DISSERTATION

CONJUNCTIVE USE MANAGEMENT STRATEGY WITH SMALL AQUIFERS TO MINIMIZE DRY-SEASON DAMAGE AND MEET INSTREAM FLOW TARGETS

Submitted by:
Young-Dae Cho
Department of Civil and Environmental Engineering

In partial fulfillment of the requirements
for the Degree of Doctor of Philosophy
Colorado State University
Fort Collins, Colorado
Spring 2008

ProQuest LLC
789 E. Eisenhower Parkway
PO Box 1346
Ann Arbor, MI 48106-1346

COLORADO STATE UNIVERSITY

November 16, 2007

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY YOUNG-DAE CHO ENTITLED "CONJUNCTIVE USE MANAGEMENT STRATEGY WITH SMALL AQUIFERS TO MINIMIZE DRY-SEASON DAMAGE AND MEET INSTREAM FLOW TARGETS" BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

<u>Committee on Graduate Work</u>

Freeman M Smith

Freeman M. Smith

Deanna Durnford

Deanna S. Durnford

Darrell G. Fontane

Advisor Neil S. Grigg

Luis Garcia

Department Head Luis A. Garcia

ABSRACT OF DISSERTATION

CONJUNCTIVE USE MANAGEMENT STRATEGY WITH SMALL AQUIFERS TO MINIMIZE DRY-SEASON DAMAGE AND MEET INSTREAM FLOW TARGETS

This dissertation addresses the connections between surface and ground water when alluvial aquifer systems are small, presents a series of technical and institutional analyses to show how to manage a limited water source at the basin level, and addresses management strategies for conjunctive use to understand and provide potential solutions for water conflicts. In the case study area, the middle section of the Geum River in Korea, the major issue is increasing in-stream flow requirements during severe drought that have been imposed by downstream stakeholders and nongovernmental organizations (NGO) after dam completion. The case also involves a large trans-basin diversion.

The technical analysis includes reviews of connectivity between surface and ground waters, development of response coefficients due to pumping wells, in-stream flow requirements, and conjunctive use approaches. The institutional analysis includes reviews of water right systems, organization, in-stream flow requirements, and data management to provide comparative perspectives.

Most alluvial aquifers along the main rivers in the case study area are relatively narrow and small. These aquifers are highly interconnected with the adjacent streams and the critical time to reverse the hydraulic gradients in the gaining streams is relatively short. The ratio of groundwater recharge to average annual precipitation is about 20%. The recharge occurs mostly in the rainy season from June to September in the study area and ground-water recharge is strongly correlated with the precipitation. The response coefficients of stream depletion due to the pumping wells are presented by using analytical and numerical methods.

In order to estimate the instream flow requirements, it is necessary to simulate the daily stream-flow at an ungaged site so that a rainfall-runoff model can be used to simulate the reservoir operation by using a standard operating policy. A simulated daily

data set is used for analyzing the hydrologic alterations before and after the dam completion. Under the given conditions, the Yongdam Reservoir in the Geum River Basin highly impacts the hydrologic alterations. The main factor of hydrologic alteration is trans-basin water supply. In order to meet the water supply and downstream in-stream flow requirements for fish and aquatic habitat and minimize hydrologic alterations, the downstream in-stream flow requirement obtained by the method was determined to be about $3m^3/s$ based on the simulated data alteration.

In order to evaluate conjunctive use strategies, a multi-objective linear optimization model was developed to consider trans-basin diversion, in-stream flow requirements for fish and aquatic habitat, and withdrawal of groundwater and surface waters for irrigation. The response coefficient of stream depletion was estimated using a numerical method for transient state and fixed multiple wells and was incorporated into the conjunctive use model. For reservoir operation, a hedging rule was used to ration deficits from various water demands during the drought periods. An optimization software package was used for running the mixed-integer linear model.

In the application of the model, the first step was performed to set the priority of water supply for trans-basin diversion, in-stream flow requirements, and irrigation water use. Then, the priorities of in-stream flow requirements, trans-basin diversion, and irrigation water uses were quantified. Effects of using both surface and ground waters are evident, even though the thickness of aquifers developed along a main stream is relatively thin.

If water managers and decision makers understand the connection between groundwater and surface water, water management for the limited water resources can be more effective and efficient. However, the connection between surface water and groundwater has been ignored in water policy in Korea and rivers and aquifers have been managed by separate institutions. This occurs due to the hidden attribute of groundwater, stream-flow domination, time frames for groundwater movement and response, and institutional separation of expertise and administration.

In the institutional arrangements, four elements are highlighted, including the water rights system, organization, in-stream flow requirements, and data management. Institutional arrangements in Korea are compared to a limited extent with those at the

federal level and in two states of the United States, California and Colorado. The comparisons provide a perspective on appropriate institutional arrangements for conjunctive use in Korea.

For conjunctive management, gaps that occur include problems related to water allocation including conflict coordination systems, vagueness of legal status of current water use rights in water allocation law and institutions, unclear permit criteria, in-stream flow requirements, and shortage and inaccuracy of observed stream-flow and groundwater level data. Alternatives or options for Korea are presented such as organizational coordination in cooperating between agencies or creating river basin organizations, one permitting system including total water accounting, linking of water management plans, one permitting system, trigger or thresholds, management zones, and monitoring performance.

In conclusion, even though in Korea alluvial aquifers along main rivers are narrow, small and thin, surface and ground waters must be considered and managed as a single source in both technical and institutional aspects. It is hoped that this dissertation can contribute to the understanding of interactions between surface and ground waters in Korea, and with more understanding, water managers and regulators can find better paths to water management and that legislation about water management can recognize the interaction between surface and ground waters.

Young-Dae Cho
Department of Civil
and Environmental Engineering
Colorado State University
Fort Collins, CO, 80523
Spring 2008

ACKNOWLEGEMENTS

I would like to thank the many individuals who have been helpful in numerous ways on the path to this dissertation and degree. Family, friends, instructors, advisors, and colleagues have all contributed to my life and to the process of completing this work.

Some must be thanked for tremendous support. Thanks first to my wife, who has supported me unfailingly and given so much to this work, especially in encouragement and impetus. Thanks to my kids, Min-Sung, Seung-Wan, and Min-Soo, who have followed me and adjusted well to America life.

My appreciation is given to my four committee members who are: Dr. Neil Grigg, Dr. Deanna Durnford, Dr. Freeman Smith, and Dr. Darrell Fontane. I would like to express my heart-felt appreciation to my academic advisor, Dr. Neil Grigg, who always encouraged me to improve and motivate my understanding on my research and the institutional arrangements. I have learned a lot about engineering approaches to manage water resources from Dr. Darrell Fontane. Dr. Deanna Durnford gave me a very important guidance on the groundwater problem. Dr. Freeman Smith encouraged me to improve my research. Thanks to Dr. John W. Labadie, Dr. Jorge A. Ramirez, and Dr. Jose D. Salas for their great teaching and considerations. Thanks to K-water President Mr. Kwak Kyolho, and ex-president Mr. Ko Seokgu for supporting. Thanks to Dr. Noh Jaekyung, Dr. Park Sungje and Dr. Lee Dongryul for providing valuable advices and encouraging me. Thank to Dr. Park Myungky, and Mr. Kim Jeongyep for providing data and valuable advices. Thanks to Mr. Choi Byungman, and Mr. Lim Chanuk for encouraging me. Thanks to my colleagues: Mr. Cha Keeuk, Mr. Lee Hangu, Mr. Kim Bongjae, Mr. Kim Hyunsik, Mr. Shin Youngho, Mr. Jo Youngdeok, and Mr. Joeng Yongbae for sharing happiness and sadness during staying here. I would like to express my appreciations to CSU students: Mr. Jo Sengho, Mr. Lim Gwangsup, Mr. Lee Taesam, Mr. Song Taejung, Mr. Lee Dongjin, and Mr. Park Daeryung for assistances. I also thank to Dr. Chung Daesuk and his wife for great helps to my family.

From the help of all these people and those I have not mentioned above, I was able to successfully graduate from CSU.

Young-Dae Cho (Fort Collins)

TABLE OF CONTENTS

6. MANAGEMENT STRATEGY FOR CONJUNCTIVE USE AND INSTREAM FLOW ················ 136

APPENDICS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Economic development usually increases water demand and competition, causing conflict among water users. This is the case in South Korea, where until the late 1980s, the nation had focused on new water sources and infrastructure for economic development and population growth. However, conflicts between environmental and developmental goals require new water policies and comprehensive planning and decision-making approaches. Water supply problems are local in nature, and the unique terrain in South Korea creates a situation where ground water use causes conflicts during the irrigation season for several reasons. First, drought is common in the early spring, the months of from March to June, and precipitation is relatively small. Second, most aquifers in Korea are shallow with 10m to 20m of depth and unconfined aquifers along the rivers are thin and shallow, with little storage capacity. Finally, using well water for irrigation is a common practice during drought seasons. This combination of shallow aquifers and their extensive use in irrigation has led to stream-flow depletion. When dams were built in the past, this interaction between stream and aquifer was not considered. Today with so much pressure on water use, both storage and aquifer withdrawals must be considered. These issues make joint management of ground and surface water difficult but important to sustain required in-stream flow to protect ecosystems, fisheries, and habitat.

In Korea the government dominates the field of water resources management.

Even in participatory water management efforts, the government plays a dominant role. As these efforts are rarely based on any internally generated demand from the water users, they usually do not emphasize the creation of viable local organizations. This contributes to political and institutional barriers to integrating groundwater resources into surface water systems.

Given these problems, the main need is for a conjunctive water management system that has viable technical and institutional aspects and that utilizes both aquifers and reservoirs. However, despite the attention to conjunctive use, until recently there has been a lack of case studies in the technical literature that consider the impact of conjunctive use on reservoir management and in particular on reservoir operating rules, especially in Korea. The entities that develop water supply projects have often ignored groundwater conjunctive use when planning and operating surface reservoir systems and planning and operations models are usually restricted to the surface water system. Groundwater management models focused on hydraulic management or conjunctive use of stream-aquifer systems are usually restricted to a local problem. Most of the technical approaches in the literature are also focused on the stream-aquifer system with a large aquifer, while Korea's alluvial aquifers along main rivers are typically small and narrow. In the institutional approaches, most methodologies are broad in dealing with conjunctive use and usually not based on a technical evaluation. Their applications for a practical problem are limited in terms of the efficient operation of reservoir and stream-aquifer systems during drought.

Because the aquifers in South Korea are small, to mitigate damages of severe drought, it is necessary to develop a conjunctive management[1] tool with small aquifers, considering reservoir operation. Efficient strategic tools considering institutional arrangements in terms of implementation of integrated basin water resources management must also be developed. Thus, this study focuses on the development of a conjunctive use model for the condition of a small aquifer, alternatives of in-stream flow requirements with reservoirs, and alternative strategies for conjunctive management and instream flow through institutional arrangements.

The model will be applied to the Geum River Basin, one of the four major rivers in South Korea and an area where conflicts between resource development and conservation are particularly evident.

In the upstream portion of the Geum River, the issue of water resources management focuses on managing the impact of large trans-basin diversions, minimum instream flow downstream of the dam, and existing water withdrawals in close proximity to the stream. Before the completion of the Yongdam Reservoir in 2001, withdrawals from the Geum River did not produce water quality problems. However after dam completion, the decrease in water quantity and the many requirements, such as downstream senior water rights of dam, minimum instream flow requirements for aquatic habitats and recreational use, resulted in water quantity and quality issues. These excessive diversions have limited the use of stream-flow that can be withdrawn in the stream and have limited the amount of water that can be retained in dam storage, particularly during low flow season. These minimum instream flow requirements, senior

---

[1] Conjunctive management is the management of hydraulically connected surface and groundwater resources in a integrated way, such that the total benefits of integrated management exceed the sum of the benefits that would result from independent management of the surface water and groundwater components (Sahuquillo and Lluria, 2003)

water rights, and trans-basin diversions add much complexity to the evaluation of water resources planning alternatives. A way to solve these problems is through integrated water management that considers stream-aquifer interaction due to well pumping as well as surface water diversions.

1.2 Objectives of Study

The objective of this study is to develop a conjunctive use strategy for the combined reservoir-aquifer water resources system with small and narrow aquifers hydraulically connected to large rivers. It will consider stream depletion due to pumping for irrigation water use, the operation of a multipurpose reservoir dependent on surface and groundwater withdrawals, and downstream flow requirements during a drought. To mitigate the damages of drought, the study focuses on developing the strategic tools through institutional arrangements. This study has the following objectives:

1) Demonstrate the effects of pumping wells by developing the matrix of response coefficients due to the pumping wells near a stream for a stream-aquifer system, considering the effects of recharge;
2) Develop minimum instream flow requirements for fish and the aquatic habitat, considering the hydrologic alterations before and after dam construction;
3) Develop and evaluate a conjunctive use model considering the surface and groundwater withdrawals, minimum instream flow requirements, downstream water demand for irrigation, and efficient reservoir operation to maximize groundwater available for withdrawal during the low flow seasons;
4) Incorporate the results obtained through technical methods into the institutional

arrangements to enhance the potential for conjunctive use of a small aquifer to reduce gaps of understanding between practical and managerial issues.

The significance of this work is to increase understanding of the connections between surface and ground water within a small alluvial aquifer system, show a series of technical and institutional analyses in order to effectively and efficiently manage a limited water source at the basin level, and examine and provide the potential solution for conflicts.

1.3 Dissertation Organization

This study has been organized into seven chapters. Chapter One describes the background and objectives of the study. Chapter Two presents previous works on the analytical and numerical methods of groundwater management problems, reservoir operation, instream flow requirements, and institutional arrangements for conjunctive water use. Chapter Three describes the geological and hydrological characteristics in the case study area; the connectivity between and surface and ground waters; a statement of overall methodology for stream-aquifer interaction, recharge, and optimization programming incorporated in this study; and the development of the response coefficient for the stream-aquifer system. Chapter Four addresses instream flow requirements for fish and the aquatic habitat, and considers the hydrologic alterations produced by the Yongdam Reservoir. The simulation of stream data is also discussed. Chapter Five presents conjunctive management models for the stream-aquifer-reservoir system. In the first section of Chapter Five, the response coefficient matrix for the stream-aquifer system is developed. The objective function and constraints of linear optimization programming and the response coefficient of the conjunctive water management model for stream-aquifer-reservoir system are formulated and analyzed for several scenarios to mitigate damages in times of drought. In the following section, the application of the developed conjunctive use model to the case study area is described. Chapter Six explains institutional arrangements applicable to water management in Korea including the water right system, water management structure, instream flow requirements, and the data management for surface and ground waters. Chapter Six shows the incorporation of the technical results into institutional arrangements, and recommendations of efficient conjunctive management are also discussed. The final chapter summarizes the results and conclusions obtained in this research. In addition to the summary and results, recommendations and future research are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter deals with the fundamental concepts and applied issues concerning stream-aquifer interaction, instream flow, optimal reservoir control, and the institutional aspects of water management. It also touches on the basic concepts of groundwater flow, stream-flow depletion response, the stream-aquifer system, and multi-objective reservoir operating systems. Although there are many available methods for modeling the stream-aquifer with an infinite boundary, the focus is on stream-aquifer interaction with a pumping well in the vicinity of the stream with a finite horizontal extent. Traditional methodologies are presented for the estimation of instream flow and the analysis of institutional arrangements.

2.2 Stream-Aquifer Interaction with Pumping Well near a Stream

2.2.1 Analytical Model

Many analytical solutions are available for computing drawdown and stream depletion caused by pumping in proximity of a stream (for example, Theis (1941), Glover and Balmer (1954), Hantush (1965), Jenkins (1968)). These solutions typically incorporate image well theory to predict the rate at which a pumping well depletes flow in a nearby stream. The solutions are based on simplifying assumptions such as:

1) The stream fully penetrates the aquifer,

2) The stream and the aquifer are hydraulically connected,

3) The streambed is unclogged,

4) The stream is infinitely long and straight,

5) The aquifer underlying the stream is isotropic, semi-infinite in extent, of constant transmissivity, and only horizontal flow (that is, Dupuit flow) occurs in the aquifer.

2.2.1.1 Steady-State Solution

A few analytical solutions are available for stream depletion problems with pumping near a stream in a steady state. However, the stream depletion problem is inherently time dependent. When pumping starts, the well initially obtains its supply of water from aquifer storage. As pumping continues, the well's cone of depression intercepts the stream and drawdown comes to a dynamic equilibrium, with the stream-flow reduced by the rate at which the well is pumping. If under ambient conditions the steam is gaining, it is not necessary for the well to actually reverse gradients and induce infiltration. In this case, it depletes stream-flow simply by capturing some of the ambient aquifer discharge before it reaches the stream as base flow. In fact, as long as the stream and aquifer are hydraulically interconnected, the rate of stream-flow depletion is relatively independent of whether or not the stream is actually gaining or losing and the actual water sources pumped.

Wilson (1993) evaluated induced infiltration[2] in a well pumping in a semi-infinite aquifer, a well between a stream and a barrier, and a well between two streams. The

---

[2] Induced infiltration represents the effects that pumping wells near a stream create at sufficiently pumping rates. With induced infiltration, a stream that is normally gaining becomes a losing stream in the vicinity of the well (Wilson, 1993)

author assumed that the rate of induced infiltration should be greater in a well between a stream and a barrier because of the enhanced drawdown caused by the barrier. The final dimensionless form of the induced infiltration equation for a well between a stream and a barrier is the following equation (2.1).

$$\frac{Q_s}{Q_w}=\frac{2}{\pi}\left[\frac{-X'}{\alpha}+\tan^{-1}\left(\frac{\sinh X'}{\sin\delta}\right)\right]=\frac{-2x'q_a}{Q_w}+\frac{2}{\pi}\tan^{-1}\left(\frac{\sinh \pi x'/2L}{\sin \pi d/2L}\right) \tag{2.1}$$

where, $q_a=(q_L+NL)$ is the ambient discharge toward the stream(lateral inflow is q_L and recharge N);

$\delta=\pi d/2L$ is the scaled dimensionless distance to the well;

$X'=\pi x'/2L$ is the dimensionless stagnation point location;

$\alpha=Q_w/2Lq_a$ is the dimensionless pumping rate;

Q_s is the induced infiltration;

$x'=x$ is the length of stream when the discharge to or from the stream is zero;

L is the width of the aquifer;

d is the distance from the stream to the well.

