summers, and cold wet winters. On the Köppen climate scale, southern New Hampshire is classified as Dfa, a continental climate (D Group) with significant precipitation in all seasons (f), and temperatures with the warmest month averaging > 22°C and four months > 10°C (a). The annual precipitation is approximately 100 cm (39 in) with precipitation distributed uniformly throughout the year.

The Souhegan River watershed has an area of about 441 km² (170 mi²) mostly within the State of New Hampshire but including a small piece of Massachusetts. It is forest covered except for several small towns along the Souhegan River with populations less than 30,000 people. The Souhegan River is about 56 km (34.8 mi) long, extending from its origin where the South and West Branches join together in New Ipswich to the Merrimack River. It is one of the largest tributaries to the Merrimack River.

The Souhegan River flows close to the southeaster and southern boundary of the watershed. It receives drainage from the Wapack Mountains along the western watershed boundary and highlands to the north (Figure 1.1). A management report on the Souhegan River watershed, prepared by the Nashua Regional Planning Commission (NRPC, 2006), listed 12 named brooks as major tributaries. The largest of three are Stony Brook (15.4 km; 9.6 mi long), Caesar’s and Beaver Brook (12.4 km; 7.7 mi long), and Mill Brook (12 km; 7.4 mi long) (Figure 1.1). There are other unnamed and ephemeral streams as well. Dams associated with small reservoirs are located on the Souhegan River and many of the smaller tributaries.
Annual average discharge at the Souhegan River mouth (from 2001 to 2012) is about 10.8 m$^3$/s (339 cfs) with low flows, less than 1.7 m$^3$/s (60 cfs) sometimes occurring during cold winter months when the ground is snow-covered. Since 2001, the maximum flood of record occurred in April 2007 with a maximum discharge of 297 m$^3$/s (10,500 cfs). The Souhegan River is considered Class B for water quality, which means that the river is fishable and swimmable (www.souheganriver.org).

The towns along downstream reaches the Souhegan River (e.g., Wilton, Milford, and Amherst) rely on the groundwater to serve their water needs. The most important aquifers are associated with permeable sands and gravels, which were deposited in bedrock valleys from meltwater as the last ice sheet began to retreat.

The Milford - Souhegan aquifer has been extensively studied since 1989. Two of Milford’s water supply wells (Savage Well and Keyes Well) were found to be contaminated by volatile organic compounds (VOC’s) at concentrations far above the maximum contaminant level (MCL) for these compounds. Four small, industrial facilities that operated from 1940s to 1980s were identified as possible sources. Eventually, this site became known as the Savage Well Superfund site and subsequent studies found careless handling and disposal of solvents OK Tool facility was the major source of aquifer contamination. A broad plume of dissolved tetrachloroethylene (PCE) extended eastward and down-gradient from OK Tool approximately 1829 m (6,000 feet). Control measures have recently been put in place to control the source.
CHAPTER 2: Study Area Characterization

2.1 Climate and Surface Water Monitoring

There are two weather stations within the Souhegan River watershed - East Milford (USC00272302) and Greensville (USC00273658). Average annual temperature of the Souhegan River watershed is about 7.5 °C and average annual precipitation record is 1288.6 mm, according to the record period between 2002 and 2013 (GSFLOW study period). The year 2012 was the warmest year with an average temperature of 8.9 °C. 2003 was the coolest year with an average annual temperature of 6.6 °C. The highest precipitation on record during the study period was 2008 (Table 2.1).

Within the watershed, there is a single surface water gaging station, located 2.1km (1.3 mi) from the confluence with the Merrimack River. Stream flow measurements began in July 1909 and continued to September 1976, at which time the station was converted to partial-record operation. In October 2001, continuous monitoring was resumed and it is this more modern record which is focus of the present study.
<table>
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<th>Tmax (°C)</th>
<th>Tmin (°C)</th>
<th>Precipitation (mm)</th>
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</table>

Table 2.1. Annual Average Temperature, Maximum Temperature, Minimum Temperature, and Precipitation during the study period

During this period of stream-flow monitoring, the largest flood recorded on the Souhegan River was 507m³/s (17,900 cfs) on March 19, 1936. The Souhegan watershed, and New England overall was hit by a series of rainstorms that dumped heavy rains on a thick snowpack and frozen ground. The result was the flood of record for the 20th century,
causing considerable property and other damages. Damaging floods occurred again in 1938 and 2007 with measured flows of 306 m$^3$/s (10,800 cfs) and 297 m$^3$/s (10,500 cfs), respectively. Studies by FEMA (2008) suggest that the 1936 event was close to the 500-year flood (estimated at 532 m$^3$/s or 18,800 cfs) and the 1938 and 2007 floods were estimated to be 50-year floods.

2.2 Topography, Land Use and Land Cover

Overall, the topography of the watershed is dominated by two main physiographic features, the Wapack mountain range that forms the western boundary of the watershed, and the Souhegan River valley to the south. Elevations range from a maximum of about 2280 fasl at the summit of Pack Monadnock Mountain near Peterborough to 50 fasl at the confluence of the Souhegan and Merrimack Rivers (Figure 1.1).

Thus, the western third of the watershed is characterized by steep slopes with drainage southeast towards the Souhegan River. In contrast, the eastern third of the watershed is rolling, with large flat floodplains found along the Souhegan River and major tributaries (Figure 1.1). Generally, floodplains occur along the entire Souhegan River corridor that extends some 34 miles from the headwaters at New Ipswitch, where the South and West Branches join to form the Souhegan River, to the Merrimack River. Floodplains are generally narrow in the west but widen to 0.5 mi downstream of Milford. Fast flowing upstream reaches of the Souhegan River develop because of high stream gradients. The gradient declines at downstream of Wilton, as the Souhegan meanders across the widening flood plain.
The watershed is mainly forest covered (Figure 2.1) with trees native to southern New Hampshire. The trees include white pine, hemlock, red maple, red oak, sycamore, mountain laurel, and are found along with numerous species of grasses and shrubs (NRPC, 2006). Forests are actively managed to provide wildlife habitat and timber.

Figure 2.1 Map of the Souhegan River watershed showing the large forest coverage and distributions of different forest types (from NRPC, 2006).

The largest towns and population densities are found along the Souhegan valley from Milton to Merrimack (Figure 1.1) with associated land uses including industrial and residential and transportation representing less than 8% of the watershed area (NRPC, 2006). Farming across the watershed is relatively minor (i.e., about 8% of total area) with hay and pastureland as the dominant land covers (NRPC, 2006). In upper reaches of the watershed, the land is mostly undeveloped.
2.3 Regional Geologic Setting

Bedrock in the Souhegan River watershed is comprised predominately metamorphic rocks with local igneous intrusions. The Littleton Formation underlies much of the western portion of the watershed. It consists of quartzite, mica schist. The far eastern portion of the watershed near the mouth of the Souhegan River is underlain by Merrimack Group. This unit is comprised of various kinds of schist and granulite (NRPC, 2006). These rocks are poorly permeable and relatively unimportant in the cycling of groundwater.

Much more relevant to the hydrology of the Souhegan watershed are glacial deposits related to the most recent Pleistocene glaciation, which ended approximately 14,000 years ago. Bedrock across highlands away from river valleys is commonly covered by glacial till, commonly less than 10 m in thickness. At higher elevations along steeper slopes of the Wapack Mountains, bedrock is exposed at the ground surface.

De-glaciation of this region of New Hampshire produced sediment-laden meltwater that flowed down bedrock valleys that broadly corresponded to the present-day drainage system for the watershed. Large thicknesses of sand and gravels were deposited, especially along channels in the lower reaches of the watershed. For example, alluvial sands and gravels deposited along the Souhegan River formed the Souhegan and Amherst Aquifers, which supply water to the Towns of Wilton, Milford, and Merrimack.

In some areas of the watershed, there are extensive geologic data available on the types and thickness of sand and gravel aquifers in the Souhegan River and downstream
tributaries. As mentioned in the introduction, in 1983, sampling of drinking water wells revealed serious groundwater contamination with several different chlorinated solvents occurring at concentrations far above the U.S EPA standards for these compounds.

Extensive test drilling at Milford defined the glacial drift units present in the valley fill. At Milford, the most prevalent deposit is a heterogeneous stratified sand and gravel. The permeable sand and gravel at Milford is up to 30 m (100 feet) thick (Harte, 2006).

Locally, glacial till occurs beneath the sands and gravels and above the bedrock. When it occurs the till occurs, is usually 1 to 3 m thick (3 to 10 ft) but can be as much as 10 m (30 ft). Away from the drift filled, bedrock valley at Milton, bedrock uplands are covered by glacial till.

2.4 Groundwater

Generally, little is known about the hydrogeologic setting across most of the watershed. The reason is that for the most part the geologic conditions in the watershed are such that groundwater resources are poor to nonexistent. As was discussed in Section 2.2, the bedrock is comprised of various kinds of metamorphic rocks that are poorly permeable, except for localized fracture zones. Similarly, most of watershed is by mantled by glacial till that also has a low hydraulic conductivity.

The only productive groundwater resource in the watershed is associated with the sands and gravels that were deposited along Souhegan River valley and smaller tributaries (Figure 2.2). The greatest sediment accumulations and most productive aquifers are located downstream along the Souhegan River valley. For example, at the Savage Well Superfund site near Milford, the valley fill is about 1.5 km (0.9 mi) wide, 4
km (2.5 mi) wide and up to 30 m (100 ft) thick. Similar deposits occur further downstream at Amherst.

Figure 2.2 Map showing important valley-fill aquifers in the Souhegan River watershed. The most transmissive aquifers are located along the lower reaches of the watershed. The map also describes the 100 and 500 year flood zones (from NRPC, 2006)

In the vicinity of Milton, the water saturated drift deposits are called the Souhegan Aquifer or Milton-Souhegan aquifer (Harte and Mack, 1992). Further downstream, similar types are sometimes referred to as the Amherst aquifer (NRPC, 2006). At least
six, high capacity wells are completed in the Milton-Souhegan Aquifer with sustained yields range from 0.75 to 1.9 cubic meter per minute (200 – 500 gpm). As shown in Figure 2.3, these aquifers along the downstream reaches of the Souhegan River are permeable with maximum transmissivities upwards of 743 square meters per day (8,000 ft²/d). Summaries of hydraulic/aquifer test data for the Milford-Souhegan aquifer are provided by Harte and Mack, 1992; Table 2). They found aquifer transmissivity to be highly variable ranging from less than 9.3 square meters per day (100 ft²/d) to greater than 1858 square meter per day (20,000 ft²/d).

Model studies (Harte and Mack, 1992) of the Milton-Souhegan aquifer indicate that recharge is mainly due to rainfall. However, induced infiltration from the Souhegan River provides a significant component of the recharge, especially during dry times. Along the western reach of the Souhegan River, water leaves the river to recharge the aquifer. Further downstream along eastern reaches of the Souhegan River at Milford, water flows toward the Souhegan River and discharges (Hart and Mack, 1992).

2.5 Conceptual Hydrologic Souhegan River watershed

Figure 2.3 shows the simple conceptual model of the hydrologic cycle for this watershed. This figure comes directly from the GSFLOW manual of Markstrom and others (2008). In the conceptual model, water is delivered by precipitation in the form of rain or snow in winter. When the precipitation falls on the ground surface, it can end up as surface runoff, infiltration into subsurface, interflow, evapotranspiration back to the atmosphere, or recharge to the groundwater system.
This general model applies to the Souhegan River watershed. What is particularly important there, however, are the steep slopes in the watershed. In particular, the slopes promote significant surface runoff and interflow. Surface runoff (overland flow) occurs over the earth’s surface when soil is fully saturated to full capacity or higher intensity of precipitation falls on the land than soil can absorb water. Interflow accounts quick subsurface flow just under the ground surface. In this watershed, interflow should be important, especially in headwater reaches of the stream. There are two types of interflow: slow and fast interflow. If the interflow follows long flow paths in the soil layer, it is typically slow interflow. Fast interflow develops with pathways adjacent to streams and is dependent upon distinct gradient of the topography (Vassilopoulos et al., 2007).

Figure 2.3 Conceptual hydrologic model of GSFLOW, directly from the GSFLOW report (Markstrom et al., 2008).
Evapotranspiration is also a significant hydrologic process within this model. Evaporation from the bare soil and transpiration from the plants are considered as outflows in the model. The potential evapotranspiration rate depends upon canopy cover, and effectively represents a reduction in the quantity of inflows, such as precipitation.

The conceptual model also provides for some proportion of the precipitation to flow through soil zone and becomes groundwater. Groundwater recharge is the excess precipitation, which finds its way into the groundwater reservoir once other processes like interflow, surface runoff, and evapotranspiration are considered. In this watershed, groundwater provides the slowest of the pathways available for water to enter the surface-water system. Groundwater inflow is locally important but as the watershed description will make clear, the most permeable deposits are restricted to areas close to the stream and river channels.

The flow of water in surface-water systems is the last important processes provided by the conceptual model. In this watershed, the high gradients promote the rapid flow of water, especially in the headwater reaches.
CHAPTER 3: Methods

As mentioned in the introduction, the USGS modeling system GSFLOW is used to model the surface and groundwater components of the hydrologic cycle in the Souhegan River watershed. GSFLOW is based on two robust and well documented USGS models, PRMS and MODFLOW. With GSFLOW, the user has the option to run the codes together in a fully integrated fashion or to run each of the models independently. Within GSFLOW, both codes are fully coupled and capable of providing the feedbacks from surface water to groundwater resources *vice versa*. It is essential to include such feedbacks within GSFLOW for they affect the timing and rates of evapotranspiration, surface runoff, soil-zone flow, and groundwater interactions (Markstrom et al., 2008).