As a result, the author concluded that the presence of the barrier boundary increases the propensity for and rate of induced infiltration because the well has less aquifer to draw from other sources of recharge.

2.2.1.2 Transient-State Solution

Over a few decades, many models have been developed to assess the influence of adjacent streams on ground water development. Theis (1941) was the first to propose a transient model for the evaluation of stream impacts on pumping activities. This method, later generalized by Glover and Balmer (1954), is based on a series of idealistic assumptions that include a fully penetrating stream and a perfect hydraulic connection between the stream and adjacent aquifer. Jenkins (1968b) extended Glover's method in order to use water management design and water rights adjudication, but most of the analytical solution is developed under the assumption that an aquifer has infinite width. The methods mentioned above, therefore, are difficult to use in practical applications with lateral boundaries. Jenkins (1968b), for example, presented simple curves and tables to estimate stream depletion effects that relate the rate and volume of stream-flow depletion to the rate of pumping at a well. In these solutions, three sources of water contribute to well discharge: aquifer storage, captured discharge, and induced infiltration. The last two components listed are lumped into the stream-flow-depletion term. The curves and tables are all based on the assumption of a homogeneous, isotropic, and semi-infinite aquifer from which a fully penetrating well pumps at a steady rate; water is assumed to be released instantaneously from storage (that is, there is no delayed yield of water). All solutions treat transmissivity of the aquifer as constant with time; thus, for a water-table aquifer, drawdowns are assumed to be negligible compared to the saturated thickness of the aquifer. The stream that forms a boundary of the aquifer is straight, hydraulically connected to the aquifer, and fully penetrates the aquifer.

Jenkins' (1968b) solution assumes that the volume of stream-flow depletion approaches the volume of water pumped by the well as pumping time approaches infinity. Hunt (2003) obtained a solution for flow a well near a stream in an aquifer that extended to infinity of aquifer width. Fox et al. (2003) proposed an approximating solution that estimates aquifer drawdown and stream depletion under saturated/unsaturated hyporheic zone flow conditions and the infinite width of stream-aquifer system.

For the finite horizontal stream-aquifer system which has a finite width, Hunt (2006) and Butler (2001) considered the dependence of stream width, aquifer width, and clogging in the analysis of the interaction of the stream-aquifer system with pumping in vicinity of stream. Butler (2001) developed an analytical model using dimensionless parameters for estimating the drawdown and stream depletion produced by pumping well in proximity of a finite-width stream of shallow penetration. This method shows that the conventional assumption of a fully penetrating stream leads to a significant overestimation of stream depletion in many practical applications. Because the influence of each dimensionless parameter, such as dependence on stream properties, stream width, lateral boundaries, and degree of penetration, on drawdown and stream depletion calculations, is based on the width of stream. Hunt (2006) also developed an analytical solution. His solution differs from in that the distance from the bank of the stream to the pumping well is used as a reference. This method was developed for the calculation of stream depletion involving confined aquifers, but can also be used to depict horizontal unconfined flow in a homogenous aquifer.

2.2.2 Numerical Model

Numerical methods are usually used to evaluate the effects of pumping wells nearby a stream in practical stream-aquifer problems. Since the mid-1960s, numerical modeling has been the principal tool for analyzing the interaction of groundwater and surface water. Most models continue to use a simple Darcy calculation as well as highly idealized stream geometry, to transfer water (seepage) through the stream sediments (clogging) based on head differences between the surface water and groundwater.

McDonald and Harbaugh (1988) developed the three-dimensional, finite-difference model MODFLOW that is a widely used simulation model for the analysis of ground-water-flow systems.

Prudic (1989, 2004) has developed a stream-flow routing (SFR1) package for use with the MODFLOW code to track stream-flow in one or more streams that interact with ground water. This package has five options for simulating stream depth and four computations to model stream diversions. The options for computing stream depth are: a specified value; Manning's equation using a wide rectangular channel or an eight-point cross section; a power equation; or a table of values that relate flow to depth and width. The third approach for simulating stream-aquifer interaction is not a true surface-water flow model but an accounting of stream-flow gains and losses along individual stream reaches whose extents are coincident with model cells.

2.3 Instream flow Requirements

The instream flow requirement has been given various names, including environmental flow (regime), instream flow, environmental allocation and ecological flow requirement. Gustard et al. (1987) described compensation flows which have been set for other purposes such as downstream human uses (e.g. irrigation, hydropower), pollutant dilution and navigation. However, in practice, a particular flow in a river will serve multiple functions.

The first environmental flows were conceptualized as a minimum flow level. Minimum flow levels were based on the idea that all river health problems are associated with low flows and that as long as the flow is kept at or above a critical level the river ecosystem will be conserved. However, it is increasingly recognized that all elements of a flow regime, including floods, medium and low flows are important to ecosystem health (Poff et al. (1997), Hill and Beschta (1991), Junk et al. (1989)). Thus, any changes in the flow regime will influence the river ecosystem. Consequently, if the aim is to maintain a pristine natural river ecosystem, the environmental flow will have to be very close to the natural flow regime. However, most river systems are managed to a greater or lesser extent for human requirements and removal of water from the river for the public water supply, irrigation and industrial processing are essential to mankind's survival and development. In some cases, water is returned to the river after use in the form of non-consumptive uses such as hydropower generation or cooling of industrial plants. In the case of run-of-river hydropower, there may be little effect on flows although upstream water velocities may be affected and scheme itself could interrupt river connectivity.

Since the mid-1970s, methods have been developed to define just what the environmental flow for a given river should be to maintain the riverine ecological integrity (Tharme (1998), Acreman and King (2003)). Each method has advantages and disadvantages which make it suitable for a particular set of circumstances.

The approaches developed in various countries around the world to define environmental flow allocations can be divided into four categories (Acreman and Dunbar, 2004): 1) Look-up tables, 2) Desktop analysis, 3) Functional analysis, and 4) Hydraulic habitat modeling. Look-up tables have been adopted to determine simple operating rules for environmental flow setting for dams or off-take structures where few or no local ecological data are available. Desktop analysis focuses on the analysis of existing data such as data from hydrological models. An example of a desktop method is the Range of Variability Approach (RVA, Richter et al., 1996). Functional analysis builds on understanding the functional links between several aspects of the hydrology and ecology of the river system. An example of functional analysis is the Building Block Methodology (BBM) developed in South Africa (Tharme and King, 1998). Hydraulic habitat modeling uses habitat for target species as an intermediate step; this method considers the environmental niche required by an individual animal or plant living in a river, and takes into account that physical aspects of river habitat are affected by changes to the flow regime.

2.4 Conjunctive Management Model of Stream-Aquifer-Reservoir Systems

2.4.1 Groundwater Management Models

The response-matrix approach was first described in petroleum engineering literature by Lee and Aronofsky (1958) and subsequently first applied to groundwater by Deniger (1970). This method is based on the principle of superposition of linear systems. The hydraulic head at any node in the model can be expressed in terms of the initial head and the sum of unit responses to pumping at each well location during each time step. The groundwater simulation model is considered independent of the optimization model to develop a set of fixed response equations or a response matrix that is incorporated as part of the LP constraint set. For unconfined aquifers, changes in the saturated thickness with pumping result in a nonlinear relationship between pumping and head. Reilly et al. (1987) showed that this could be ignored where changes in transmissivity are less than 10%, otherwise the nonlinearity requires an iterative solution procedure (Heidari, 1982). Mixed integer programming combined with the response matrix approach has been used to determine optimal well locations. Examples of the response–matrix approach for water supply are Maddock (1972, 1974), Morel-Seytoux and Daly (1975), Illangasekare and Morel-Seytoux (1982), Heidari (1982) and Willis (1984). The embedded approach is best suited for small or steady-state problems. In comparison, the response matrix approach yields overall information about the response of the system but is usually much less computationally demanding because of the response matrix being of smaller dimension than the discretized governing equations.

2.4.2 Reservoir Operation during Drought

A multi-purpose reservoir is operated for purposes such as hydropower production, flood control, navigation, fish and wildlife enhancement, recreation, and as water supply for an agricultural, municipal, and industrial water supply. The complexities of multi-purpose reservoir operation require release decisions to be made. In terms of water supply, water can be either released for beneficial uses or stored in the reservoir for possible future drought seasons. It is becoming increasingly important to deal with water resources efficiently and to reduce the conflicts for the limited available water during these droughts. One of the most common measures implemented during droughts is water supply rationing, which reduces demand and stores more water for future use. In order to avoid the occurrence of one severe and sudden water shortage, water managers prefer to store more water and create a sequence of smaller water shortages before impending drought. This is called hedging in reservoir operations (Maass et al., 1962). Good hedging can reduce the possibility of a high-percentage-single-period water shortage. Unnecessary hedging, however, increases more frequent small shortages that deteriorate water supply reliability.

Hashimoto et al. (1982) pointed to new directions in the analysis of risk in reservoir operation, focusing on the importance of risk criteria in addition to the traditional reliability of failure, and proposed several alternatives for measuring these risks. However, these measures were not combined into optimization models of reservoir operation.

Moy et al. (1986) presented the multi-objective linear model into which they incorporated performance measures such as reliability, resilience and vulnerability. They note that as reliability increases or as the maximum length of consecutive shortfalls decreases, the vulnerability of a water system of larger deficits increases.

Shih and ReVelle (1994) developed a continuous linear hedging rule for a single water supply reservoir. They formulated a nonlinear mixed integer programming model that minimized the maximum deficit considering a constant demand. After obtaining the optimal rule, they converted the continuous hedging rule into multiple discrete hedging rules, which are more appropriate for the solution of practical water resources problems. Shih and ReVelle (1995) developed a multiple hedging model using mixed integer programming for a single water supply reservoir. The primary purpose of the model was to maximize the number of months in which no water rationing is required and to minimize the trigger volumes at which rationing is occurred.

Srinivasan et al. (1999) developed the mixed integer programming model in which spill-deficit constraint was added to control spills in relation to reservoir capacity and storage. Their mixed integer programming model was fundamentally the same formulation developed by Moy (1986).

Draper and Lund (2004) maximized the sum of immediate and carryover storage benefits to derive the optimal hedging rule. This carryover storage value function describes the expected value of future economic benefits or other benefits by keeping water in the reservoir when it otherwise could be released.

Shiau and Lee (2005) derived optimal reservoir hedging rules that minimize two competing shortage features such as the short- and the long-term water shortages. They used a multi-objective programming technique called compromise programming to derive the optimal hedging rules.

2.4.3 Coupled Simulation-Optimization Models

Simulation models combine mathematical equations for physical processes with predefined rules for management decisions to determine step-by-step system operation for a deterministic sequence of inflow data. Through repetitive model runs the system response to various operating rules or strategies can be mapped. For conjunctive use these include put and take rules, extraction and recharge rates and ground water storage capacities. Though simulation allows the physical system to be represented in greater detail than other mathematical techniques, determining optimal rules and management decisions is often a time-consuming trial and error affair.

Optimization models use mathematical techniques to determine management decisions that maximize or minimize a stated quantifiable objective subject to the physical governing equations and any imposed operational constraints. Objectives might be system yield, system reliability, or economic performance. For the majority of optimization models, optimal operating rules and required system (well) capacities must be deduced from the prescribed system operation. To remain computationally tractable, it is common that optimization models must greatly simplify the system being modeled.

The majority of conjunctive use optimization models in the literature use Linear Programming (LP) solvers. Integer LP may be required for determining optimal well locations and representing well development costs.

Complex groundwater management decisions require groundwater to be represented at a level of detail afforded only by simulation models. Often this requirement has led to the development of separate groundwater simulation and surface water optimization models. The models either exchange data at time steps determined by the needs of the surface model, usually monthly or annually, or the response characteristics of the groundwater model are incorporated into the surface water model using the response matrix approach. Young and Bredehoft (1972) developed a coupled groundwater-surface water model to study conjunctive use schemes in the South Platte Valley in Colorado. The surface water model included a LP agricultural production model. For a given stream-flow and policy the surface model determined a set of monthly diversions and groundwater pumping that maximize revenues from irrigation subject to stream outflow requirements and predetermined well capacities. At each time step the groundwater model was run to determine aquifer recharge from irrigation and groundwater stream accretions. These become fixed inputs for the next time step of the surface water model.

Danskin and Freckton (1992) analyzed the problem of high groundwater levels in the San Bernardino Valley, California caused by a decrease in agricultural pumping. Linear programming was coupled with a transient pseudo three dimensional aquifer model to determine the most efficient pumping policy. Lall and Lin (1991) developed a management model for Salt Lake Valley, Utah. The objective is to minimize the annual cost of groundwater supply subject to drawdown, water rights and water quality restrictions.

Lall (1995) used a hybrid simulation-optimization approach for planning surface storage and groundwater development on the Jordan River in Utah. A reservoir yield model was used to identify the required reservoir capacity as a function of firm yield. A unit response matrix describing changes in head with pumping was developed from a separate groundwater simulation model. These model outputs were combined into a least-cost optimization model for resource development. The nonlinear optimization problem was solved using penalty successive linear programming. The author notes that the conjunctive use of groundwater leads to quite different optimal reservoir sizes and well capacities. Lall's approach uses a deterministic reservoir yield model based on the critical period. A standard linear operating policy is followed with no consideration of hedging.

Fredericks et al. (1998) developed a decision support system for conjunctive management of surface water and groundwater under the Doctrine of Prior Appropriation which most western states in USA follow. This system was built around the generalized river basin network flow model MODSIM. This model consists of three components: the database management subsystem, the model base management subsystem, and a dialog generation and management subsystem. This model was applied to the South Platte River in Colorado using two different sets of response coefficients: 1) numerical coefficients calculated using the MODRP finite-difference groundwater model, and 2) analytical coefficients calculated with the Glover equation (1968) using the values of a predefined stream-depletion factor (SDF). The results of the application indicates that use of analytically based SDF coefficient produces lower net river return flow values when compared with the values from the numerically based finite-difference coefficients. This difference is primarily attributed to improved inclusion of tributary inflows in the simulation using the MODRSP finite-difference coefficients.

Belaineh et al. (1999) present a water resources management model that explicitly accounts for conjunctive use of groundwater in determining optimal reservoir operating rules. The model represents a reservoir-stream-aquifer system that supplies a collection of separate irrigated areas. Groundwater response to recharge and pumping is calculated using the response matrix approach. Matrix coefficients are determined from a separate three-dimensional groundwater simulation model. The authors determine parameters for S- and S-Q type linear decision rules that maximize water supply from surface and groundwater sources subject to various management constraints. The model is solved using linear programming. This approach has the advantage of a detailed representation of groundwater (through it is restricted to confined aquifers or unconfined aquifers of sufficient depth). Economic values for water use and cost of groundwater pumping could easily replace the existing objective of yield maximization. The main drawback is the use of monthly linear decision rules that result in an over-simplistic reservoir operation.

Basagaoglu et al. (1999) present a nonlinear simulation-optimization model to determine optimal polices for a reservoir-stream-aquifer system that supplies an agricultural region. A goal-programming approach is used to define a mixed objective of minimizing operating costs and minimizing weighted deviations from predefined reservoir storage targets. The nonlinearity due to the pumping cost is solved using separable programming and piecewise linear approximations of the resulting quadratic functions. Monthly demands are fixed rather than a function of the cost of water so that the resulting operating policies may not be optimal under drought conditions. Penalties of weights for deviation from target storage are arbitrarily fixed and do not represent the relative benefits of storage versus releases. Basagaoglu et al. (1999) extend the concept of rule curves that have been used for surface reservoir operations to stream storage. It could similarly be extended to groundwater to maintain levels within an environmentally sound range.

Jenkins et al. (2001) developed California Value Integrated Network Model (CALVIN) that is a network flow model based on an economic-engineering model. This model achieves optimal conjunctive use operation by maximizing the net economic benefits of water deliveries to agricultural and water users within the limits of the infrastructure, and considering environmental and other constraints. CALVIN could be applied to integrated long-term regional and statewide planning, integrated supply and demand data management, preliminary economic and financial evaluation, planning, and operations studies.

The sections above have described the basic problem definition, numerical models, and simulation/optimization methods for conjunctive use of stream-aquifer-reservoir systems. Each conjunctive-management model consists of an objective function, a set of design constraints, and decision (or control) variables. For this study, the design objective are to maximize sustained yields from a set of pumping wells to meet agricultural demand, to maintain the required minimum instream flow for ecological health, and to determine the optimal reservoir release rule for drought conditions. The decision variables are reservoir release and trigger volume, the minimum instream flow requirement, rates of ground-water withdrawals, and reservoir release for specific periods. The objectives are often constrained by pumping capacities, available drawdown, allowed stream-flow depletions, minimum instream flow requirement, and allowed reservoir release conditions.

The solution of stream-aquifer conjunctive-management models requires the linkage of the physical stream-aquifer system as represented by an analytical or numerical model with optimization methods. Both linear and nonlinear optimization methods have been used in stream-aquifer-reservoir systems.

2.5 Institutional Arrangements for Conjunctive Use

Conjunctive use is a comprehensive water management method that co-ordinates surface and groundwater operation. The inscrutable physical and legal nature of groundwater makes it difficult to quantify in institutions. Groundwater basins have ill-defined limits, natural recharge cannot be measured directly and records of groundwater use are seldom complete. The lack of data for groundwater is compounded by the absence of understanding of how to use these data. Much of groundwater is extracted by individuals especially farmers for irrigation in dry seasons and is not regulated or managed by governmental or local agencies. Managed development of groundwater has focused on the concept of safe-yield and mining. However these simple concepts ignore the dynamics of the system and have resulted in water policies that deplete groundwater, dewater streams and damage wetlands. Under natural conditions groundwater basins are in long-term equilibrium; recharge is balanced by aquifer discharges to streams. Groundwater pumping may initially deplete the aquifer and if groundwater levels are to stabilize extraction must be balanced by long-term increases in induced recharge or decreases in aquifer discharge.