GSFLOW is capable modeling system with potential applications to a variety of research questions, such as (i) how surface water processes affect recharge and water-table responses, (ii) how climate change is likely to impact groundwater and surface water, and (iii) surface and groundwater effects on the behavior of springs, wetlands, and ecological systems (Markstrom et al., 2008).

This chapter begins with an overview of the modeling approach, including the basic design of PRMS and MODFLOW and the data requirements. This chapter also includes a discussion of the integration of PRMS and MODFLOW as GSFLOW, and
then explains how the input data for the watershed are prepared for implementation within GSFLOW.

### 3.1 Surface Water Flow Model (PRMS)

PRMS is essentially a land-surface hydrologic model that simulates water cycling at land surface as a function precipitation, climate, land cover/use, and hydrologic processes operating at the land surface (e.g., infiltration, evapotranspiration). The model provides estimates of stream discharge, rates of groundwater recharge rate, and water balance relations. PRMS can be run using either distributed or lumped parameters (Leavesley et al., 1983).

The basic element of PRMS is an HRU or hydrologic response unit, a subarea of a study area/watershed, which is homogeneous in terms of features such as land use/cover, distribution of rain/snowfall, temperature, drainage properties, geologic settings, and other factors. In practice, the spatial variation in some watershed characteristic is accounted for by sub-dividing a study area into many HRUs.

Figure 3.1 is a conceptual diagram of the PRMS model. As originally designed, PRMS functioned as a lumped system simulator essentially quite similar to the Stanford Watershed Model. As the Figure shows, the land-surface model is comprehensive and accounts for most important hydrologic processes. However, groundwater is only included in a very rudimentary and empirical way. With GSFLOW, this empirical component is replaced with MODFLOW, which provides a powerful capability to simulate groundwater flow in a physically realistic manner, including flow processes and
well know hydraulic parameters. MODFLOW has evolved to the point where for example natural connections exist between the codes along rivers and with recharge and evapotranspiration.

A watershed is conceptualized in PRMS as a series of storage components, such as the impervious zone reservoir, soil zone reservoir, subsurface reservoir, and groundwater reservoirs (Figure 3.1). These four reservoirs are organized such that precipitation is routed to each reservoir, taking care to provide for the water mass balance. As Figure 3.1 shows, water is lost by evaporation and surface runoff on the impervious zone reservoir. Within the Soil Zone Reservoir, PRMS takes account of water cycling due to transpiration, plant uptake, infiltration, subsurface recharge, and groundwater recharge.

Mathematically, PRMS uses an empirical set of rules to route water from one storage component to another. This empirical approach is much simpler than, for example, MODFLOW that is based upon rigorous physics described by the equation of groundwater flow. PRMS routes water within individual subareas of watershed over the desired study period, and at some specified time step, usually daily. The model can simulate the hydrologic cycle of a watershed, based on weather information (precipitation and air temperature) and land cover and canopy distribution (potential evaporation and transpiration). Air temperature plays is an important parameter in the model, because the model calculates potential evaporation and transpiration as a function of temperature.

The air temperature also determines the form of water and behavior of water through the hydrologic cycle. For example, if the temperature is at or below 0 °C, there is
no immediate infiltration or surface runoff because precipitation arrives as snow. In other words, snow does not move to other parts of the hydrologic system (soil zone or groundwater reservoir) immediately during the winter. Snow is accumulated on surface until the temperature rises above 0 °C, when the snow is allowed to melt and enter the system.

If precipitation falls on an impervious surface, that water will runoff directly to adjacent streams or lakes, Impervious-zone can occur for example as paved road or parking lots in urban setting area. In other areas of the watershed precipitation can infiltrate to some extent. Water that does not infiltrate runs off as Hortonian flow when rain and snowmelt falls on the impervious-zone. The extent to which runoff occurs is adjusted in the model by various empirical parameters (Markstrom et al., 2008).
Figure 3.1 Schematic diagram of a watershed and its climate inputs (precipitation, air temperature, and solar radiation) simulated by PRMS (Leavesley et al., 1983; Markstrom et al., 2008).

3.2 Groundwater Flow Model (MODFLOW-2005)

MODFLOW-2005 is a powerful modeling tool, which the U.S. Geologic Survey has developed over many years to solve problems that are central to the practice of
hydrogeology (Harbaugh, 2005). The first version of this code was developed by McDonald and Harbaugh and released by the USGS in 1984. MODFLOW-2005 is a finite-difference flow model that can be applied to simulate steady-state or transient flow of groundwater having a constant density. The current version of MODFLOW is 1.11.00, which was released in 2013. Other members of the MODFLOW family of codes include MODFLOW-CFP, MODFLOW-LGR, GWM-2005, MF2005-FMP2, and MODFLOW-NWT and are available for download as open source software products.

MODFLOW-2005 is extremely powerful and is capable of simulating the complex problems encountered in practice. For example, it can represent complex heterogeneity in hydrogeological properties in three dimensions. This lets a user simulate even the most complicated hydraulic conductivity or transmissivity fields. The model can simulate inflows and outflows of water fully representing processes like pumping, stream recharge/discharge, drainage, and evapotranspiration (Harbaugh, 2005). A user has tremendous flexibility in outputting a variety of different kinds of results including hydraulic head distributions, drawdowns and fluxes.

MODFLOW provides a numerical solution to the following equation describing the three-dimensional transient flow of the groundwater:

$$\frac{\partial}{\partial x} \left[ K_{xx} \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_{yy} \frac{\partial h}{\partial y} \right] + \frac{\partial}{\partial z} \left[ K_{zz} \frac{\partial h}{\partial z} \right] + W = S \frac{\partial h}{\partial t}$$

Where $K_{xx}$, $K_{yy}$, and $K_{zz}$ are the values of hydraulic conductivity along the x, y, and z coordinate axes (L/T), h is hydraulic head (L), W is a volumetric flux per unit volume representing sources and/or sinks of water, where negative values are extractions,
and positive values are injections. \((T^{-1})\), \(S_s\) is the specific storage of the porous material \((L^{-1})\), \(t\) is time \((T)\) (Harbaugh, 2005).

For a derivation of the Eqn. 1, see for example Rushton and Redshaw (1979). In general, \(S_s, K_{xx}, K_{yy}, \text{ and } K_{zz}\) are the function of space and \(W\) is a function of space and time. The equation describes ground-water flow under non-equilibrium conditions in a heterogeneous medium (Harbaugh, 2005).