The success of conjunctive use lies in exploiting differences in the characteristics of surface and groundwater. In Korea, surface water is available seasonally in form of summer rain. In agricultural areas irrigated by surface water, underlying aquifers are recharged primarily by irrigation return flows. In this situation groundwater often acts as a contingent water sources used in the dry season to buffer variations.

Management of surface reservoirs typically is guided by formalized operating rules. These vary from simple release rules as required when storage levels in a reservoir infringe on the flood control space or more complex rules that balance storage between reservoirs, determine delivery deficiencies in dry seasons and set storage targets. A successful conjunctive use scheme requires the definition of similar operating rules.

The legal status of groundwater affects its use and management. Groundwater has no single legal meaning. Various categories are recognized by different laws, including mineral water; artesian water; tributary water, percolating water and seeping water. Although the inter-dependence of surface and groundwater is now recognized, groundwater law has evolved under the premise that surface and groundwater are distinct entities.

Falling water levels and deteriorating water quality have resulted in concern over how groundwater resources should be managed. In general the property rights apply to the use of water rather than the water itself.

Maknoon and Burges (1978) present general characteristics and a literature review of conjunctive ground-surface systems outlined in an attempt to develop a systematic approach for analyzing such systems. The complexity of conjunctive management factors is shown in the interaction matrix shown in Table 2.1. Eleven aspects associated with conjunctive use management systems have been included, with the rows representing the affectors (causative factors) and the columns the affectees (items influenced by affectors).

Bowmen (1990) presents a specific example of management doctrine for groundwater where designated groundwater management areas are used to address groundwater quantity issues. The author suggested that the definition of groundwater management areas should include the following two factors: 1) specific legislation either designating management areas or enabling the designation of areas, and 2) regulation of groundwater withdrawal within management areas. Other mechanisms used in states to control groundwater withdrawals are use permit requirements, water use monitoring and reporting, the well spacing requirement, well construction standards, prioritized allocations, and restricted usage in times of shortage.

Moigne et al. (1994) states that the term “institutions” refers to both the set of rules governing water development use and the specific organizational arrangements involved in the formulation and implementation of water resources laws, policies, strategies and programs.

Howe (2002) presents five brief case studies illustrating conjunctive use. The lack of coordination between groundwater and surface water management in conjunctive use management create problems due to the division of regulatory power among different agencies. The lack of institutional arrangement, therefore, inhibits efficient conjunctive management.

Table 2.1 Interaction Elements of General Conjunctive Use Systems

Affector	Affectee										
	Level of the Problem	Nature of the Problem	Physical System	Legal System	Econo-mic System	Objec tive(s)	Data	System Policy	Optimal Criteria	Social Criteria	Optimal Policy Imple-mentation
Level of the Problem			•	•	•	•	•	•	•	•	•
Nature of the Problem	a		b	•	•	•	•	•	•		•
Physical System		•				•	•	•	•		•
Legal System	a				c	•	•	•	•		•
Economic System		b				•	•	•	•		
Objective(s)						•	•	E			•
Data		f	f	f	f	f	f	•			f
System Policy							•	•	•		
Optimal Criteria					g	•	•				•
Social Criteria	•					•	•	•	•		•
Optimal Policy Implementation						•	•	•	•		

Notes:

a. Determines agencies and publics that are involved.
b. Determines what parts of the physical system are of interest
c. Interpret as constraints on water transfer
d. Economic demand may contribute significantly to the physical problem.
e. The overall objectives define the type(s) of model(s) to be used.
f. Data availability or collectability can be overriding constraints.
g. The optimal policy may cause a significant change in economic activities

Source: Maknoon and Burges (1978)

The United Nations (UN) presents a comprehensive approach used to solve complexities in groundwater management. The UN recommends the following to simplify arrangement;1) collaborative initiatives in groundwater management (which involves the development of a detailed research program to gather groundwater data directly from governments and other sources, and focus on the development of adaptive responses to water problems and policy approaches), 2) rethinking the approach to groundwater management (that the alternative approaches are essential in order to address the types of problems now emerging), 3) basic research, groundwater monitoring and data collection, 4) data dissemination and access, and 5) integrated management in strategic locations.

Grigg (2004) presents institutional analysis of the water quality problem in distribution systems through the gap analysis. Five questions are identified as follows: 1) who has control?, 2) what are the laws and controls?, 3) what are the incentives?, 4) who has what role?, and 5) what is the management culture?. A three-step process is then applied to improve institutions for the water distribution system: 1) Situation analysis involves a conceptual model of how the management and control system work (what goes on here?); 2) Needs analysis that involves identification of the key issues in each category of institutional element (what processes need adjustment?); and 3) Gap analysis which identifies institutional practices that should lead to improvement (what ought to go on here?). This promising approach would begin with a technical analysis, proceed to management analysis, then to the institutional issues that influence the potential for success.

Zekster and Everett (2004) present a few key types for groundwater management strategies based on aquifer types such that building a typology appears to hinge on two main criteria: storage-flow ratios and the interrelationship between aquifers and surface watercourse with high variability. For example, average storage-average flow ratio, that is, the capacity of the reservoir of an irregularly recharged aquifer to regulate overall flow (which expressed in overall turnover time) can vary from under a year to somewhere to 10^5 years in the case of deep aquifers; interrelationship between aquifers and surface rivers or streams can range from very strong, steady and continuous linkage (narrowly spread alluvial groundwater bodies connected to unclogged watercourse) to full independence (confined deep aquifers or some coastal aquifers). Table 2.2 shows types of aquifer systems and related management conditions.

Schlager (2005) recommended replacing prior appropriation with a permitting system through analyzing the relationships of surface development and governance, groundwater development and governance. According to Schlagar, The prior appropriation system selected in three western states should be dispensed with entirely and replaced with a permitting system that is not based on priority when excessive surface diversions occur.

The importance of managing surface water and groundwater as a single resource is becoming increasingly evident. A major advantage of groundwater as a source of supply arises from the buffering effect of aquifer storage in relation to climatic variability and changing demand. An important aspect of groundwater in drought conditions is the time-lag between recharge and response of surface waters. Acts and laws related to groundwater and surface water must be recognized as a single source instead of two sources.

Table 2.2 Types of Aquifer Systems and Related Management Conditions

Type of aquifer system	Linkages to surface water	Sensitivity	Suitable pumping regime	Constraints
Alluvial (in most cases unconfined) aquifer. Limited expanse and storage capacity. Low regulating capacity	Strong. Two-way aquifer/river exchange possible.	Sensitive to watercourse development and land use. Vulnerable to pollution from surface and boundary watercourses.	Regime 1. Short term equilibrium. Overbalance permitted by induced inflow from rivers. Management mainly flow.	External: clogging of banks, low-flow discharge conservation. External: spring and low-flow watercourse discharge conservation
Shallow, lowland/plateau or Karst aquifer. Large reservoir (storage often >10times average annual flow). Good regulating capacity. High hydro-dynamic inertia.	Broad, one-way linkage: drainage via rivers (which may disappear in Karst zone). Density differs with hydrographic structure.	Sensitive to variable inflows during periods of drought, etc. Sensitive to land use. Vulnerable to pollution above all diffuse	Regime 1 or 2. Long-term equilibrium. Management: flow and regulating storage.	External (upper-layer unconfined aquifers): spring and low-flow watercourse discharge conservation
Multi-layered system of interconnected shallow and semi-confined aquifers. Large reservoirs (storage > 100 to 1000 times average annual flow). Partial regulating capacity. Variable inertia	Variable: restricted to upper-layer unconfined aquifers.	Sensitive to land use(upper-layer unconfined aquifers). Vulnerable to pollution. Risk of aquifers holding different quality water becoming interconnected by boreholes.	Regime 2. Equilibrium may be restored after a long period of disequilibrium. Management: flow and storage at start, then just flow.	Internal constraints (confined aquifers): drawdown only possible within max. acceptable limits.

Source : Zekster and Everett (2004) pp 312

CHAPTER 3

METHODOLOGY AND RESPONSE CHARACTERISTICS OF THE CASE STUDY

3.1 Introduction

This chapter describes the methodology and the response characteristics of the case study. In addition to the characteristics of the case study, it addresses the connectivity between surface and ground waters, the methodology for stream-aquifer interaction, recharge, and optimization in the study, and the development of response coefficient for the stream-aquifer system.

The chapter is organized into five sections in addition to the introduction. Usually, the methodology would be introduced before the case study, but in this study the attributes of the case study are used to explain the methodology and will be presented first. Next, the methodology is presented to show the full picture of the analysis. Then, analysis of connectivity between surface and ground waters is presented. In the fourth section, the analysis of stream-aquifer system is described. Final section summarizes the topic and results.

3.2 Geological & Hydrological Conditions

3.2.1 Geological & Hydrological Conditions in Korea

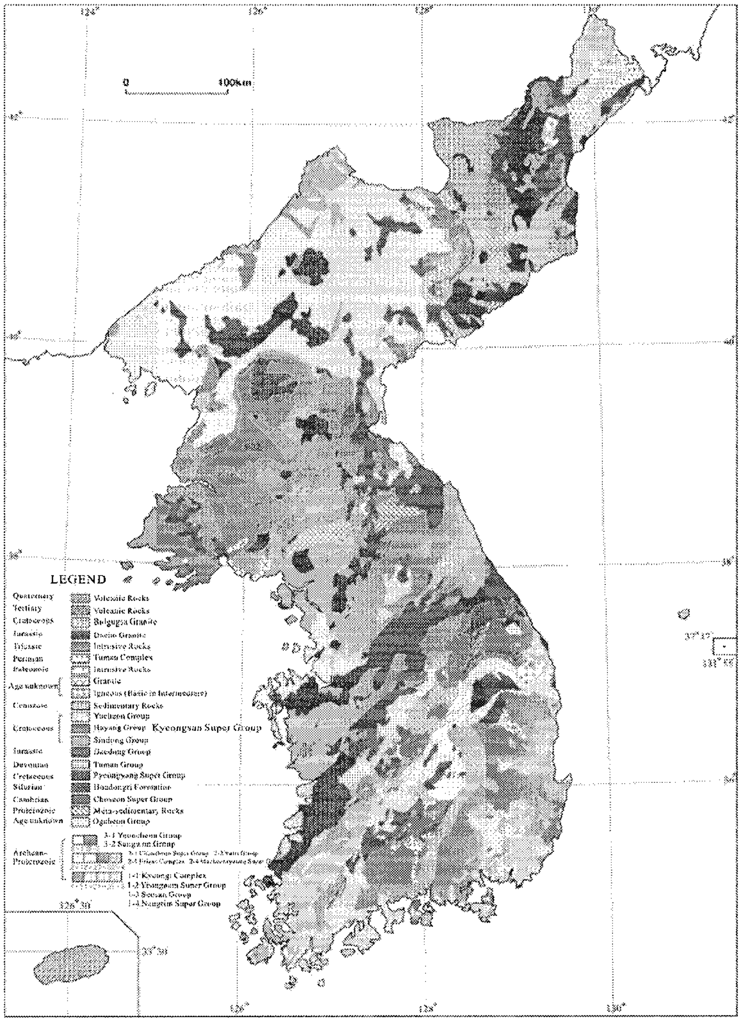
Geological Conditions

The geology of Korea is comprised mainly of granite, gneiss, schist, limestone, and metamorphic sedimentary rocks. Metamorphic sedimentary rocks were largely formed in the pre-Cambrian and the Paleozoic eras, while geologic layers in the Cenozoic era are rare. Figure 3.1 shows the geologic composition of the Han Peninsula. The pre-Cambrian metamorphic sedimentary rocks are distributed mainly in central parts of North Korea and in the northern and central parts of South Korea. Two Paleozoic layers that extend over a large lateral area are visible in southern parts of North Korea and in eastern parts of South Korea. The geologic layers in Tertiary of the Cenozoic era outcrop along the east coastal line in the northeast parts of North Korea. Granite and gneiss cover about 60 % of the total surface of the Han Peninsula (Lee et al., 2006).

Two main types of aquifers exist in Korea, the shallow alluvial aquifers along the main rivers and deep bedrock aquifers. Shallow aquifers cover 28% (27,390 km^2) of Korea and are distributed along the main rivers. The thicknesses of shallow aquifers range from 2 to 30m with groundwater yields from 30 to 800m^3/day for each well installed. The transmissivity and storage coefficient of these shallow aquifers are 50 – 2,000 m^2/day and 0.1 – 0.01, respectively (Ministry Of Construction & Transportation (MOCT) and Korea Water Resources Corporation (KOWACO), 2004). These shallow aquifers are the main source of irrigation water supply for most of the rural areas during drought seasons. Shallow aquifers are recharged by infiltration from precipitation during the wet season, but they are very vulnerable to groundwater pollution.

Bedrock aquifers are normally comprised of faults, fractures, joints or boundaries of rocks formed by tectonic movement; these aquifers are generally overlain by shallow aquifers. Groundwater yields of this type of aquifers vary greatly within a range from 10 to 5000 m^3/day. Continued increases in the demand for clean water force groundwater wells to be dug deeper and deeper; consequently bedrock aquifers are becoming more important in Korea, as most drinking groundwater depends on bedrock aquifers.

Table 3.1 represents eight hydrological units in Korea based on the groundwater yields, geologic ages and units, lithology topologic conditions, as well as opening types (KOWACO, 2002). Unconsolidated sediments, porous volcanic rocks, and limestone units produce high groundwater yields, whereas metamorphic units have low yields.



Source: Korea water Resources Corporation (KOWACO, 2002)

Figure 3.1 Geological Map of the Han-Peninsula

Table 3.1 Hydrogeologic units in Korea

Hydrogeologic units	Geologic ages and units	Lithology	Topology	Opening type	Groundwater yield(m^3/day)
1. Unconsolidated sediments	Quaternary sediment	Clay, silt, sand, gravel	Plain, Valley	Pore	100 – 3000
2. Porous volcanic rocks	Quaternary volcanic rocks	Basalt, trachybasalt, tuff	Plateau, hill	Vesicle, fracture, lava tunnel	1000-5000
3. Semi-consolidated sedimentary rocks	Quaternary marine sedimentary rocks Tertiary sedimentary groups	Semi-consolidated shallow marine-non marine sedimentary rocks with interbedded volcanic rocks	Hill	Pore, fracture	10-2000
4. Non-porous volcanic rocks	Tertiary to Cretaceous volcanic rocks	Rhyolite, andesite, basaltic andesite, tuff	Mountain	Fracture	10-1000
5. Intrusive rocks	Cretaceous Bulguksa granites Jurassic Daebo granites Paleozoic to Triassic intrusive rocks	Granite, diorite, gabbro, foliated granite, hypabyssal rocks	Hill, mountain	Fracture	50-1500
6. Clastic sedimentary rocks	Cretaceous Gyeongsang groups Triassic to Jurassic Daedong groups Carboniferous to Triassic Pyeongan groups	Shallow marine-non marine sedimentatry rocks	Mountain	Fracture	50-2000
7. Limestone	Cambro-Ordovician great limestone group	Marine carbonate rocks with interbedded clastic sedimentary rocks	Karst, mountain	Fracture, cavern	100-5000
8. Metamorphic rocks	Carboniferous to Permian Pyeongan groups Cambrian Yangdeok group Okchoen group Pre-Cambrian schist and gneiss complex	Schist, quartzite, phyllite, slate Gneiss, schist, granitic gneiss, basic plutonic rocks	Mountain Hill, mountain	Fracture	50-500

Source: MOCT and KOWACO (2002)

Climate

The climate of Korea is characterized by four distinct seasons: spring, summer, autumn and winter. The contrast between winter and summer is striking. Winter is bitterly cold and is influenced primarily by the Siberian air mass, while summer is hot and humid due to the maritime Pacific high. The transitional seasons of spring and autumn are sunny and generally dry. Temperatures of all seasons are somewhat lower than those at the corresponding latitudes in other continents. The variation of annual mean temperature ranges from 10 degrees Celsius to 16 degrees Celsius except for the mountainous areas where elevation affects temperature. August is the hottest month with the mean temperature ranging from 23 degrees to 27 degrees Celsius. January is the coldest month with a mean temperature ranging from -6 degrees to 7 degrees Celsius.

Annual precipitation is from 500 to 1,500mm in the central region. More than half of the total rainfall is concentrated in summer, while precipitation in the winter is less than 10% of the total precipitation. Annually, about 28 typhoons occur in the western Pacific. Generally speaking, only two or three among them approach the Korean Peninsula from July through September.

The monsoon front approaches the Korean Peninsula from the south in late June, moving gradually to the north. Rainy season is called the "Jangma" season in Korea and generally lasts for a month from late June until late July. A short period of rainfall comes in early September when the monsoon front retreats back from the north. This rain occurs over a period of 30 days from June through July and is distributed over South Korea, with only some lag in time at different stations. This short burst of rainfall accounts for more than 60% of annual precipitation at most stations.

3.2.2 Issues of Water Management in Case study Area

With the modernization and urbanization of cities, there is more demand for water to meet the increasing levels of life; this increased demand results in inevitable conflicts between stakeholders in the use of limited water resources. Similarly, since the completion of dam construction, conflicts have arisen in water use between water demands downstream of Yongdam Reservoir and trans-basin water supply in Jeonju. People in the downstream area are concerned about the water quality in the Geum River which in turn depends on the release of water from the reservoir and the amount of trans-basin water transferred to Jeonju. Downstream users, cities, and associated agencies have argued that the required minimum flow is 12m^3/sec based on the population density, downstream sub-basin area, and instream flow required for fish and aquatic habitat. However, the opposing stakeholders, including the Korean government and basin-transfer users have suggested that the value of downstream instream flow is adequate at 5.0m^3/sec. The survey of the Geum River Basin (MOCT/KOWACO, 1998) reported that the historical minimum drought flow was 2.25m^3/sec at Yongdam Reservoir, which was sufficient for the vested appropriation. Downstream stakeholders, including non-governmental organizations (NGO), require more water to meet demands and achieve instream flow requirements in order to conserve fish and aquatic habitat.

The water supply in the Geum River was seriously affected by two severe droughts in 2001. In the fall of 2001, Daechung Reservoir reached its lowest storage level since the beginning of reservoir operation. The intensity and magnitude of drought in this basin brought about conflicts among stakeholders. Furthermore, instream flow requirements, regional water needs, and trans-basin diversion made conflicts far worse.

3.2.3 Base Conditions in the Case Study Area

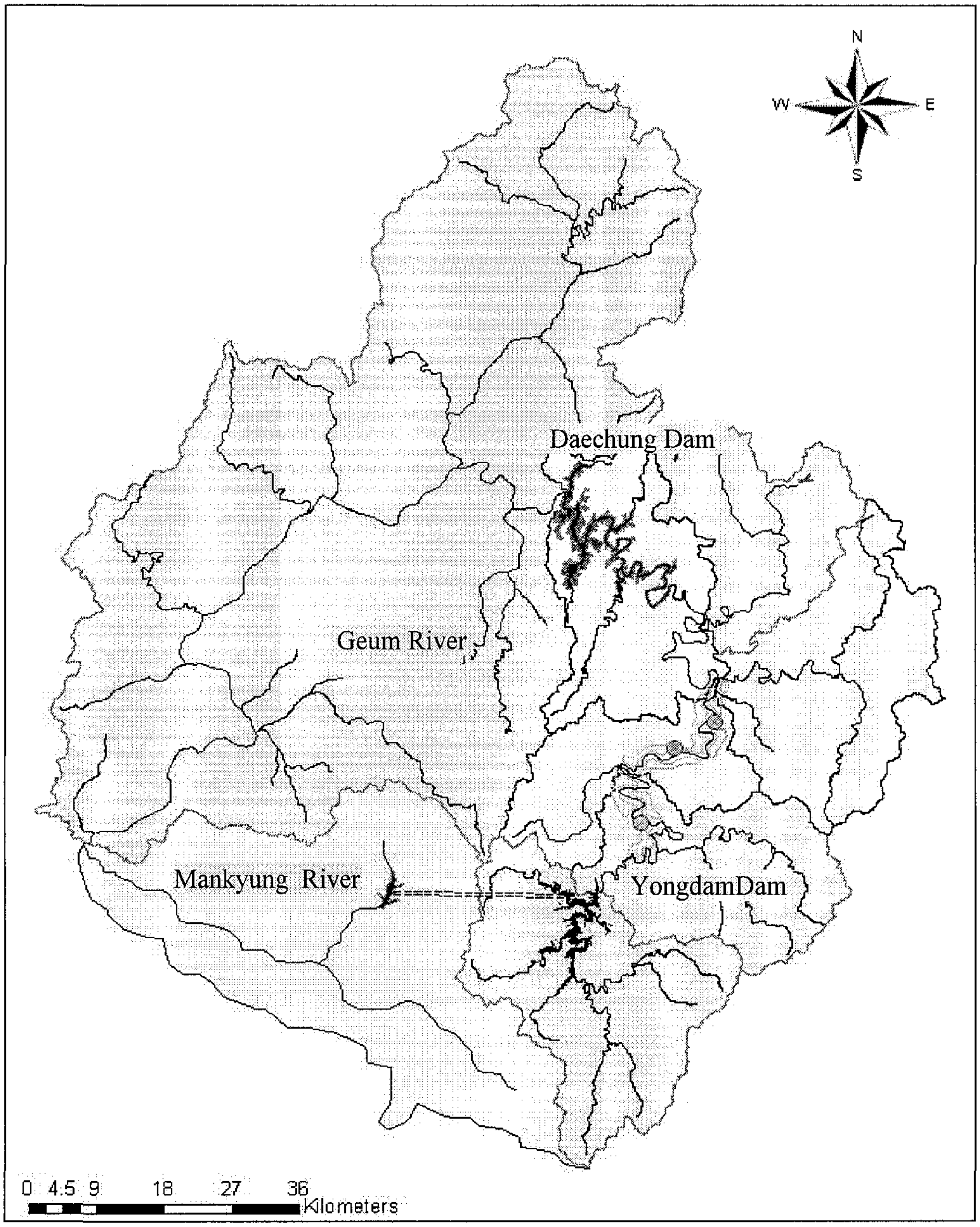
The case study area selected to evaluate conjunctive management is the upstream region of the Geum River basin. The Geum River is one of four major rivers in Korea and its flows are controlled by two multi-purpose reservoirs, Daechung Reservoir and Yongdam Reservoir. Figure 3.2 shows the Geum River basin located in the middle of Korea; it has a drainage area of 9,810km^2 and a main-stream length of 396km. This river is crucial in all aspects of water supply, flood control, and environment for several areas in South Korea.

Table 3.2 lists the characteristics of Daechung Reservoir and Yongdam Reservoir. About 75 percent of this area is covered with mountains and forests; the balance is composed of agricultural lands, cities, streams and reservoir surface water. The annual supply of water from Dacheong Reservoir and Yongdam Reservoir is 1,649 million m^3 and 650 million m^3, respectively.

Table 3.2 Characteristics of Multi-purpose Reservoirs in the Geum River Basin

Reservoir	Basin Area (km^2)	Height (m)	Capacity (10^6 m^3)	Eff. Capacity (10^6 m^3)	Power (kW)	Inflow (m^3/s)	Water Supply (10^6 m^3)
Daechung	4,134	72	1,480	790	90,000	88.6	1,649
Yongdam	930	70	815	672	24,400	26.5	650

Source: www.wamis.co.kr



Source: Cha (2007)

Figure 3.2 Map of the Geum River Basin

Characteristic climate features of the study area are a flood season during summer and a periodic drought between fall and late spring. Table 3.3 lists the monthly mean precipitation and inflow data for Daechung Reservoir and Yongdam Reservoir. The mean annual precipitation of Daechung Reservoir for 24 years was 1,203.0mm, while that of

Yongdam Reservoir was relatively larger, 1,693.3mm due to the influence of Typhoons "Rusa" and "Maemi" in 2002 and 2003. The mean annual inflow of Daechung Reservoir was 88.6m^3/sec for 25 years from 1981 to 2005. Yongdam Reservoir inflow is 26.5m^3/sec for three years from 2002 to 2005. In Figure 3.3, which was plotted to compare the monthly average precipitation for that time, this illustrates the monthly average precipitations of Daechung Reservoir and Yongdam Reservoir. It also illustrates that monthly precipitation is unevenly distributed over the year with a minimum of 26.5mm and a maximum of 275.3mm. Over 65 % of the average annual precipitation takes place between late June and September. As stated in the previous section, the monsoon characteristics of the South Pacific Ocean dominate the weather over this period. The monthly average inflows of the Daechung Reservoir and the Yongdam Reservoir were obtained after the completion of both reservoirs construction and are plotted in Figure 3.4. Figure 3.4 shows the monthly average inflow of the Daechung Reservoir is greater than that of the Yongdam Reservoir. Like the average monthly precipitation, the monthly average inflow is intensively concentrated during the flood season.

Table 3.3 Monthly Average Precipitations and Inflows of the Daechung Reservoir and the Yongdam Reservoir

(Unit: mm, m^3/sec, 10^{6}m^3)

Div.		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Precipitation	DC[1]	29.0	33.4	46.6	70.5	81.9	159.6	275.3	253.5	132.6	49.5	44.7	26.5	1203.0
	YD[2]	39.1	33.6	45.4	165.4	131.1	144.3	368.5	480.7	173.4	25.0	48.9	37.9	1693.3
Inflow	DC	19.8	28.6	44.1	54.6	52.2	94.9	277.8	223.9	169.0	41.9	26.5	23.7	2792.8
	YD	4.6	7.7	8.9	23.3	18.2	23.2	99.6	66.3	50.0	4.8	4.2	4.5	834.0

Source: www.wamis.go.kr

1: DC means the Daechung Reservoir

2: YD represents the Yongdam Reservoir

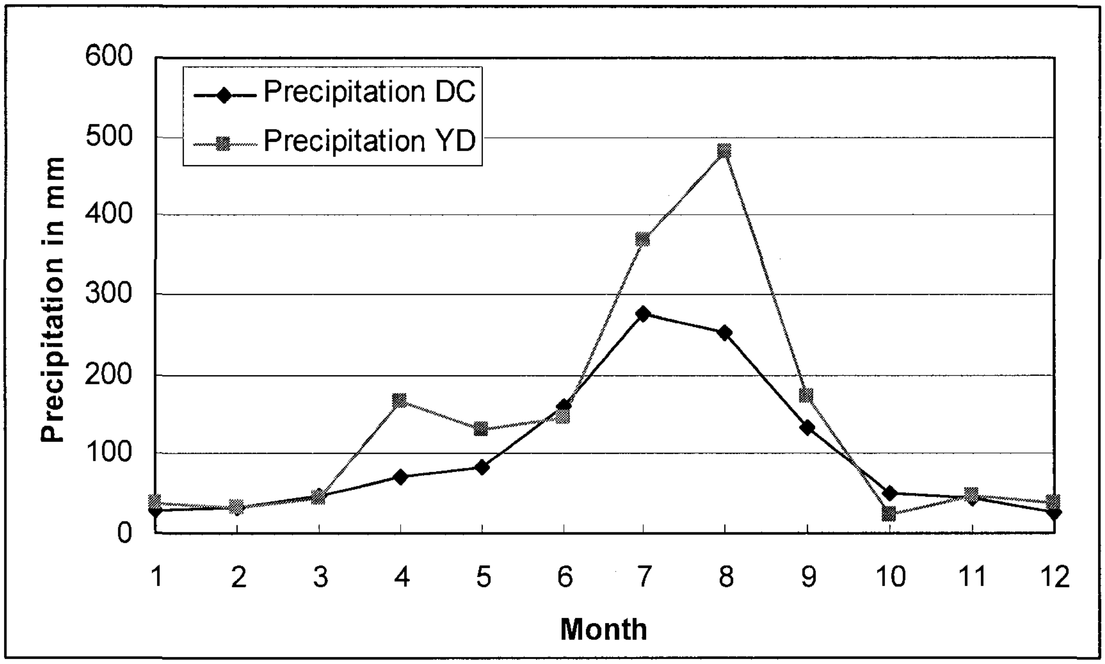


Figure 3.3 Monthly Average Precipitations of Daechung and Yongdam

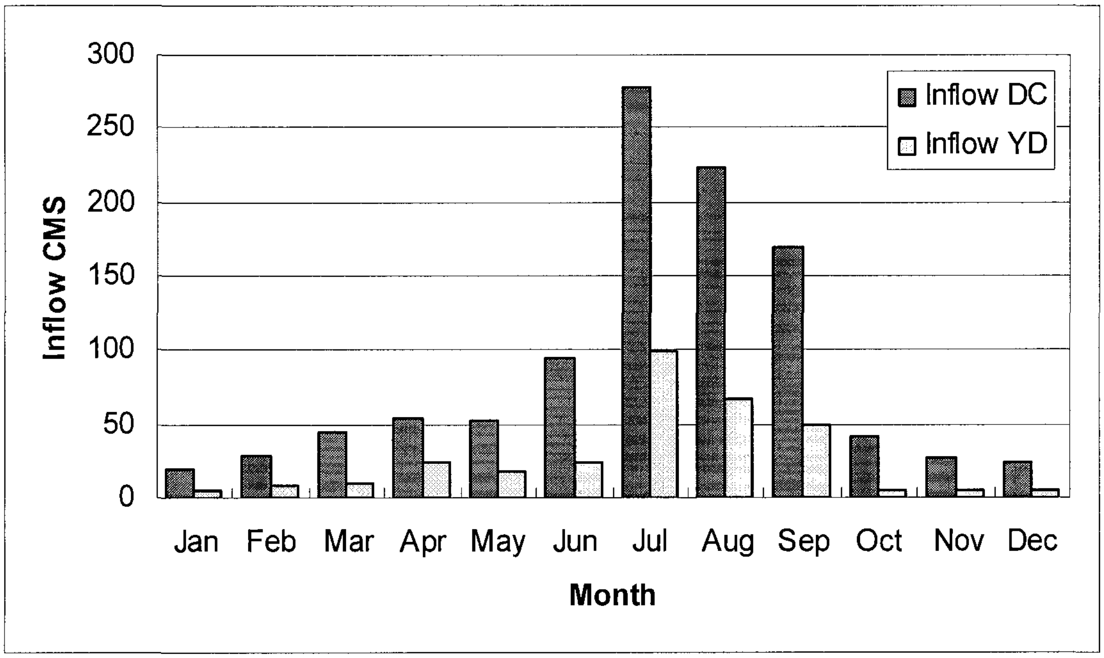


Figure 3.4 Monthly Average Inflows of Daechung and Yongdam

3.3 Methodology

As described in Chapter One, this research focuses on the conjunctive use of narrow, small aquifers and multi-purpose dams in determining water resource management strategies during times of drought. Aquifer recharge, surface and ground water withdrawals and downstream instream flow requirements are considered, as wells as the development of strategic tools through institutional arrangements.

It is important to know the sustainable yield of the water resources in a basin in terms of water-supply and the delivery system of a particular river basin due to the economic development, and minimum instream flow requirements for fish and aquatic habitats, recreational use, and aesthetic aspects. It also requires conjunctive water management which is the management of hydraulically connected surface and groundwater in a coordinated way.

In order to meet the demands of the statement above in an efficient way, the following tasks are required in demonstrating the response coefficients for the stream-aquifer system: analyzing the overall degree of hydrologic alterations before and after a dam completion including generating stream-flow data at an ungaged site, developing the conjunctive model for the stream-aquifer-reservoir system, and finding the institutional arrangements in order to implement conjunctive management. Figure 3.5 shows an overall approach of this study. The detailed methodology will be discussed in each chapter.

The data analysis contains water demand, daily and monthly stream-flow data, instream flow requirements and characteristics of surface and ground waters, and reservoirs.

For the stream-aquifer system, it is necessary to demonstrate the response matrix of stream depletion with the distances and hydraulic parameters by using simulation techniques of MODFLOW. Connectivity between surface water and groundwater is established at this point.

Instream flow requirements will present the effect of before and after dam completion to affect the hydrologic regime. In order to analyze the effect, the daily stream-flow data requires so that stream-flow data will be simulated at this point. The hydrologic alterations will also be discussed.

The calculated response coefficient is incorporated into the stream-aquifer-reservoir system to estimate the reservoir release and groundwater withdrawal. In order to find the optimal reservoir release during the drought and trigger volume of reservoir operation rules, "hedging rules" are employed for the stream-aquifer-reservoir system.

Analyzing the results of the stream-aquifer-reservoir system, setting the alternatives, considering instream flow requirements will lead to finding of institutional arrangements in order to effectively manage limited water resources as a single source of groundwater and surface water.

In the next sections, the connectivity between surface and ground waters will be depicted based on the indicators as suggested the literature. For the stream-aquifer system, the conceptual model will be developed to find the response coefficient of stream depletion due to the pumping wells by using the simulation techniques of the MODFLOW program and also an analytical method.