MODFLOW has certain assumptions and requirements for information. First, the numerical solution is developed assuming that the principal axes of hydraulic conductivity are aligned with the coordinate directions. In most problems, this assumption is not an issue. Like any differential equation, the solution of the groundwater flow equation requires boundary and initial conditions. Boundary conditions represent the influence of the conditions outside of the simulation domain on the solution to equation. For example, groundwater may be moving in or out across a boundary; and this condition needs to be represented in the conceptualization and design of the MODFLOW model. Initial conditions are required for transient model runs. The initial condition provides the value of hydraulic head at the start of the simulation (i.e., \(t = 0\)) for every node in the simulation domain.

MODFLOW-2005 uses iterative approximations to solve the groundwater flow equation, based on discretized in space and time. This version of MODFLOW is designed to use a column, row, and layer numbering system to represent the spatial discretization of the simulation domain. Details of theoretical approach, governing equations and
numerical schemes used to solve the system of finite-difference equations are described in the user’s guide (Markstrom et al., 2008).

MODFLOW-2005 is written in the Fortran 90 programming language and the program code is divided into modules with a series of packages (Harbaugh, 2005; Markstrom et al., 2008). A user ends up creating a data set for each of these packages. Nine packages were used in this model, and Table 3.1 lists the MODFLOW-2005 packages that were used.
Table 3.1. MODFLOW-2005 Input Packages and Files.

<table>
<thead>
<tr>
<th>MODFLOW-2005 Packages and Files</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Package File (BAS)</td>
<td>Specifies the locations of active and inactive cells with the initial heads</td>
</tr>
<tr>
<td>Discretization File (DIS)</td>
<td>Specifies the number of rows, columns, layers, cell sizes, and time discretization</td>
</tr>
<tr>
<td>Gage Package File (GAG)</td>
<td>Specifies gage stations on lakes and streams.</td>
</tr>
<tr>
<td>Layer Property Flow Package File (LPF)</td>
<td>Specifies properties controlling flow between cells</td>
</tr>
<tr>
<td>Output Control Option File (OC)</td>
<td>Specifies which head, drawdown, or budget data should be printed or saved.</td>
</tr>
<tr>
<td>Preconditioned Conjugate Gradient Solver Package File (PCG)</td>
<td>Solves the finite difference equations in each step of a MODFLOW stress period.</td>
</tr>
<tr>
<td>Unsaturated Zone Flow Package File (UZF)</td>
<td>Simulates vertical flow of water through the unsaturated zone to the saturated zone.</td>
</tr>
<tr>
<td>Streamflow-Routing Package File (SFR)</td>
<td>Simulates streams in a model.</td>
</tr>
<tr>
<td>Name File (NAM)</td>
<td>Specifies the names of the input and output files in the model.</td>
</tr>
</tbody>
</table>
3.3 Design of Coupled Flow Model (GSFLOW)

Figure 3.2 shows how PRMS and MODFLOW work together to cycle water from the land surface to groundwater. As is evident, MODFLOW is responsible for simulating saturated and unsaturated flow, below the soil zone (Region 3), and routing water in streams and lakes (Region 2). PRMS deals with various land surface processes represented within Region 1. The arrows define pathways by which water moves from one region to another and effectively describe how they are coupled together. The processes in region are uniquely defined by a set of parameters.

Figure 3.2 The exchange of flow among the three regions in GSFLOW (from Markstrom et al., 2008)
3.4 Integration of PRMS and MODFLOW-2005

The creation of gravity reservoirs is an important feature for integrating the two component models. PRMS and MODFLOW-2005 have different ways of representing hydrologic variability; PRMS uses HRUs and MODFLOW-2005 uses rectangular finite-difference cells. Gravity reservoirs are the cells, which are defined at the intersections of HRUs and finite-difference cells. Hence, connecting HRUs of PRMS to finite-difference cells of MODFLOW-2005 by creating gravity reservoirs is the key role in the process of integration.

GSFLOW requires data components associated with both PRMS and MODFLOW-2005. Weather, land use/cover, vegetation data, and soil information components are required for PRMS; river channels, boundary conditions and various soil properties (e.g., hydraulic conductivity) are required for MODFLOW-2005. The Soil zone is an important component for integration because all inflows and outflows in each HRU occur through the soil zone. Unsaturated Zone File (UZF) simulates flow and storage of water under soil zone; it also simulates groundwater discharge to the soil zone or land surface while calculating the amount of evapotranspiration. The Streamflow-Routing Package simulates flow in the streams and unsaturated flow under the streams (Markstrom et al., 2008). Table 3.2 describes in tabular form how key pieces of the codes work.
### Five components of GSFLOW from the integration of PRMS and MODFLOW-2005

| **PRMS** | 1) Distributes precipitation, temperature, and solar radiation  
2) Computes potential evapotranspiration, interception, snowmelt, and surface evaporation. |
| **Soil Zone (PRMS)** | Partitioning precipitation into surface infiltration, surface runoff, evapotranspiration, and subsurface flow |
| **SFR2** | Routes flow in the channels and stream segments |
| **UZF** | Computes vertical unsaturated flow beneath the soil zone |
| **MODFLOW-2005** | Computes groundwater flow |

Table 3.2. Five components from the integration of PRMS and MODFLOW-2005 model for GSFLOW.

### 3.5 Development of Data Sets for the Souhegan River

GSFLOW was used to construct a model of Souhegan River watershed to simulate flow in groundwater and surface water systems. To create necessary input data for GSFLOW, various hydrological, meteorological, and hydrogeological data are required for the study area. These include:

- Basic GIS data, such as digital elevation data (DEM), land use/land cover data (NLCD), and soil composition data (SSURGO), available from the USGS EarthExplorer portal;
- Climatic data: daily mean values of precipitation, temperature, solar radiation, evapotranspiration, and stream flow data (2002-2013);
- Hydrologic data, such as the information on the HUCs, and stream channel network;
- Hydrogeologic data, including features of the geologic setting such as unit thicknesses and hydraulic parameters, such hydraulic conductivity values, aquifer storativity values and water levels;

The actual input packages/files for GSFLOW consist of various data files, some of which are simple and other long and complication. The preparation of these files is helped by the various software packages listed in Table 3.3. Their function is discussed in following sections.

Besides the commercially available software, most of the packages listed in Table 3.3 can be downloaded from U.S. Geological Survey website (http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/GSFLOW.html). Downsizer is a program to create temperature and precipitation file in PRMS format. Downsizer is an application used to examine, gathering and formatting time-series data for use with GSFLOW. Downsizer version connects directly to appropriate web sites and automatically collects the specified data. Climate data are available from NOAA’s National Weather Service, and USDA snow networks maintained by the Natural Resources Conservation Service (NRCS). Stream flow data come from the National Water Information System maintained by the USGS.
Soil Data Viewer 6.1 is a product created by the NRCS and used to create spatial information on soil composition information for specified areas. PRMS Paramtool is also used to create PRMS files after ArcGIS generates HRUs map and parameter values from DEM file. For example, Paramtool provides all the information that is needed to run PRMS and GSFLOW. After ArcGIS has generated data applying to the HRUs and parameter values, Paramtool arranges every parameter value such as stream segments data, weather information, and more, into each HRU.