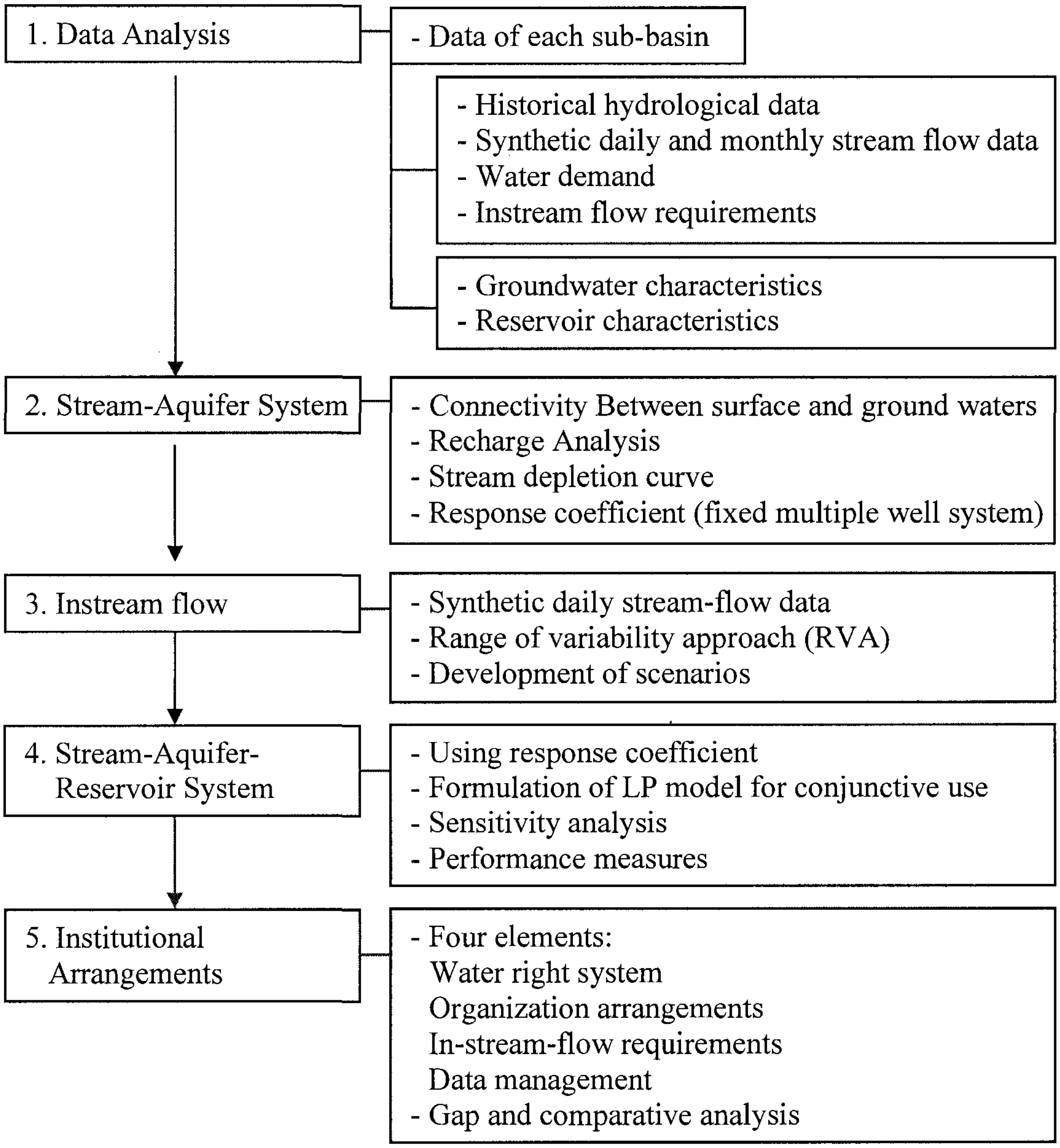


Figure 3.5 Overall Approach of this Study

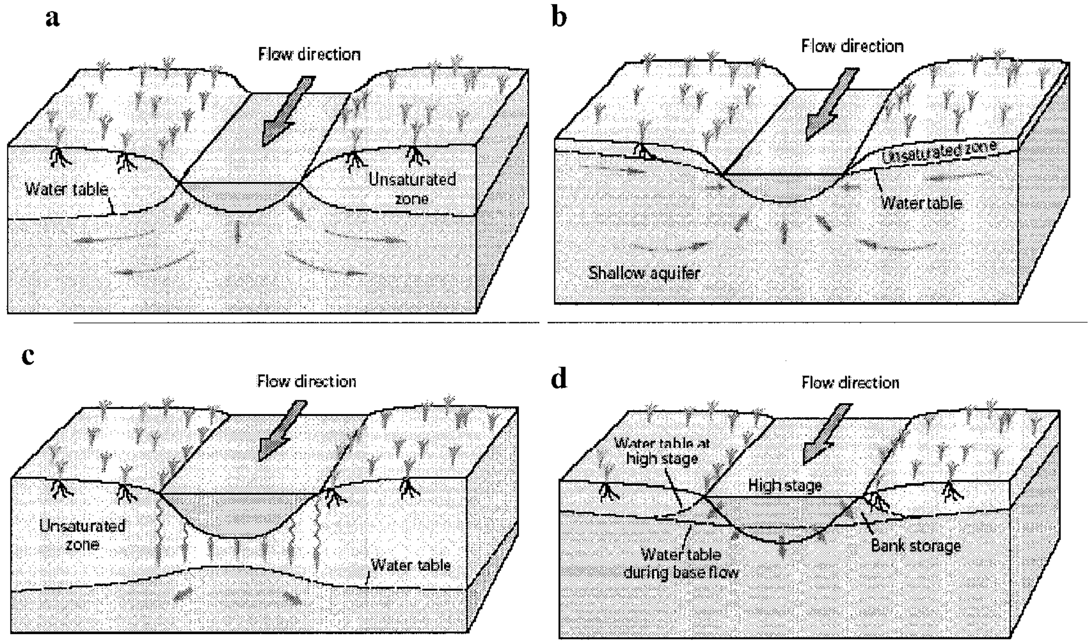
3.4 Connectivity between Groundwater and Surface Water

3.4.1 Connectivity

Surface water features such as streams are located within a boundary defined by watershed topology, geology and climate. Geological settings are many and varied.

Consequently, there is variability in the nature and the degree of connectivity between surface water and groundwater systems. For example, a stream can gain groundwater from highly dissected fractured rock aquifers in its upper reaches, but lose considerable water to its alluvial aquifer downstream. In its lower alluvial reaches, its seepage of surface to groundwater is dependent upon deposits of clays and silts within the site geology. These interactions between streams and aquifers vary at times, as they are defined by the differences in stream and groundwater levels, which fluctuate with the season. Thus, water flow between a surface water feature and the underlying aquifer is mainly constrained by:

1) *The difference between the surface water and the groundwater level.* Water flows down gradient from high to low potentials. If the stream level is higher than the groundwater level measured within the aquifer, then the stream has the potential to lose water to the aquifer. Figure 3.6 (a) shows where negative seepage flux takes place because a shallow water table is lower than the stream stage. Conversely, Figure 3.6 (b) shows groundwater discharges to a stream due to the groundwater level being higher than the stream level.
2) *The hydraulic properties and features of the aquifer, as well as the geological settings*. If a stream has a coarse gravel bed, it allows a high degree of interaction between the river and the underlying aquifer, as gravels have a high hydraulic conductivity. If a stream bed consists of clay, the movement of water will be restricted due to the low hydraulic conductivity of the soil.



Source: Winter et al. (1998)

Figure 3.6 Different Settings for Stream-Aquifer Connectivity
(a) a continuous losing system (b) a continuous gaining system (c) a perched losing system (d) continuous fluctuating stream, with stream gaining during low-stage period but losing during high stage period

Seepage flux can be controlled by the hydraulic properties of a stream bed as well as through the properties of the ambient aquifer. As seepage flux accounts for the relationship between stream and groundwater levels, the factors that affect these water levels will affect the connectivity between surface and ground waters. Interactions between surface and ground waters can vary in time and space in response to natural factors such as climate; however, watershed development and management can also considerably change stream-aquifer connectivity over time. Specific activities that can influence connectivity include a) stream regulation where flow is controlled by hydraulic facilities such as dams, locks or weirs; b) return flows that can maintain stream stage during dry periods; c) surface water extraction from the stream for consumptive uses such as irrigation, municipal and industrial water use; and d) groundwater abstraction that can be sufficient to lower the water-table and decrease or reverse the hydraulic gradient towards the stream (Brodie et al., 2007).

Scale issues in time and space are significant in the assessment and management of stream-aquifer connectivity. There are three main scales concerning connectivity as shown in Table 3.4:

1) *Watershed-scale*, where the stream is placed within the overall hydro-geological settings of the watershed;
2) *Feature-scale*, where individual surface water features such as lakes or a stream reach are the focus;
3) *Site-scale*, where site-specific studies provide insights into interaction between surface and ground waters.

Table 3.4 Spatial Scales in Stream-Aquifer Connectivity

Scale	Typical Units	Relevance
Watershed-scale *Regional*	> 100 km^2	Hydro-geological setting Water management areas watershed management targets Watershed monitoring and reporting
Feature-scale *Intermediate*	1 – 100 km^2	Water management decisions Environmental planning
Site-scale *Local*	< 1 km^2	Process studies Ecosystem dependencies Water quality protection

Source: Brodie et al. (2007)

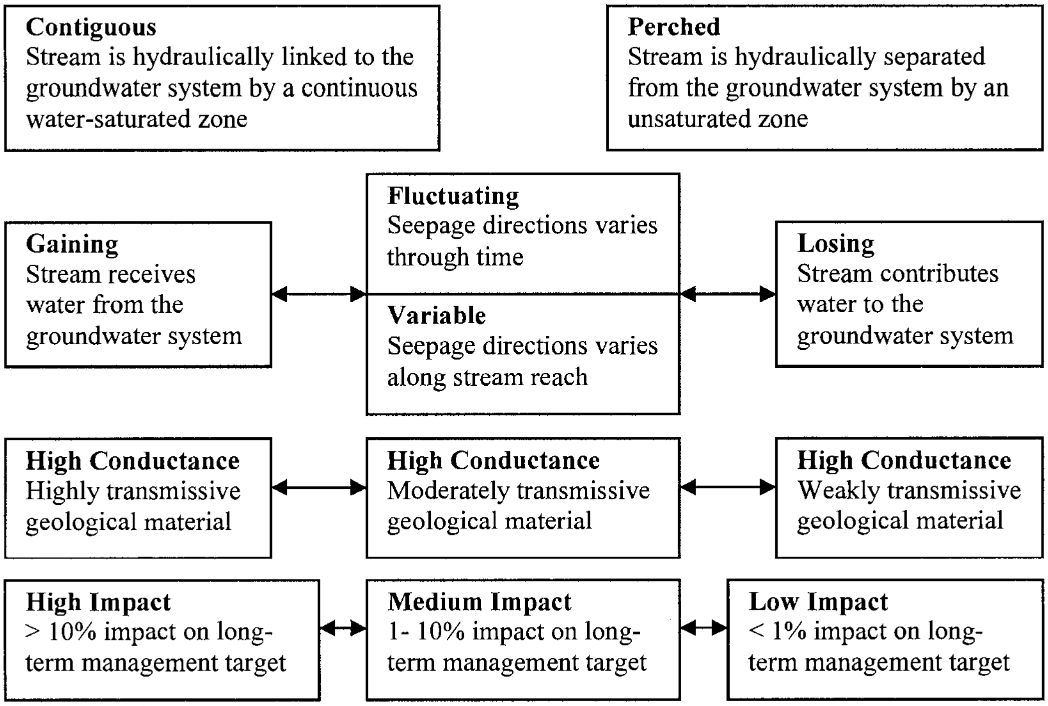
Like the spatial issue, variations in time scales concerning connectivity need to be considered. The interactions between surface water and groundwater can be considered over short, medium, and long-term time frames as shown in Table 3.5.

Table 3.5 Time Scales in Stream-Aquifer Connectivity

Scale	Typical Units	Relevance
Long-term	Decades – centuries	Climate variation Land use change Groundwater extraction
Medium-term	Seasons – years	Water management cycle Allocation and planning Water quality protection
Short-term	Days-months	Episodic events Evapotranspiration Tidal effects Ecosystem dependencies

Source: Brodie et al. (2007)

In general, the interactions between surface water and groundwater can be classified on the basis of the four key aspects of contiguity, seepage direction, conductance, and impact. Figure 3.7 illustrates this classification of streams.



Source: Brodie et al. (2007)

Figure 3.7 Classification of Stream-Aquifer Connectivity

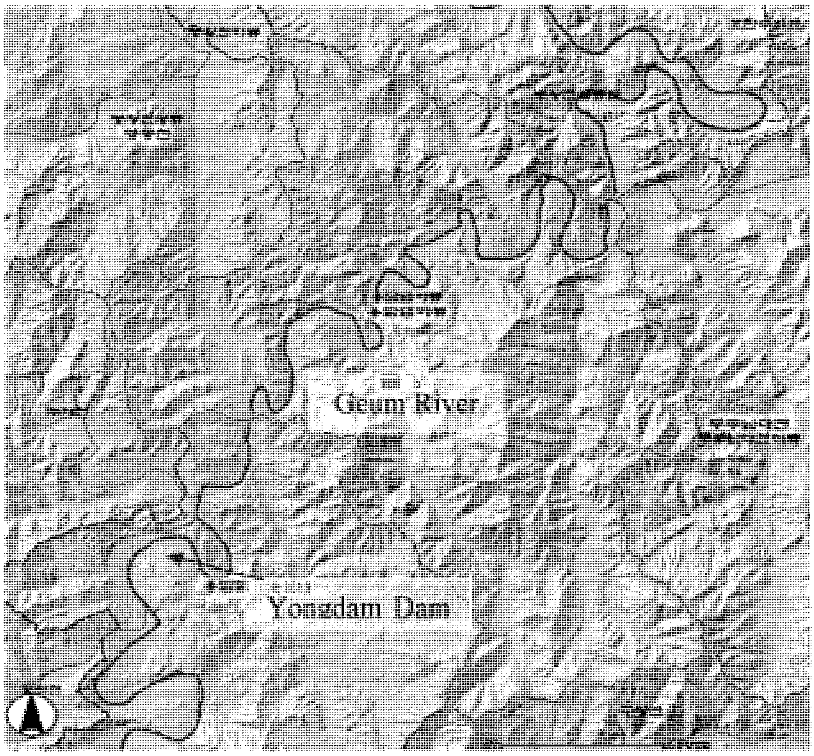
Classification of streams can also be applied on the basis of hydraulic conductance, which is ability of the geological material to transmit water. Table 3.6 illustrates some features of this type of classification.

Table 3.6 Typical Features of Various Conductance Classifications for Stream-Aquifer Systems

Features	**High Conductance**	**Moderate Conductance**	**Low Conductance**	**Mountain-ous area in Korea**
Typical lithology	Gravels, coarse sands, karst	Fine sands, silts, fractured rock, basalt	Clay, shale, fresh unfractured rock	Gravels, Coarse sands
Typical hydraulic conductivities(K)	> 10 m/d	10 – 0.01 m/d	< 0.01 m/d	>25-70m/d
Typical seepage flux	> 1000 m^3/d/km	10 - 1000 m^3/d/km	< 10 m^3/d/km	NA*
Ratio of seepage to total flow	> 0.5	0.1 – 0.5	< 0.1	NA
Typical near-stream response times	Days-months	Years	Decades	Days-months

Source: Brodie et al. (2007)
Note: * is not applicable

Comprehensive stream-aquifer connectivity can be characterized on the basis of conductance and impact. Surface water and groundwater are highly connected if the properties of high conductance and/or high impact are identified. As mentioned in the previous section, the area of the case study is more than 100km^2, but the aquifer is less than 100km^2, because aquifers along the main rivers are narrow and small as shown Figure3.8. The time scale of analysis is one month, and the hydraulic conductivity of alluvial aquifers is so high that its value ranges from 25 to 70m/day. According to the classifications stated, most alluvial aquifers in Korea are highly interconnected with main rivers; this means that these two sources, surface water and ground water, must be managed as the connected water resource.



Source: www.wamis.go.kr

Figure 3.8 Typical Example of Alluvial Aquifers of the Geum River

3.4.2 Critical Time

Highly interconnected stream-aquifer systems are ones where groundwater abstraction results in equivalent stream-flow depletion within a relatively short time frame of days or weeks. Equation (3.1) represents the critical time when the reversal of hydraulic gradient begins (Chen, 2002). In evaluating stream infiltration and baseflow[3] reduction induced by groundwater pumping in nearby aquifers from a stream, the critical time, infiltration reach, and travel time can also be calculated to determine the hydraulic

---

[3] Baseflow represents that without pumping aquifers discharge to streams which are gaining.

connectivity between the well and the stream. Equation (3.1) can be used to calculate the critical time for a reversal of hydraulic gradient to take place,

$$t_c = -\frac{L^2 S}{4T \ln(\pi i T L / Q)} \tag{3.1}$$

where, t_c is the critical time for a reversal of hydraulic gradient to occur, L the distance between the stream and the well, S the specific yield for an unconfined aquifer, T the aquifer transmissivity, π the constant, i the hydraulic gradient, and Q the pumping rate of the well.

Figure 3.9 shows variations of the critical time for a number of hydraulic gradients. Each of the curves was calculated for a different distance L that ranges from 50 to 500m. The hydraulic gradients used are 0.0001, 0.0003, 0.0005, 0.0008, and 0.001. The values of the following parameters remain constant in the computation: K = 25 or 70 m/d, S = 0.22, and thickness of aquifer h_0 = 10 or 30 m. These figures were assumed on the basis of values in section 3.2.1. As shown in these curves, a larger i or L results in a longer critical time of pumping. When the hydraulic conductivity is K = 70 m/d, and aquifer thickness h_0 = 30 m, the critical time is less than 100 days depending on the hydraulic gradients and the distance between the well and the stream. When the hydraulic gradient is less than 0.0005, the critical time is less than 10 days. The thickness of the aquifer significantly affects the critical time. The critical time decreases with the increased thickness of the aquifer. The results obtained show a relevant connection between groundwater and surface water in Korea due to the pumping of wells near a shallow aquifer.

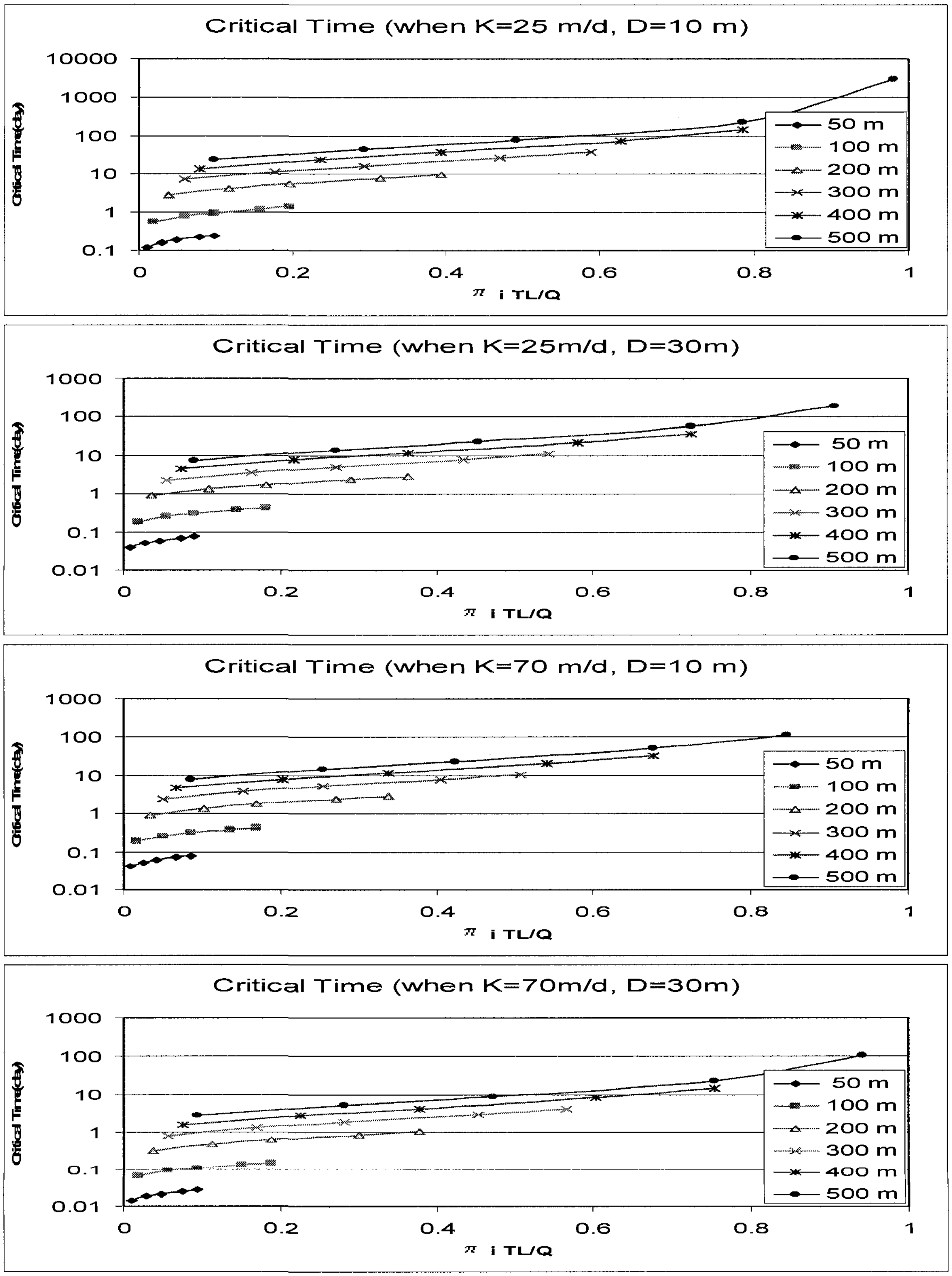


Figure 3.9 Critical Time of Stream Infiltration for Varied Baseflow Gradients

3.4.3 Stream Depletion due to the Pumping of a Well

Numerous methods are used to obtain analytical solutions for the interaction between groundwater and surface water; these methods offer insight into the interaction between these elements. To analyze stream depletion due to the pumping with a finite aquifer width in this study, the Hunt (2006) method was employed to present an analytical solution for a well pumping in the vicinity of a stream where stream and aquifer have finite widths. It was assumed that the pumped aquifer was overlain by an aquitard, or a series of aquitard layers, containing a free surface. The assumptions of drawdown and steam depletion are that flow in the aquitard is vertical, flow in the pumped aquifer is horizontal, and the geologic cross section remains unchanged for $-\infty < y < \infty$. This aquifer is identical to the aquifer used in the Boulton delayed-yield solution for flow to a well in an infinite aquifer. This solution, which was developed by Hunt, can be used to describe horizontal unconfined flow in a homogeneous aquifer. The following setting for unconfined aquifer was specified by:

1) Setting the vertical hydraulic conductivity of the aquitard equal to zero,
2) Replacing the storativity (elastic storage coefficient) of the pumped aquifer with its specific yield (effective porosity).