ArcGIS is a well-known tool for managing geospatial information. Of all the software used in the preparation of data for GSFLOW, it is most important because of its capabilities and the fact that some of the other packages (e.g., Soil Data Viewer) are run

<table>
<thead>
<tr>
<th>Software Requirements for GSFLOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS Downsizer</td>
</tr>
<tr>
<td>ESRI ArcMap and Workstation (Version 10.1)</td>
</tr>
<tr>
<td>CRWR ArcHydro extension</td>
</tr>
<tr>
<td>XTools Pro extension</td>
</tr>
<tr>
<td>Microsoft Excel</td>
</tr>
<tr>
<td>USGS PRMS Paramtool</td>
</tr>
<tr>
<td>USGS ModelMuse</td>
</tr>
<tr>
<td>Soil Data Viewer 6.1</td>
</tr>
</tbody>
</table>

Table 3.3. Software used in the creation GSFLOW input packages.
as an add-in to ArcGIS. For this particular application, ArcGIS also requires extensions, ArcHydro and XTools Pro, which are used to delineate watersheds and to create grid cells.

ModelMuse is a Graphical User Interface (GUI) that helps users to create the necessary input files for MODFLOW–2005. ModelMuse offers significant flexibility in setting up a modeling problem because it lets the spatial data be independent of the row column grid. In addition, time-related data are considered to be independent of the stress periods. This capability facilitates easy re-gridding.
CHAPTER 4: Results

This section begins first with a description of the data collected and prepared as input files to GSFLOW. It then discusses the results of the simulation including the validation of the model results. Finally, it provides a hydrologic assessment of the Souhegan River watershed.

4.1 PRMS and GSFLOW Data

PRMS can be run as a stand-alone program or as part of GSFLOW. Accordingly, the conceptualizations of the hydrologic system represented by the input data here apply to both codes. A variety of physical and hydrologic parameters need to be provided to PRMS by itself or within GSFLOW as a PRMS Data file, a PRMS Parameter file, and a PRMS Control file. The values of some of these parameters already exist, and others are defined through the model calibration process. In addition, some parameters are assigned as default values from other studies because the logical range could not be determined.

The USGS DownSizer-Client was used to create the necessary PRMS data files. Daily discharge for the Souhegan River is available at a single river gage (Merrimack, New Hampshire, USGS 01094000). Daily stream discharges interpreted from stage measurements at Merrimack, NH are plotted for the period of study from 2002 to 2013 stream-flow (Figure 4.1). During the study period, daily discharges varied from a low of 0.243 m$^3$/s (8.58 cfs) on 9/12/2012 to a high of 286 m$^3$/s (10100 cfs) on 4/17/2007.
Figure 4.1 Measured daily discharge at the USGS gaging station at Merrimack from 2002 through 2013.

Figure 4.2 shows the river discharge for 2008, the year during the period of interest when the highest total annual discharge was recorded at the USGS gaging station at Merrimack. In 2008, a total discharge was 449 million m$^3$ resulted from 1588 mm (62.5 in) of precipitation (Table 1.1). Daily discharge ranges from 1.19 m$^3$/s (42 cfs) to 66.8 m$^3$/s (2360 cfs) in 2008.
Figure 4.2 The year of highest discharge record during the study period at the USGS gaging station at Merrimack.

Figure 4.3 The year of lowest discharge record during the study period at the USGS gaging station at Merrimack.
In contrast with 2008, 2002 saw the lowest total annual discharge during the study period. The total yearly discharge in 2002 was 187 million m$^3$ from a total of 1124.2 mm (44.3 in) of precipitation (Table 1.1). In 2002, daily discharge ranged from 0.368 m$^3$/s (13 cfs) to 47 m$^3$/s (1660 cfs) in 2002.

Figure 4.4 shows a higher resolution hydrograph for the flood that occurred in 2007. Flooding was caused by an intensive rain storm that produced upwards of 18 cm (7.1 in) of rain falling on April 16$^{th}$ to 18$^{th}$ across New Hampshire. Peak discharge on the Souhegan River on April 17$^{th}$ was 286 m$^3$/s (10,100 cfs). FEMA (2008) determined that this 2007 flood had an approximate return interval of 50 years. Although 2007 recorded the 50-year flood, the total precipitation for 2007 was 1217.7 mm (47.9 in) (Table 1.1), which was 370.3 mm (14.6 in) less overall than the total for 2008 (the wettest year during the study period). During the intensive rainfall period (April 16$^{th}$ to April 24$^{th}$), the discharge ranged from 35.1 m$^3$/s (19 cfs) to 286 m$^3$/s (10,100 cfs).

Weather data were downloaded from two weather stations (East Milford; USC00272302 and Greensville USC00273658). The text file for the weather data includes precipitation, min/max air temperature, evapotranspiration, and solar radiation data. As is often the case, measured solar radiation data and pan evaporation data were unavailable for the study, so default values were used, recommended from GSFLOW (Markstrom et al., 2008). Figure 4.5 illustrates the average temperature for each month during 2002 – 2013.
Figure 4.4 50-Year Flood discharge record on 2007 at the USGS gaging station at Merrimack.

Temperatures fall below 0°C (32°F), starting around the middle of November until the end of February. The average temperature is about -3.7°C (25.34°F) during winter season (December through February).

Figure 4.6 represents the monthly average precipitation on the study area during the study period with the average rainfall per month is about 100.3 mm (3.95 in). November tends to receive the highest rainfall with 130.2 mm (5.13 in), while the January tends to receive the lowest rainfall with 74.8 mm (2.94 in).
HRUs form the basis for the discretization of the watershed using PRMS. Within a given HRU, parameter values are assumed to be constant, but can change from one
HRU to another (Markstrom et al., 2008). Figure 4.7 shows the discretization of the watershed as 31 HRUs, which was generated by ArcGIS. The HRUs ranged in area from 59 to 3850 ha (146 to 9503 acres) and elevation from 57 m asl (187 ft asl) to 689 m asl (2260 ft asl).

Figure 4.7 Hydrologic Response Units (HRUs) defined within the watershed.

The elevation values for the HRUs were determined from a DEM within ArcGIS. Figure 1.1 shows digital elevation map that I created for the watershed. Similarly, information on land-cover for HRUs came from a raster land cover map. Figure 4.8 is a
simplified map of the land cover across the watershed. It was prepared in ArcGIS and shows the tree canopy fraction as a continuous variable from 0 to 100%. As the map shows, most of the area is well treed (50% - 75%), as represented by the light-green and dark green colors. Areas classified as ‘bare soil’ correspond to cities.

Figure 4.8 Map showing the basic land cover across the watershed.
Soil data for each of the HRUs was estimated in the same manner using ArcGIS in conjunction with a digital soil map (not shown).