The expression is as follows:

$$T\left(\frac{\partial^2 s}{\partial x^2}+\frac{\partial^2 s}{\partial y^2}\right)=S\frac{\partial s}{\partial t}+\left(\frac{K'}{B'}\right)(s-\eta)-Q\delta(x-L)\delta(y), \qquad (-\beta L<X<-\gamma L, 0<x<\alpha L) \tag{3.2}$$

$$\sigma S\frac{\partial \eta}{\partial t}+\left(\frac{K'}{B'}\right)(s-\eta)=0, \quad (-\beta L<X<-\gamma L, 0<x<\alpha L) \tag{3.3}$$

$$T\left(\frac{\partial^2 s}{\partial x^2}+\frac{\partial^2 s}{\partial y^2}\right)=S\frac{\partial s}{\partial t}+\left(\frac{K''}{B''}\right)s, \quad (-\gamma L< x <0) \tag{3.4}$$

$$\frac{\partial s(\alpha L, y, t)}{\partial x}=0 \tag{3.5}$$

$$\frac{\partial s(-\beta L, y, t)}{\partial x}=0 \tag{3.6}$$

$$s(x,\pm\infty,t)=0, \quad (-\beta L<x<\alpha L) \tag{3.7}$$

$$s(x,y,0)=\eta(x,y,0)=0, \quad (-\beta L<x<\alpha L) \tag{3.8}$$

where, s is the drawdown in the pumped aquifer;

η is the free surface drawdown in the aquitard;

t is the time;

T is the aquifer transmissivity;

S is the aquifer storativity;

K’/B’ is the hydraulic conductivity / saturated thickness of the aquitard at points not beneath the stream;

K”/B” is the hydraulic conductivity / thickness of the aquitard beneath the stream;

Q is the well abstraction rate;

δ(x) is the Dirac’s delta function, and;

σ is the aquitard specific yield;

L is the distance between stream and well.

The drawdown of the stream’s free surface is assumed to be zero for all time. With the conditions, partial equations, and boundaries described above, Hunt determined the flow, ΔQ, depleted from the stream by using dimensionless parameters and also through a coded solution as user-defined functions entitled Q_13 (Hunt, 2006) in Excel. The expression used in the program follows:

$$\frac{\Delta Q}{Q}=Q\_13\left(\frac{tT}{SL^2},\frac{(K'/B')L^2}{T},\frac{(K''/B'')L^2}{T},\frac{S}{\sigma},\alpha,\beta,\gamma\right) \tag{3.9}$$

Figure 3.10 shows the results using the Q_13 program in order to analyze the connectivity between groundwater and surface water due to the pumping of the wells for the aquifer in Korea. In the Geum River basin, the known thickness of the shallow aquifers ranges from 2 to 30m. The transmissivity and storage coefficient of these shallow aquifers are from 50 to 2,000m^2/day and 0.1–0.01, respectively (MOCT and KOWACO, 2004). This type of aquifer is the main source of irrigation water supply for most rural areas during drought seasons. The shallow aquifers are directly recharged by the infiltration of rainfall during the wet season, but they are very vulnerable to groundwater pollution due to the high interconnection between surface water and groundwater. For analysis of the case study, the thickness of the aquifer was assumed to range between 10 to 30m, the hydraulic conductivity ranges between 25 to 70m/day, and the specific yield was assumed to be 0.22.

According to the results obtained, the stream depletions due to pumping vary with the distance between the well and the stream, and the thickness of the aquifers. If the distance between the well and the stream decreases, the response to pumping occurs quickly. This means that the interaction between the aquifer and the stream is highly interconnected. Within a relatively short distance between the well and the stream, the equilibrium in response to a stress is reached in a short time. The thickness of aquifers affects the reestablishment of the equilibrium. If the thickness of aquifers increases, creating a new equilibrium requires a short period of time. This means that a new equilibrium is affected by the transmissivity.

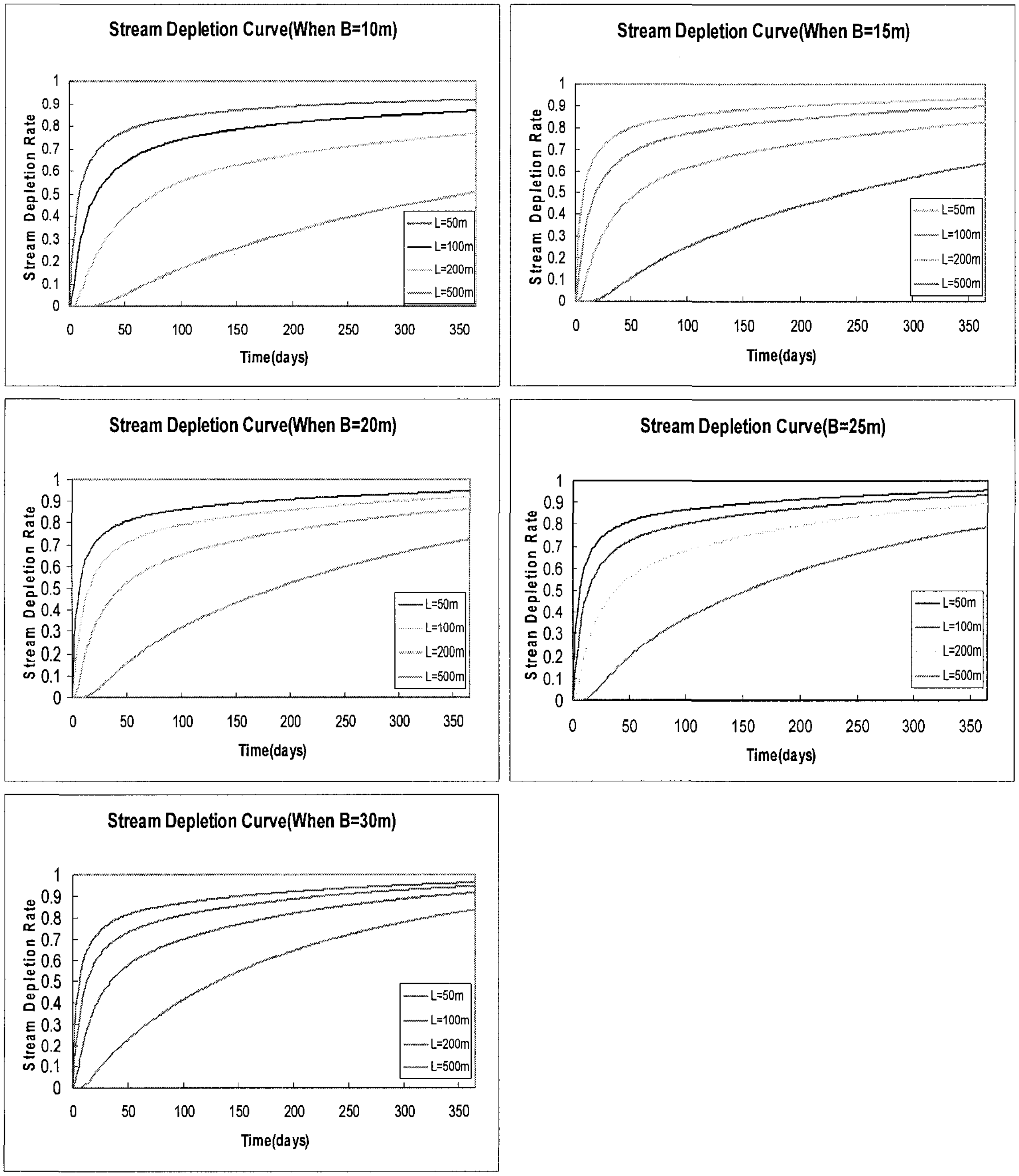


Figure 3.10 Stream Depletion Curves Due to the Pumping

For the duration of pumping, the thickness of the aquifer was assumed to be 30m, the hydraulic conductivity ranges between 25m/day, the specific yield was assumed to be 0.22, and the thickness of aquitard was specified as 0m. Figure 3.11 shows the results of the stream depletion factors within 30, 60, and 180 days. By increasing the pumping periods, the rate of the stream depletion increases. When the distance between the well and the stream is short, the stream depletion takes place in a short time; it also quickly reaches stable state in response to the stress of pumping. After the pumping stops, the effects of stress to the system dissipate in a short time. By increasing the distance between the well and the stream, the response time takes a relatively longer time.

The last graph of Figure 3.11 shows the benefits between the direct stream withdrawal and conjunctive use where conjunctive use includes pumping near the stream. This example illustrates how strategies of conjunctive management as a single source might be handled. The difference between direct stream withdrawal and groundwater withdrawal near a stream is regarded as an advantage using conjunctive use. A major benefit to conjunctive use as a source of supply arises from the "buffering effects" of aquifer storage in relation to climatic variability and changing demand, which are often closely linked especially for irrigation.

On the other hand, an important physical mechanism to consider in conjunctive use in drought conditions is the "time-lag" between recharge and response in groundwater levels and well yields.

Understanding that the surface water and groundwater are fundamentally linked means that management of these two sources needs to be integrated. Such an integrated approach is called conjunctive management which is implemented to better manage water in terms of economic, environmental and/or social results. This means considering the interaction between surface water and groundwater, thereby combining this understanding into management policy and practice including institutional arrangements and on-going technical support.

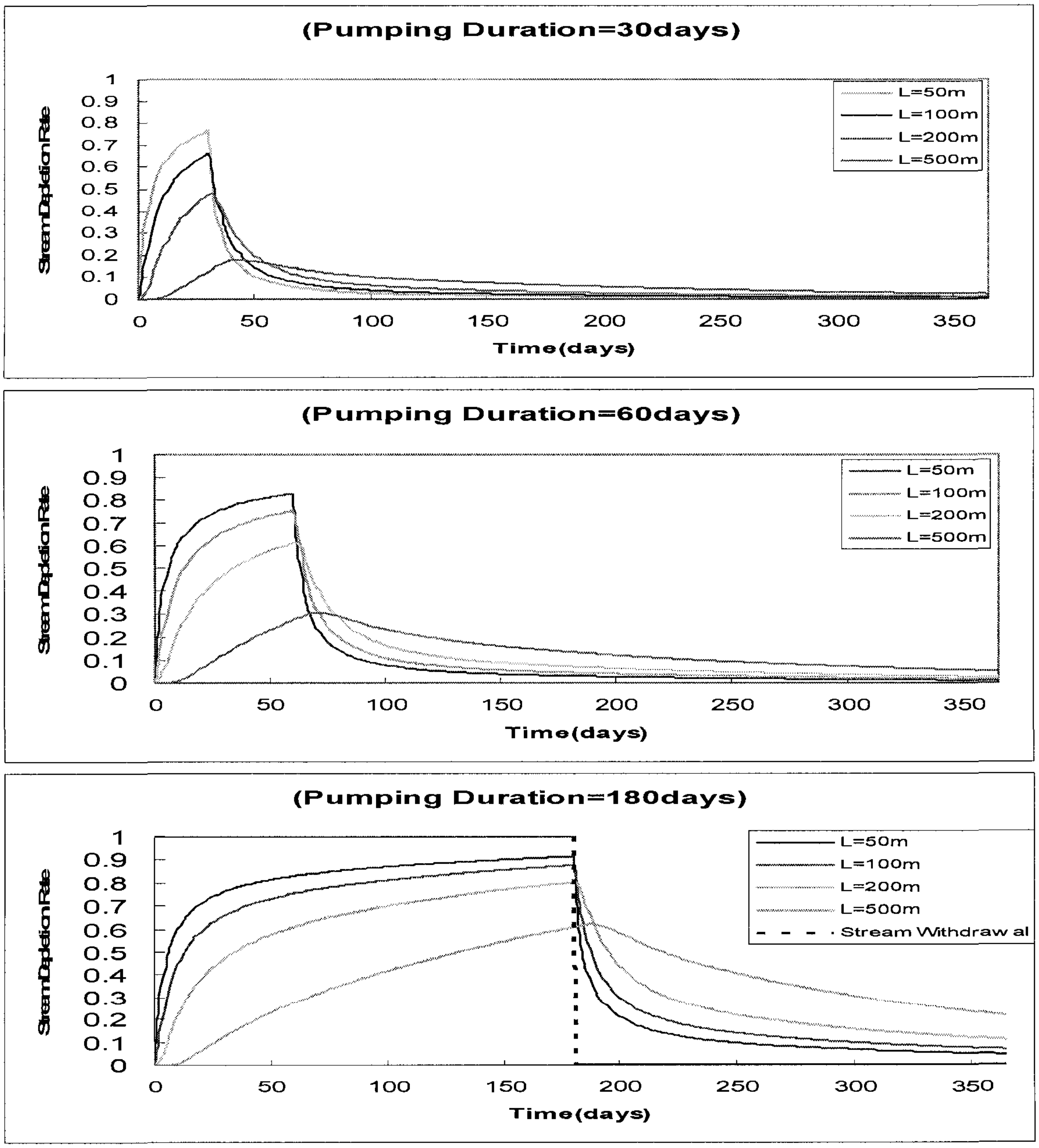


Figure 3.11 Stream Depletion over the Different Periods

3.5 Fundamental Analysis of the Stream-Aquifer System

3.5.1 Analysis of Recharge by Stream-flow

The analysis of the recharge of the study area was performed by simulations of the stream-aquifer system using MODFLOW. Therefore, monthly recharge pattern of the aquifer was considered in alluvial aquifers developed along the stream. The daily inflow data of the Daechung reservoir was used for the recharge analysis in the study area. The data available are the historical records of the study area for 26 years from 1981 to 2006; the daily inflow data from 1981 to 2001 was used in this analysis in order to maintain the homogenous time series except data after the completion of the Yongdam Reservoir in 2001.

To estimate the groundwater discharge, the analysis of stream-flow hydrographs such as separation between baseflow and direct runoff is required. The computer program, RORA (Rutledge, 1998, see Appendix A for the theory and method), which is based on the recession-curve-displacement method, allows automated analysis of stream-flow hydrographs to estimate ground-water recharge.

The computer program PART (Rutledge, 1998) was used to estimate monthly and annual baseflow rates that were the actual net groundwater recharge rates specified to the models. PART used stream-flow partitioning to estimate a daily record of baseflow under the stream-flow record. PART can also calculate daily stream-flow rates for stream-flow records.

The RORA program automatically estimates the ground water recharge using the recession-curve-displacement method. It requires that a recession index be specified for the analyzed area, which is the time required for baseflow to decline through one logarithmic cycle on a semi logarithmic plot of stream-flow and time. The computer program RECESS (Rutledge, 1998) was used to estimate the recession index and to define the master recession curve for the basin. The inflow data of the Daechung Reservoir already takes evaporation into account. Therefore, evaporation in the analysis is not considered in the analysis. Figure 3.12 and Figure 3.13 show the results of the recharge analysis. The recession curve decreases with time.