Table 4.1 lists a range in some values of the model parameters used in the PRMS/GSFLOW simulations. As mentioned, some parameters are represented by default values for well characterized settings or based on experience. Examples include the Jensen-Haise coefficient used in calculating potential evaporation, values for maximum water equivalent used to describe snow covers, and a value for the transmission coefficient for short wave radiation. Also, the area indexes of impervious roadways are assumed to be negligible; therefore, a default value of 0% is used on this modeling. Other examples of the default values used in this modeling include \texttt{carea\_max}, \texttt{adj\_wppt}, \texttt{settle\_const}, \texttt{freeh2o\_cap}, \texttt{ssr2gw\_rate}, etc (see Markstrom et al., 2008).
Table 4.1. PRMS/GSFLOW input parameter, created by ArcGIS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covden_sum (dimensionless)</td>
<td>0.622</td>
<td>0.940</td>
</tr>
<tr>
<td>Covden_win (dimensionless)</td>
<td>0.334</td>
<td>0.743</td>
</tr>
<tr>
<td>Snow_intcp (inch)</td>
<td>0.232</td>
<td>0.647</td>
</tr>
<tr>
<td>Srain_intcp (inch)</td>
<td>0.342</td>
<td>0.750</td>
</tr>
<tr>
<td>Wrain_intcp (inch)</td>
<td>0.232</td>
<td>0.647</td>
</tr>
<tr>
<td>Hru_elevation (meter)</td>
<td>76</td>
<td>378</td>
</tr>
<tr>
<td>Sand (dimensionless)</td>
<td>0.274</td>
<td>0.920</td>
</tr>
<tr>
<td>Clay (dimensionless)</td>
<td>0.0998</td>
<td>0.383</td>
</tr>
<tr>
<td>Hru_area (Acres)</td>
<td>146.64</td>
<td>9503.12</td>
</tr>
<tr>
<td>Hru_slope (dimensionless)</td>
<td>0.01424</td>
<td>0.326</td>
</tr>
<tr>
<td>Hru_id (no unit)</td>
<td>1</td>
<td>31</td>
</tr>
</tbody>
</table>

4.2 MODFLOW Grid Boundary Condition

It is necessary to provide the boundary conditions in order to solve groundwater flow problems. The simulation domain is the Souhegan River watershed where the basin boundary is defined by the topographic divide that is also the surface-water divide for the basin. For basin-scale simulations with MODFLOW, it is often assumed that the surface-water divide also defines the groundwater divide.
MODFLOW is constructed to accommodate three types of boundary conditions, (i) specified head (including constant head), (ii) specified flux (including no flow), and (iii) head-dependent conditions (Harbaugh, 2005). Assuming the groundwater divide correspond with the surface-water divide makes the watershed boundary an imaginary no flow boundary within MODFLOW. In a numerical model, the edges of the model grid or boundaries with inactive cells are implicit no flow boundaries. Thus, really nothing has to be done in the input data to create the no flow boundaries.

MODFLOW is being run within GSFLOW in a transient mode. Thus, initial conditions are required. For the simulations here, the initial head is assumed to be represented by the elevation of the ground surface for each column of nodes.

4.3 MODFLOW Data

The software ModelMuse is used to create MODFLOW-2005 input files. After selecting the desired MODFLOW-2005 packages, shapefiles, generated from ArcGIS, are imported to ModelMuse from ArcGIS. The resulting discretization provided by this analysis has resulted in a model grid with 170 columns and 160 with 200-meter-by-200-meter-grid grid blocks (Figure 4.9). The model is vertically discretized into four layers, the Land surface layer, upper layer, middle layer, and bedrock.
Figure 4.9 Map of the MODFLOW grid created by ModelMuse.

Streams and all subsurface units beneath the soil zone are simulated by nine MODFLOW-Packages: the Basic Package File (BAS), Discretization File (DIS), Gage Package File (GAG), Layer Property Flow Package File (LPF), Output Control Option File (OC), Preconditioned Conjugate Gradient Solver Package File (PCG), Unsaturated Zone Flow Package File (UZF), Streamflow-Routing Package File (SFR), and Name File (NAM).
The SFR package is used to accumulate surface and groundwater flows into the streams and route the water (Niswonger and Prudic, 2005). For the MODFLOW simulation, there are 31 stream segments made up of 805 reaches. Figure 4.5 is a map of these distribution of stream segments along with the USGS gaging station (ID: 01094000) located at Merrimack, New Hampshire.

Figure 4.10 Map of the watershed showing the stream network as represented within MODFLOW.
4.4 Calibration of the Models

Calibration is the process of parameter adjustment designed to minimize the difference between observed and simulated attributes of the hydrologic system. Typically, with hydrologic models, the calibration attempts to match simulated values of daily stream discharge with those measured at one or more gaging stations. For, the Souhegan River watershed there is measured discharge data at the downstream at the USGS gaging station at Merrimack. Calibration typically utilizes a subset of the measured discharge data. The remaining data are used for the validation step. Validation is an independent demonstration that the model is capable of simulating runoff from the watershed for a number of years outside of the time period represented by the calibration.

The typical strategy followed with GSFLOW is to calibrate the models one after another. Calibration begins using the PRMS model by itself. It is simpler than GSFLOW because the groundwater system is much simpler than with GSFLOW that incorporates MODFLOW. To the extent data permit, MODFLOW is next to be calibrated, typically using observed versus simulated groundwater levels as the calibration target. The last calibration involves GSFLOW with the combined PRMS and MODFLOW file sets. Experience suggests that not many of the PRMS parameters will change from the original calibration.

For the calibration here in this study, I use the observed daily stream flow at Merrimack between 2001 and 2003. The remaining portion of the discharge record, extending into 2013 is used for the validation. Normal practice involves a period of model spin-up because if the model is simply started up (e.g., in 2001), there are inherent errors in discharge estimates produced by the model because the storage reservoirs do not
have correct starting values. Here, I run the model using 10 years of the same climate data to create the spin-up period. The climate year (precipitation and temperature data) for 2005 is used for spin-up period before the model is started in 2001. Consequently, the PRMS model ultimately covers some 23 years of simulation with 10 years of spin-up and 13 years of study period (2002 and 2013) with real data. The length of the spin-up time was appropriate because the simulation results reached equilibrium during the 7th year of spin-up. The discharge hydrograph for this period of interest from 2002 to 2013 is shown in Figure 4.1.