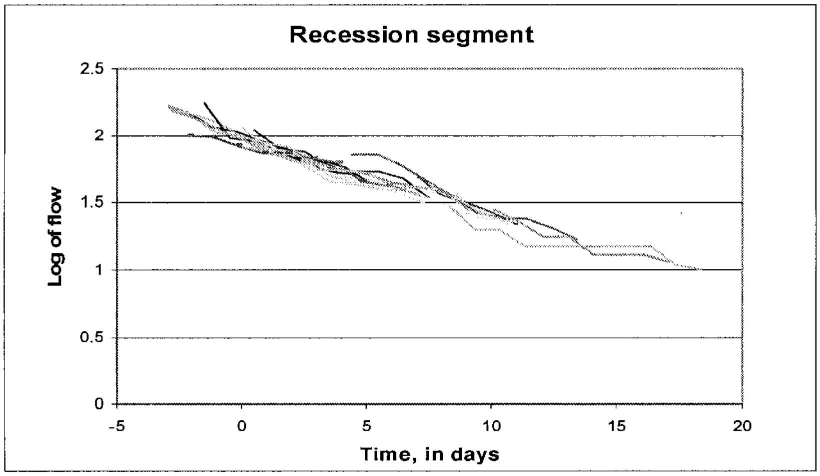


Figure 3.12 Recession Segment for the Case Study Area

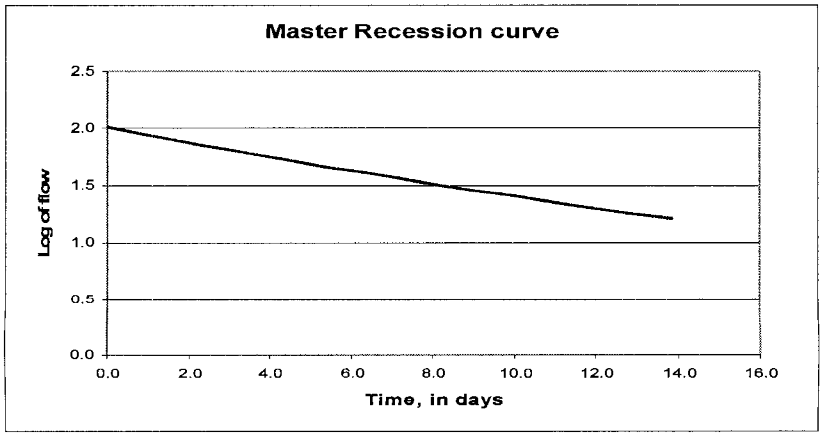


Figure 3.13 Master Recession Curve in the Case Study Area

Table 3.7 and Figure 3.14 represent the monthly recharge pattern obtained from the RORA program. According to the results obtained, the total groundwater recharge is 220.3 mm which is relatively small. The rate of the groundwater recharge to the average annual precipitation is about 20%. The groundwater recharge normally occurs in the rainy season from June to September in the study area. According to the results, the ground-water recharge is strongly correlated with precipitation. When the precipitation is large, the groundwater recharge is also large.

Table 3.7 Monthly Recharge of the Daechung Reservoir

(Unit: mm)

Div.		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Precipitation		29.0	33.4	46.6	70.5	81.9	159.6	275.3	253.5	132.6	49.5	44.7	26.5	1203.0
Recharge	Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	1st Quartile	0.0	0.0	0.0	0.0	0.0	0.0	17.0	14.7	0.0	0.0	0.0	0.0	31.8
	2nd Quartile	0.0	0.0	8.9	12.7	6.6	13.7	37.8	34.5	23.4	7.6	0.0	0.0	145.3
	3rd Quartile	0.0	2.8	27.4	21.1	15.5	29.2	70.6	67.8	32.3	19.3	13.7	5.1	304.8
	Max.	30.5	65.3	39.1	66.8	41.4	84.1	195.6	240.3	78.5	61.0	20.3	20.1	942.8
	Avg.	2.6	7.5	13.2	15.1	11.2	19.5	48.4	56.1	23.7	12.9	6.2	4.1	220.3

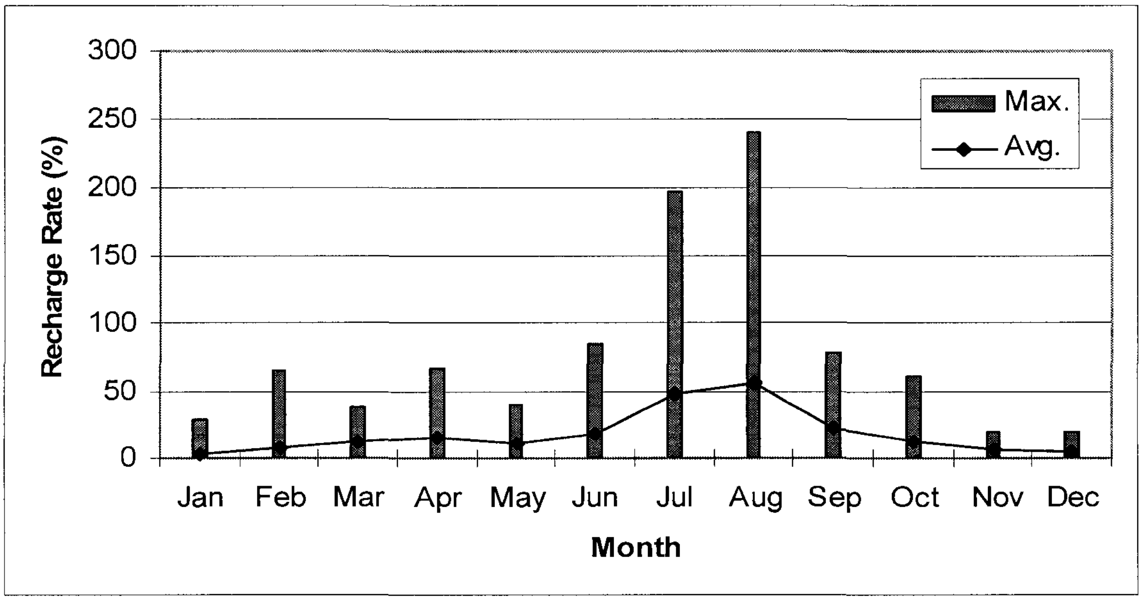


Figure 3.14 Average Monthly Groundwater Recharge of the Daechung Reservoir

3.5.2 Simulation of Stream-Aquifer System

Stream depletion of a gaining stream, due to pumping wells, is composed of two components, the induced infiltration and the baseflow. For the stream-aquifer system of the study, numerical groundwater models were used to estimate the stream depletion of the induced infiltration and the baseflow in the alluvial aquifers.

McDonald and Harbaugh (1988, 1996) developed the three-dimensional, finite-difference model MODFLOW that is a widely used simulation model for the analysis of groundwater flow systems. In this study, the River Package of the MODFLOW program was used to simulate the stream depletion due to the pumping of wells in the alluvial aquifers near a stream. In the MODFLOW manual, the river conductance term, *CRIV*, that produces the same effect as the river coefficient is calculated from:

$$CRIV = K_{bed} \cdot L \cdot w / b \qquad (3.10)$$

where K_{bed} is hydraulic conductivity of a river bed, L is length of river cell, w is width of river, and b is thickness of river bed.

This approach suggests that it is the nature of a river bed, especially its width and vertical hydraulic conductivity, which defines the river-aquifer interaction. Flow between the river and the ground water stream is given by;

$$QRIV = CRIV(HRIV - h) \qquad (3.11)$$

where, $QRIV$ is flow between the river and the aquifer taken as if it directed into the aquifer, $HRIV$ is water level in the river, $CRIV$ is hydraulic conductance of the river-aquifer interconnection, h is head at the node in the cell underlying the river reach.

Most aquifers developed along the river in Korea are alluvial and shallow with a finite valley. Therefore, the aquifer in this study was assumed as an unconfined and finite one with a confined valley.

Spatial Discretization

The conceptual model of this study was assumed to be 2,400m long and 2,000m wide as shown in Figure 3.15. The model domain was discretized into a grid of 120 rows and 50 columns of square cells that are a uniform size of 20m on each side. In the vertical dimension, the model domain composes a maximum of two layers and extends from the water table to the intersection of the aquifer with underlying bedrock. The top layer of cells equally extends to a depth of 25m below the water table. Layer 2 extends from 25m to 32m of the bedrock with a low hydraulic conductivity. Therefore, the thickness of the hypothetical aquifer in this study is 32m.

Boundary Conditions and Stresses

The active area of the model was surrounded laterally by no-flow boundaries that were specified along the finite valley assumed. The boundaries were based on the hydrogeologic information that was reported by MOCT/KOWACO (2004). The characteristics of the gaining stream include a gradient of 0.002m/m from upland to a stream with a stream gradient of 0.001m/m from the north to the south. It was assumed that the groundwater flow is perpendicular to the stream and that all groundwater discharge flows to the stream.

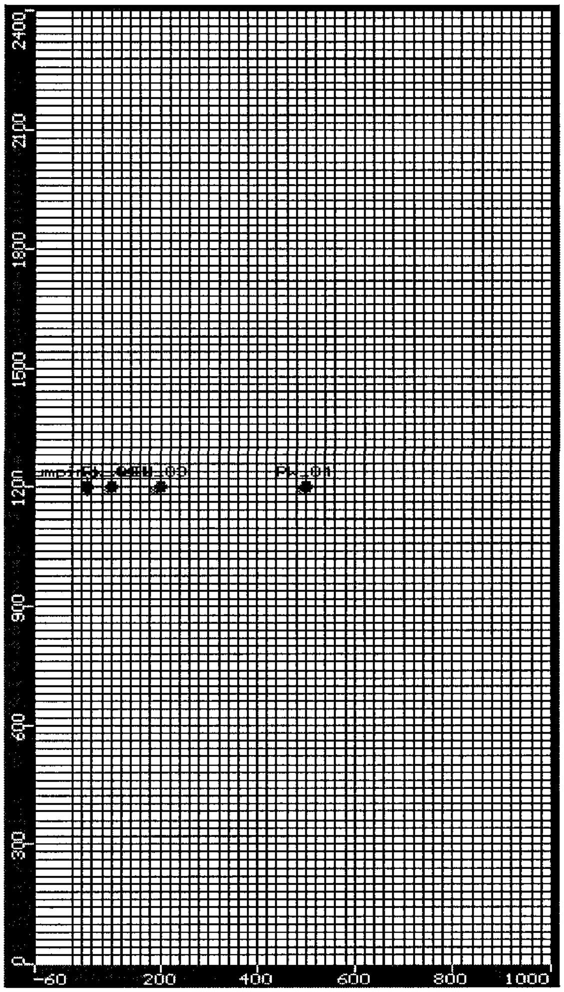


Figure 3.15 Conceptual Model Frame of Stream-Aquifer System for the Single Well

The single stream that flows through the left side at the site is 60m in width, which is the average width of streams studied by KOWACO. Streams in the upstream basin of the Geum River are typically shallow and fully hydraulically interconnected with aquifers as stated earlier. The depth of streams is from 1 to 2 m based on the discharge obtained by KOWACO.

The rate of the recharge to the groundwater from the precipitation event is assumed as 220mm/year; this figure is based on the results obtained through the analysis of groundwater recharge in the previous section.

Typical values of parameters reported by KOWACO (2004) are used for transitional simulations. These are specific yields of 0.22 and storage coefficient (or storativity) of 0.015. A horizontal hydraulic conductivity of 25-70m/day is assigned for the stream cells so that there is little resistance to flow within the simulated stream channels. The vertical hydraulic conductivity is assumed as 2.5–7 m/day; the ratio of horizontal and vertical hydraulic conductivity is 10:1.

The steady, average annual hydrologic budget of the stream-aquifer is shown in Table 3.8. Recharge from precipitation is the largest component of inflow to the system and stream-flow is the largest component of outflow from the system. In the analysis, recharge was only considered without evaporation, evapotranspiration, and precipitation. The calculated total flow rate through the system is about 1,415m^3/day. There are, however, a few differences between inflow and outflow.

Table 3.8 Steady-state Average Annual Hydrologic Budget for the System

(Unit: m^3/day)

Hydrologic Component	Inflow	Outflow
Recharge of Alluvial Aquifer	1414.87	0.0
Stream-flow from the System	0.0	1414.92
Recharge on the Stream	10.0	0.0
Storage of the System	0.0	0.0
Total	1414.87	1414.92

Stream-Aquifer Interaction

The steam-aquifer interaction in the groundwater flow system was evaluated for steady-state conditions in order to analyze the response between the stream-flow and aquifer due to the pumping of wells. The conceptual model of this study provides information on stream-aquifer interactions that includes the locations and rates of groundwater discharge to streams, stream-flow leakage to the aquifer; and stream-flow depletion caused by the groundwater withdrawal. In the first trial, a pumping rate of 1000 m^3/day was used where a single well pumped water in the system. The distance between the well and the stream varied from 50, 100, 200 and 500m. With decreasing distance between the well and the stream, the response to pumping occurred in a short time as shown in Figure 3.16. The results obtained are similar to those of the analytical method shown in the previous section. The thickness of aquifer affects the stream depletion due to the pumping well.

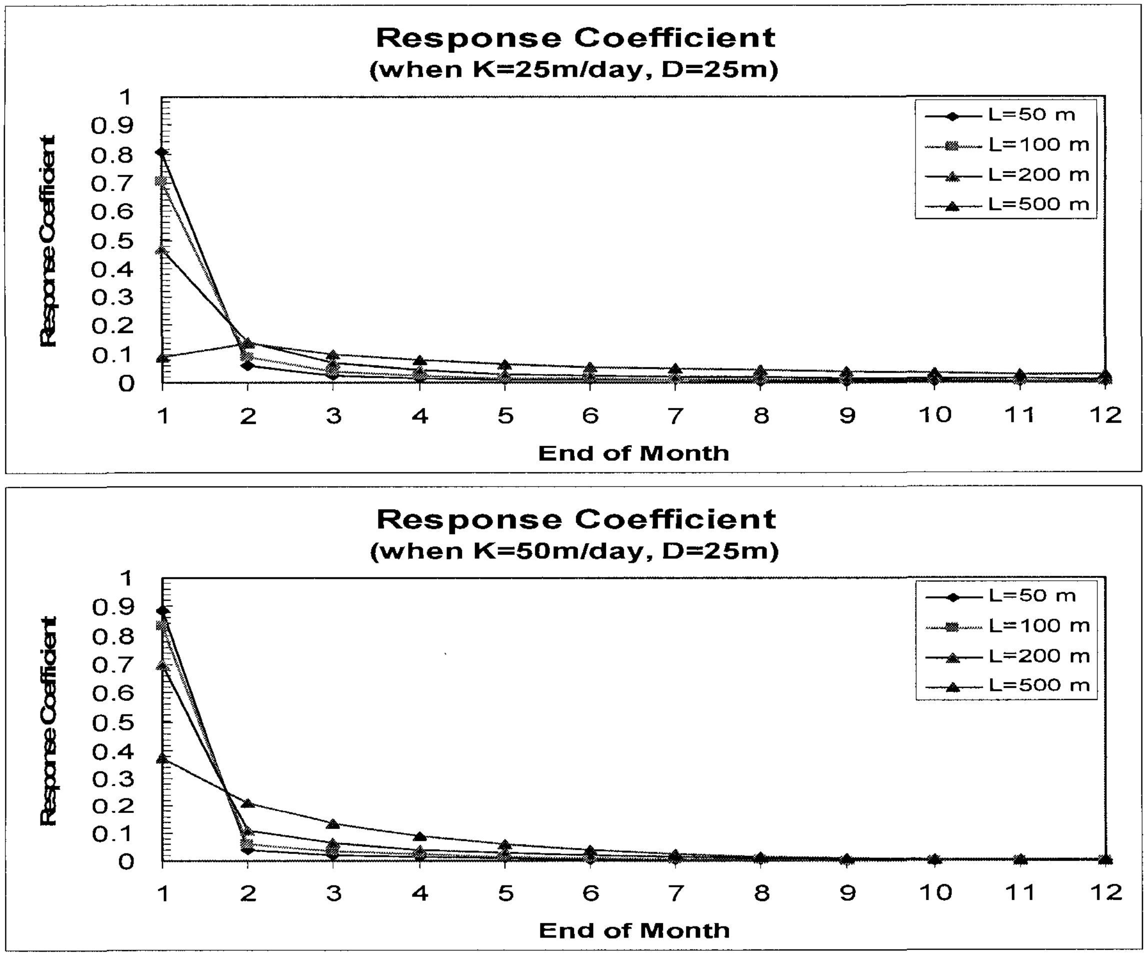


Figure 3.16 Response Coefficient of Stream-Aquifer System for the Single Well

3.6 Summary

The overall methodology is addressed as a way to examine and provide potential solutions for the arising conflicts in the case study area. It is necessary to estimate the response coefficient of stream depletion due to the pumping wells, to analyze the impacts of pre- and post-dam for the hydrologic alterations, to develop the conjunctive use model by using LP program, and to arrange the institution factors in order to implement the conjunctive use.

Most alluvial aquifers along the main rivers in the case study area are relatively narrow and small. According to the used classification, aquifers near a stream are highly interconnected with a stream. The critical time is relatively short to reverse the hydraulic gradient in the gaining stream.

In the recharge analysis, the annual amount of recharge accounts for 220.3mm/year that mainly come from the precipitation. The rate of the groundwater recharge to the average annual precipitation is about 20%. The recharge to aquifer concentrates in the rainy season from June to September in the study area. The groundwater recharge is strongly correlated with the precipitation. When the precipitation is large, the groundwater recharge is also large.

The response coefficient of stream depletion due to the pumping wells is presented by using analytical and numerical methods. Both results obtained illustrate dependence on the thickness of aquifers, hydraulic conductivity, and distance between the well and the stream.

CHAPTER 4

INSTREAM FLOW REQUIREMENT

4.1 Introduction

The development and management of water resources by humans has changed the natural flow regimes of rivers. A growing need to predict the biological impacts associated with water management activities, and set water management targets that maintain riverine biota and socially valuable goods and services associated with riverine ecosystems requires a new definition of instream flow requirement in Korea. The instream flow[4] requirement is simply defined as the value of the 10 % non-exceedance probability in the analysis horizon or the minimum flow value of 10 years through the statistical analysis at a control point. The definition of instream flow requirement requires that the protection of ecosystems and the natural condition be added to the existing definition.

This chapter aims to estimate the instream flow requirement that includes water supply, required stream-flow requirements for fish and aquatic habitat, trans-basin diversions using a rainfall-runoff model and the range of variability approach (RVA) to quantify human impacts.

---

[4] Instream flow often refers to the water flows necessary to sustain one or more specified in-stream use of water. In this way, instream flow is basically synonymous with stream-flow. The term of instream flow protection refers to the legal, physical, contractual, and/or administrative methods used to ensure that water remains in stream, natural lake beds, or other areas where water naturally flows or occurs. In this study, instream flow refers to that water flowing in a stream reach or at a control point at a given time. Instream flow protection encompasses the array of methods employed to protect water in a stream channel or lake bed for a stated purpose (Gillian and Brown, 1997). The term of instream flow program is used to refer to the institutional entities and body of rules, laws and statutes that govern instream flow protection.