4.4.1 PRMS

The calibration of PRMS was done manually by trial-and-error adjustments to the values of various parameter files. The choice of which parameters to adjust came from guidance provided by other studies (Markstrom et al., 2008; Ely and Kahle, 2012). Typically, only one parameter was changed for each model run to make clear how changes in value affected the calibration. Table 4.2 shows examples of the number of adjustments that were made with key parameters to achieve an acceptable calibration. How these parameter values affect the simulation is rather intuitive because it is clear how the parameters redistribute water at the land surface. For example, if soil_moist_init and sstor_init reach their maximum value, precipitation becomes surface runoff easily because the shallow subsurface contains considerable water already. Higher values of soil2gw_max parameter routes more excess soil-water directly to PRMS ground-water reservoir. These parameters are manually changed to calibrate for the PRMS model.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Changed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sstor_init</td>
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</tr>
<tr>
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<tr>
<td>Soil_moist_max</td>
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Table 4.2 Parameters adjusted manually calibration.
Figure 4.11 PRMS Calibration

Figure 4.11 compares the simulated versus measured hydrographs with PRMS. As is evident, there is generally a good agreement between simulated discharge from PRMS and discharge measured at the gaging station. Both the simulated and observed discharges for the gaging station match well under both low flow and high flow conditions. This is especially the case in winter and summer in 2002 and summer in 2003. However, there are three large floods, May 2002, April 2003, and December 2003 where the match is less satisfactory. The model under-predicts the first flood in May 2002 by 30 %, and under-predicts the second flood in April 2003 by 40 %, as compared to the observed discharges. The model slightly over-predicts the flood in December 2003. At low flows, the simulated values are slightly lower than the observed for the low flows, for example, April to July in 2002 and January to June in 2003.
I examined the fit between simulated and observed discharges with the help of a linear correlation diagram (Figure 4.12). The coefficient of determination ($R^2$) is used to show the goodness of fit between observed and simulated results. Ideally, if the fit was perfect, all the data points would lie along the 45 degree line shown on the Figure. In my case here, the $R^2$ statistic for the best-fit line is 0.79. At most flows then, the model tends to under-predict the observed discharge values. There are certain few exceptions where the model over-predicts mostly in winter.

![Figure 4.12 R-square value of simulated stream flow vs observed stream flow.](image-url)
4.4.2 MODFLOW

The basic method of the calibration is the comparison of simulated and measured groundwater levels and streamflow values. MODFLOW-2005 was calibrated as steady state, while comparing simulated and observed hydraulic heads. Groundwater levels from MODFLOW-2005 and measured groundwater levels from the report of Harte and Mack (1992) were used as the basis for this calibration. The calibration was done by manually. The results of the calibration are shown in Table 4-3. Generally, the calibrated MODFLOW-2005 model slightly under predicts the groundwater levels.

<table>
<thead>
<tr>
<th>Well</th>
<th>Measured ft (meter)</th>
<th>Simulated ft (meter)</th>
<th>Difference ft (meter)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>237.51 (72.4)</td>
<td>234.02 (71.3)</td>
<td>-3.49 (-1.1)</td>
</tr>
<tr>
<td>2</td>
<td>236.08 (71.9)</td>
<td>230.16 (70.1)</td>
<td>-5.92 (-1.8)</td>
</tr>
<tr>
<td>3</td>
<td>235.74 (71.8)</td>
<td>231.38 (70.5)</td>
<td>-4.36 (-1.3)</td>
</tr>
<tr>
<td>4</td>
<td>235.75 (71.8)</td>
<td>234.3 (71.4)</td>
<td>-4.45 (-0.4)</td>
</tr>
<tr>
<td>5</td>
<td>251.00 (76.5)</td>
<td>248.9 (75.8)</td>
<td>-2.1 (-0.7)</td>
</tr>
<tr>
<td>6</td>
<td>267.31 (81.5)</td>
<td>265.22 (80.8)</td>
<td>-2.09 (-0.7)</td>
</tr>
</tbody>
</table>

Table 4.3 Measured and simulated hydraulic heads from MODFLOW
4.4.3 GSFLOW Calibration

The calibration of GSFLOW is performed last, after the calibration of PRMS and MODFLOW. As expected, at this stage, only minor adjustment to just a few parameters was required. Figure 4.13 shows the measured and simulated hydrographs plotted together. A visual comparison illustrates a close agreement. A simple plot of measured versus observed discharges (not shown) provides an $R^2$ value of 0.831. One of the major discrepancies evident is my model under-prediction of the flood by about 25% in April 2003, as compared to the observed value. The other major mismatches occurred in fall season in 2002 and March, June, August, and October in 2003 as my model over-predicts high-flow discharge values. Also, my model over-predicts discharges by 20% in June and December in 2003. My model tends to over-predict the high flows. My model predicts well on low-flows, except certain period, such as spring and early summer in 2002 and winter and spring season in 2003. Simulated discharge values could not predict well during winter season because of snowmelt.

I attribute this difference in the two time series in discharge to the limited precipitation measurements across the watershed, especially at higher elevations. The reconstruction of average precipitation from January to May in 2003 typically found somewhat higher precipitation in the mountainous areas of New Hampshire, which is not represented by the few available weather stations.
Validation

After calibration of GSFLOW model, validation is performed as the next step in order to demonstrate the predictive ability of the code and to build confidence in its suitability for applications. Years from 2012 to 20013 were selected for validation purposes. Figure 4.14 compares the hydrographs of measured and simulated discharge for the Souhegan River at Merrimack. Again, there is a good match between the two. The correlation between the observed and simulated discharge has an $R^2$ value of 0.95 on Figure 4.15. Certain deviations are however apparent. For example, simulated discharge values over-predicted the observed discharges by about 50% on March and May in 2012.
The model also over-predicted the two high flows in June. Minor-mismatch occurs in August 2012, when the model did not precisely predict the low discharge values.

Another major mismatch is evident in 2013. From January to May, the model did not predict well. Simulated discharge values followed the trend of measured discharge values; however, the model slightly over-predicted the low flows during winter and early spring season, while the model under-predicted the low flows in spring 2013. Minor mismatches occur in high flows in 2013, for example, the high flows of February, March, April, and December. Other than those values, the simulated and observed discharge values are almost perfectly matched during the validation period. Again, the mismatches in peak flow are attributed to the inability to characterize the spatial variation in precipitation across the watershed. Another possible cause is that the model assumes that precipitation occurs over 24 hours. Often, however, this is not the case and short, intense rainfalls can produce storm runoff.
Figure 4.14 Results of model validation showing a favorable comparison between observed and simulated discharge hydrographs.

Figure 4.15 R-square value of simulated stream flow vs observed stream flow for Validation
CHAPTER 5: Analysis and Discussion

This chapter presents a hydrologic analysis of the Souhegan River watershed that is based on various results from GSFLOW. The follow sections then will discuss storage differences as a function of time, water fluxes, and groundwater/surface water interactions. The insights provided from these analyses could assist other researchers who may work on Souhegan River watershed on critical issues affecting New Hampshire (e.g., global climate change) and more local studies concerned for example with dam removal and flood protection.

5.1 Water Storage in the Souhegan River watershed

After the calibration and validation, the GSFLOW model was used to evaluate changes in storage in the unsaturated and saturated zones. GSFLOW provides these values as on a daily basis. As Figure 5.1 shows, cumulative storage in the unsaturated zone tends to fluctuate over a much broader range than the saturated zone storage. For simulation purposes, the shallow subsurface is assumed permeable, i.e., sand and gravel. With depth permeability was assumed to decrease with the depth as glacial till becomes more dominant. Storage within the unsaturated zone tends to fluctuate more rapidly than the saturated zone. Again, this kind of response is expected because evapotranspiration tend to act much more quickly on water stored in the unsaturated zone.
Figure 5.1 Cumulative change in unsaturated and saturated zone storage for the validation period.

Unsaturated-zone storage generally peaks in spring and early summer because in New Hampshire most excess moisture comes from summer storms and spring snowmelt. Unsaturated-zone storage reached a peak in April, 2012. Typically, saturated-zone storage tends to decrease following the snowmelt in spring but will occasionally increase due to heavy rainfall during summer. Saturated-zone storage reached a peak in June, 2013.

5.2 Fluxes of Water in the Souhegan River watershed

Water fluxes are calculated by GSFLOW model and are provided as “comma separated values” in an excel file. First, I discuss the time variation in precipitation,
evapotranspiration, and surface runoff shown in Figure 5.2 (the snowmelt represented as equivalent rainfall).

![Figure 5.2 Flux across the land-surface for the validation period.](image)

As expected, evapotranspiration peaks during spring and summer months while evapotranspiration decreases during late fall and winter. Basin runoff peaks during winter because there is less evapotranspiration.

Next, I discuss in the character of fluxes from the soil zone down to the unsaturated zone, termed gravity drainage, and then groundwater discharge that encompasses fluxes into the soil zone from the saturated zone. As shown in Figure 5.3, gravity drainage almost always exceeded ground-water discharge except for some very
dry periods in summer 2012 and fall 2013. Because the fluxes noted on Figure 5.3 represent the whole basin averages, local behaviors may be somewhat different.

Figure 5.4 shows the variation in cumulative soil zone storage with precipitation. Associated with periods of larger precipitation, are marked increase soil zone, cumulative storage. The opposite behavior is evident during dry periods. For example, during the very dry season in 2012, fluxes to the soil zone declined dramatically (Figure 5.4).

Stream flow in the watershed is contributed from surface runoff, interflow, and net groundwater discharge. The final analysis in this section looks at the relative contributions from surface runoff and interflow plus groundwater discharge. As shown on Figure 5.5, the major source for the stream flow contribution is the basin runoff.

Because of frozen soil and snowmelt, basin runoff dominates over interflow and groundwater discharge during winter and spring. Basin surface-runoff again becomes a major source of stream flow in the summer of 2013 because of the high amount of rainfall. Groundwater appears to be most important during spring to early summer (Figure 5.5).
Figure 5.3 Flux of gravity drainage of water from the soil zone to unsaturated zone and groundwater discharge for the validation period.

Figure 5.4 Cumulative change in soil zone storage with precipitation data.
Figure 5.5 Components of stream flow
CHAPTER 6: Summary and Conclusions

The last decade has seen the realization of a dream to simulate the land-based water cycle in a complete and rigorous manner. Before the development of powerful codes like GSFLOW, ParFlow and HGS, groundwater and surface water were usually studied as separate systems within the hydrological cycle, even though the two systems interact together in a continuous manner. Recently, models have emerged that facilitate the application of ground/surface water together, contributing new understanding of the water cycle. Now, these coupled models are being used to analyze the water movement system in support of research and industrial practice.

My studies here focused on the application of the Groundwater and Surface Water Flow model (GSFLOW) to study the Souhegan River watershed. Although this code is complicated, it is well supported by a comprehensive user’s guide, example problems and a growing collection of associated papers. I was able to integrate available data and create a hydrologic model of this watershed. On the basis of my experience with this code, I would conclude that GSFLOW is a mature and capable modeling package that is suitable for general applications to problems of this type. There are clearly opportunities to streamline and integrate the various supporting packages used to support the code. This was one of my most difficult challenges, getting all these supporting pieces to work. Overall, there is a great advantage in being able to develop an integrated description of the hydrological processes.
To conduct the model studies on Souhegan River watershed, I gathered information largely compiled by government agencies that describes the physical setting of the watershed. Fortunately, there was a long-term stream gage on the Souhegan River at Merrimack. Detailed geologic and hydrogeologic data were limited to just a few small areas around Milford and Amherst. Otherwise, features of the geology and hydrogeology are only understood in general. This lack of data was likely not a problem because over much of the watershed the contribution of groundwater is limited to thin alluvial deposits along tributary stream channels.

In terms of the data needed to construct the model, the greatest problem was provided by the precipitation data. It is likely that the model would have benefitted from more detailed precipitation measurements. I think that two stations were inadequate to capture the variability in precipitation across the watershed and local orographic enhancements, especially in the western mountains. It seems that progress in the construction of good codes like GSFLOW need to be matched more available precipitation products. However, success with the calibration and validation of the models suggests that the available data were sufficient to let me analyze water movement from precipitation to the land surface, and groundwater systems.

I followed the USGS guidance in first developing the surface water model (PRMS) and the groundwater model (MODFLOW-2005) before the completion of the GSFLOW. Generally, I used PRMS to provide an adequate but not excellent calibration. I spent more of an effort in calibrating GSFLOW and obtained a good calibration result with the correlation between simulated and observed discharges at Merrimack providing an $R^2$ value of 0.8258 for all year and 0.8779 for the calibration period.
Although I am satisfied with the results of my GSFLOW simulation of the Souhegan River watershed, there are still some considerations for improving the overall outcome. All of the calibrations in this study were completed manually. Manual calibration process is a quick method to check the results of GSFLOW; however, this manual calibration process may does not represent a true inverse. Some sensitive parameters are likely at or close to optimum values, but some other parameters might be un-optimized. If automatic calibration (e.g., PEST) had been used the calibration of GSFLOW would have likely improved. Also, I am not sure that certain default parameters used, because of difficulties in obtaining data (e.g., snow-fall, radiation, initial soil moisture, etc), were optimum in the calibration.

The Souhegan River watershed has the potential for interesting follow-on studies. High priority in this respect would be approaches that found ways to acquire and use weather radar data for precipitation estimates, so as to provide a better understanding of storm interactions along the Wapack Mountain front. Preliminary work by Wyss et al. (1990) using MIT radar for rainstorm characterization showed good promise for the analysis of New England storms.

A second follow-on study of particular interest would be an analysis of actual and potential extreme events. One example of such a study would be a retrospective analysis of the 1936 flooding. The sequence of storms was such that the first rains fell on a snow-covered watershed. An analysis of this component would test the capability of the land-surface model to handle this process and offer possibilities to improve the code. A second prospective analysis might look at the possibilities for storm enhancements due to climate
change. In summary, this part of New Hampshire could prove to be a useful ‘outdoor’ classroom for further research work as well as other educational products.
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