4.2 Methodology for Instream flow Requirement

4.2.1 Range of Variability Approach

Richter et al. (1996, 1997, 1998) developed and demonstrated the range of variability approach (RVA) for establishing flow-based river management targets by incorporating the concept of natural hydrologic variability. This methodology was developed to support efforts to manage water system operations in a way that minimizes impacts on natural hydrologic variability, and thereby minimizes ecological impacts. Thirty-three hydrologic parameters called indicators of hydrologic alteration (IHAs) are employed to evaluate human-induced flow alterations in terms of magnitude, timing, frequency, duration, and rate of change. Table 4.1 illustrates parameters of the indicators of hydrologic alteration, along with their ecosystem influences.

The IHA calculates parameters for the five different types of instream flow components: low flows, extreme low flows, high flow pulses, small floods, and large floods, based on the realization by research ecologists that river hydrographs can be divided into a repeating set of hydrologic patterns that are ecologically relevant. It is the full range of flow conditions characterized by these five types of flow events that must be maintained in order to sustain riverine ecological integrity. The five types are defined as follows (Richter et al., 1996);

Low flows – Dominant flow condition in most rivers during low flow seasons. In natural rivers, after a precipitation event period has passed and associated surface runoff from the drainage area has decreased, the river returns to its base or low-flow condition. These low-flow conditions are generally provided by groundwater discharges into the river. The seasonally varying low-flow conditions in a river impose a fundamental constraint on a river's aquatic communities because it determines the amount of aquatic habitat available for most of the year.

Table 4.1 Indicators of Hydrologic Alterations (IHAs) Used in the Range of Variability Approach (RVA)

IHA Group	**Hydrologic Parameters**
Group 1: Managements of Monthly Flow Conditions	Mean flow for each calendar month
Group 2: Magnitude and Duration of Annual Extreme Flow Conditions, and Base Flow Condition	Annual 1-day minimum flow
	Annual 1-day maximum flow
	Annual 3-day minimum flow
	Annual 3-day maximum flow
	Annual 7-day minimum flow
	Annual 7-day maximum flow
	Annual 30-day minimum flow
	Annual 30-day maximum flow
	Annual 90-day minimum flow
	Annual 90-day maximum flow
	7-day minimum flow divided by mean flow in each year(Base flow condition)
Group 3: Timing of Annual Extreme Flow Conditions	Date of annual 1-day maximum flow
	Date of annual 1-day minimum flow
Group 4: Frequency and Duration of High and Low Pulses*	Number of high pulses in each year
	Number of low pulses in each year
	Mean duration of high pulse in each year
	Mean duration of low pulse in each year
Group 5: Rate and Frequency of Flow Conditions Changes	Mean of all positive differences between consecutive daily flows (flow rise rate)
	Mean of all negative differences between consecutive daily flows (flow fall rate)
	Number of flow reversals

Note: * High and low pulses are those periods in which the daily flows are above the 75th percentiles and below the 25th percentile pre-impact daily flows, respectively.

Extreme low flows – During drought periods, rivers drop to very low levels that can affect many organisms, but may provide necessary conditions for other species. Water characteristics such as chemistry, temperature, and dissolved oxygen availability can drastically stress many organisms during extreme low flows.

High flow pulses – During rainstorms, a river will rise above its low flow levels. High flow pulses are defined as any water rises that do not overtop the channel banks.

These pulses offer important and necessary breakdowns in low flows. High flow pulses also provide fish and other mobile creatures with increased access to up and downstream areas.

Small floods – Small floods represent frequent floods and all river rises that overtop the main channel but does not include more extreme. During floods, fish and other mobile organisms move upstream, downstream, and out into floodplains or flooded wetlands to access additional habitat such as secondary channels and shallow areas.

Large floods – Extreme floods will typically rearrange both the biological and physical structure of a river and its floodplain. These large floods can flush away many organisms, thereby decreasing some populations but in many cases also increasing some species. Extreme floods may also be important in forming principal habitats such as floodplain wetlands.

A range of variation for each IHA determined form the pre-impact flows is set as the flow management target. The operation of hydraulic facilities aims to allow post-impact flow conditions to achieve the established RVA target ranges at the same frequency as for the pre-impact flows. The IHA program developed by Richter and others (1996) can provide explicit adaptive management guidelines that are responsive to the demands of most water management negotiations.

In this study, the RVA target range for each parameter is restricted by the 25th and 75th percentile flow value, as suggested by Richter et al. (1998). The management goal is to make the post-impact flow regime accomplish the target ranges at the same frequency as that which occurred in the natural. Richter et al. (1998) used the degree of hydrologic alteration as a measure to quantify the deviation of the post-impact flow regime from the pre-impact one. The degree of hydrologic alteration, *D*, is given by;

$$D = \left| \frac{N_0 - N_e}{N_e} \right| \times 100\ \% \tag{4.1}$$

where, N_0 is the observed number of post-impact years for which the value of the hydrologic parameter falls within the RVA target range; N_e is the expected number of post-impact years for which the value of the hydrologic parameter falls within the RVA target range (N_e can be estimated by $p \times N_T$, where $p =$ percentage of pre-impact years for which the parameter value falls within the RVA target, and $N_T =$ total number of post-impact years).

The *D* values of 33 IHAs can provide a quantitative evaluation system for the effects of water diversions on natural flow regimes. However, a single integrated index is required to represent the overall hydrologic alteration. Richter et al. suggested that the value of *D* ranging between 0 and 33% represents little or no alteration (that is, low alteration), 33~67% represents moderate alteration, and 67~100% represents high alteration. If all 33 IHAs belong to the low alteration, the overall degree of hydrologic alteration, D_0, is given by;

$$D_o = \frac{1}{33} \sum_{i=1}^{33} D_i \tag{4.2}$$

where D_i is the *D* value of the *i*th IHA.

The value of D_0 obtained lies between 0 and 33 percent, thus indicating an overall low alteration.

If at least one of the 33 IHAs belongs to the moderate alteration category and none of the remaining belongs to the high alteration one, the overall degree of hydrologic alteration is given by;

$$D_o = 33\,\% + \frac{1}{33}\sum_{i=1}^{Nm}(D_i - 33\%) \tag{4.3}$$

where, N_m is the number of IHAs belonging to the moderate alteration category; D_i is the D value of the *i*th moderately altered IHA.

The value of D_0 obtained lies between 33 and 67 percent, indicating an overall moderate alteration.

If at least one IHA belongs to the high alteration category, the overall degree of hydrologic alteration is calculated by:

$$D_o = 67\,\% + \frac{1}{33}\sum_{i=1}^{Nh}(D_i - 67\%) \tag{4.4}$$

where, N_h is the number of IHAs belonging to the high alteration category; D_i is the D value of *i*th highly altered IHA.

The value of D_0 obtained lies between 67 and 100 percent, indicating an overall high alteration.

The overall degree of hydrologic alteration D_0 lies within the continuous interval of 0 to 100 percent and can be used as an index for defining the severity of the overall hydrologic alteration but is not a continuous function of its inputs. This method places a lot of weight on the categories of high and moderate alteration such that just one highly or moderately altered IHA would cause the overall degree of hydrologic alteration to be classified as high or moderate, respectively.

An RVA-based methodology is presented to determine the feasible combinations of flow diversion and downstream instream flow release for an operated reservoir. A feasible combination of flow diversion and instream flow release is defined as one that does not cause severe hydrologic alterations and thus is considered not to seriously disturb the riverine environment.

4.2.2 Daily Stream-flow at an Ungaged Site

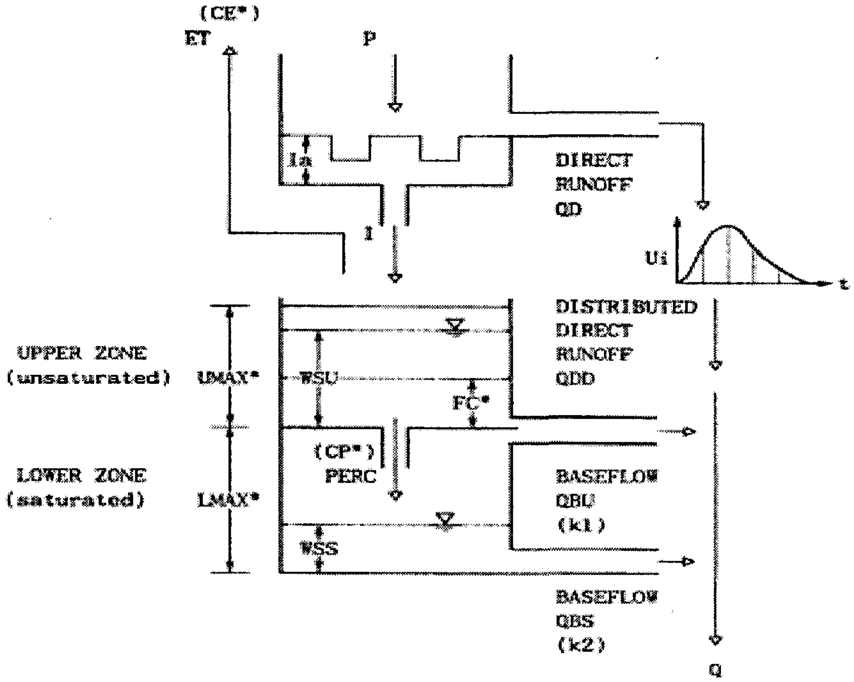
In order to run the IHA program, stream-flow data based on the time interval of a day at a given site are required. This means daily stream-flow data needs to be generated if it is not available from flow records. The DAily WAtershed Stream-flow (DAWAST) model developed by Noh (1991), which is based on rainfall-runoff response as a tank model, can provide stream-flow data at ungaged sites. The Yongdam Reservoir does not have a long historical data record available because the reservoir was built in 2001. Therefore, the DAWAST model is used to generate daily stream-flow data in this study.

The DAWAST Model (see Appendix B) developed by Noh (1991) can generate stream-flow data for an ungaged site considering site evapotranspiration, infiltration, and effective rainfall. DAWAST is a rainfall runoff model based on conceptualization. This model is composed of three parts: a rainfall-runoff module which can simulate stream-flow based on the rainfall, soil properties and others watershed characteristics; a water use module which can estimate municipal, industrial, and irrigation water use; and a dam operation module which can simulate reservoir release. This model was applied to the Geum River Basin Study (Noh, 2003).

The DAWAST Model can simulate daily continuous stream-flow depending on when rainfall events occur. This model estimates stream-flow considering the direct runoff and base flow if rainfall events occur and only base flow if rainfall does not occur. Input data includes daily precipitation and gage evaporation at a given site. Table 4.2 shows the parameters of the DAWAST model which consist of five water budget parameters and three of soil properties. Figure 4.1 illustrates the model structure which is composed of two parts; an unsaturated zone in the ground in which direct runoff is calculated based on the water budget considering precipitation, evapotransporation, and infiltration; and a saturated ground zone in which base flow is calculated by using the regression curve coefficients depending on soil moisture conditions. The model also has functions to estimate various water uses and operate reservoir.

Table 4.2 Parameters of the DAWAST Model

Div.	Parameter Name	Function	Unit
Water Budget	*UMAX*	Maximum soil moisture capacity in an unsaturated zone	Mm
	LMAX	Maximum soil moisture capacity in a saturated zone	mm
	FC	Field moisture capacity	mm
	CP	Percolation rate in a saturated zone	-
	CE	Basin evapotranspiration coefficient	-
Tracking	U_i	Distributed direct runoff ratio	-
	k1	Regression curve coefficient in an unsaturated zone	-
	k2	Regression curve coefficient in a saturated zone	-



Source: Noh (2003)

Figure 4.1 Schematic Diagram of the DAWAST Model

4.3 Application to Study Area

The reservoir-altered Geum River which has been a site of water use conflicts since dam completion was selected for assessing hydrologic alteration and instream flow requirements for fish and aquatic habitat using the IHA method. The river has two multipurpose dams to supply various water uses and control floods, Yongdam Reservoir and Daechung Reservoir.

4.3.1 Analysis of Daechung Reservoir Site

Daechung Reservoir has a long historical inflow record available for 26 years from 1981 to 2006. Yongdam reservoir which was completed in 2001 has affected the inflow of the Daechung reservoir due to its regulated release. The pre-impact data set has therefore been defined as 1981–2001, and the post-impact data set covers 2002-2006 which is relatively short time frame.

In running the IHA program, the type of statistics is specified as a parametric method which uses mean and standard deviation statistics. High and low flow pulse thresholds are defined as the mean plus or minus the standard deviation (± SD). The RVA category boundaries are the mean plus or minus the standard deviation (± SD). Instream flow component analysis (or Environmental Flow Component) of the IHA provides statistics for five different flow components: extreme low flows, low flows, high flow pulses, small floods, and large floods. Parameters used to define instream flow components are as follow;

High flow Pulses – all flows that exceed 75 % percent of flows for the period will be classified as high flow. No flows are below 50 percent of flows for the period will be classified as high flow pulses. Between these two flow levels, a high flow pulse will begin when flow increases by more than 25 percent per day, and will end when flow decreases by less than 10 percent per day.

Flood definition – a small flood event is defined as a high flow pulse with a recurrence time of at least 2 years, and a large event is defined as a high flow pulse with a recurrence time of at least 10 years.

Extreme low flow definition – an extreme low flow is defined as a flow in the lowest 10 percent of all low flows in the period.

The IHA results for Daechung reservoir are given in Table 4.3 and illustrated in Figure 4.2 and Figure 4.3. The stream-flow in the pre-impact period ranges from 7.4m^3/s

to 83.0m^3/s and the stream-flow in the post-impact from 15.5m^3/s to 32.5m^3/s for January. The lower boundary of the RVA is 12.3m^3/s and the upper boundary is 35.0m^3/s for January. The annual coefficient of variation is 2.95 for the pre-impact and 2.8 for the post-impact. The average and overall degrees of hydrologic alterations are 39.32 % and 71.25 %, respectively. After the completion of Yongdam Reservoir, overall inflow into Daechung Reservoir is increased slightly, especially low-flows. The constant release from Yongdam Reservoir has caused downstream instream flow requirement to increase in this case. In terms of low flow quantities, Yongdam Reservoir has improved Daechung's inflows, while the Yongdam has affected the occurrence frequencies of flood and low-flow.

Table 4.3 Monthly Results of the IHA Method at Daechung Reservoir Site

(Unit: m^3/s)

	Pre-impact (1981-2001)		Post-impact(2002-2006)		RVA Boundaries	
	Minimum	Maximum	Minimum	Maximum	Low	High
January	7.4	83.0	15.5	32.5	12.2	35.0
February	5.4	136.6	17.2	43.2	11.4	59.8
March	10.9	90.6	19.3	58.6	23.2	67.5
April	17.8	153.2	20.3	139.4	25.4	87.3
May	7.8	126.9	22.3	138.4	8.9	81.5
June	6.0	420.7	23.2	223.0	30.1	184.3
July	17.8	534.7	52.0	810.8	104.7	417.2
August	33.6	726.7	103.1	359.9	63.0	415.1
September	10.7	480.9	34.2	412.5	23.9	295.6
October	6.6	194.8	20.5	35.7	17.4	91.59
November	1.8	71.46	17.0	25.4	10.8	43.45
December	2	55.6	16.9	30.7	8.9	37.9

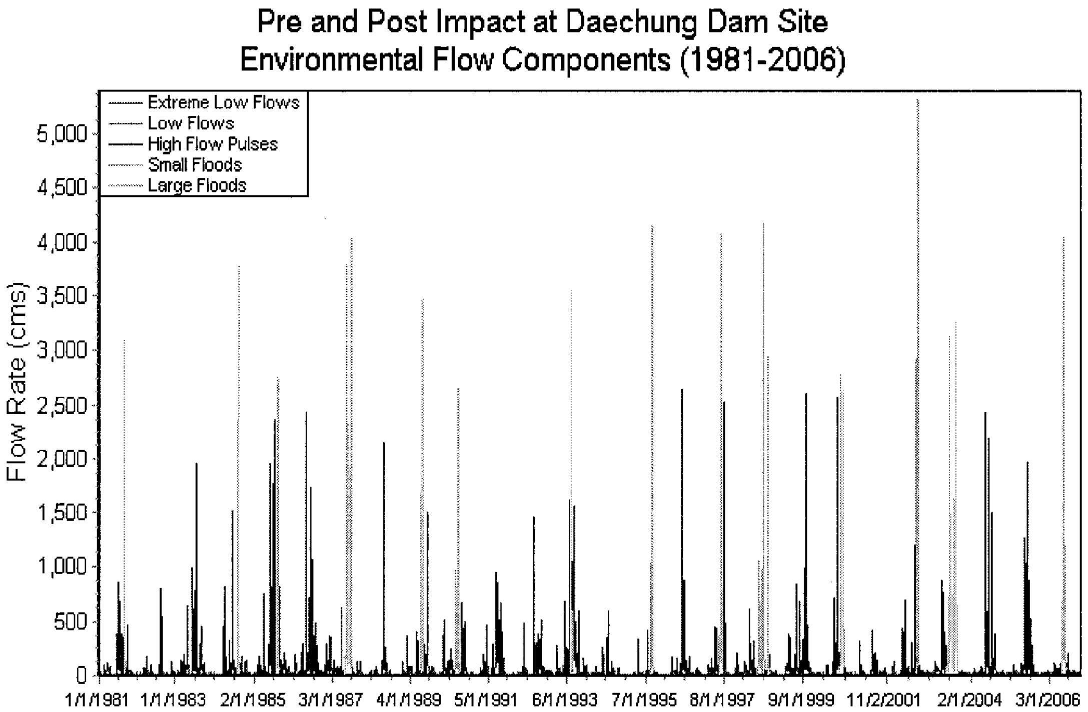


Figure 4.2 Environmental Flow Components at the Daechung Reservoir

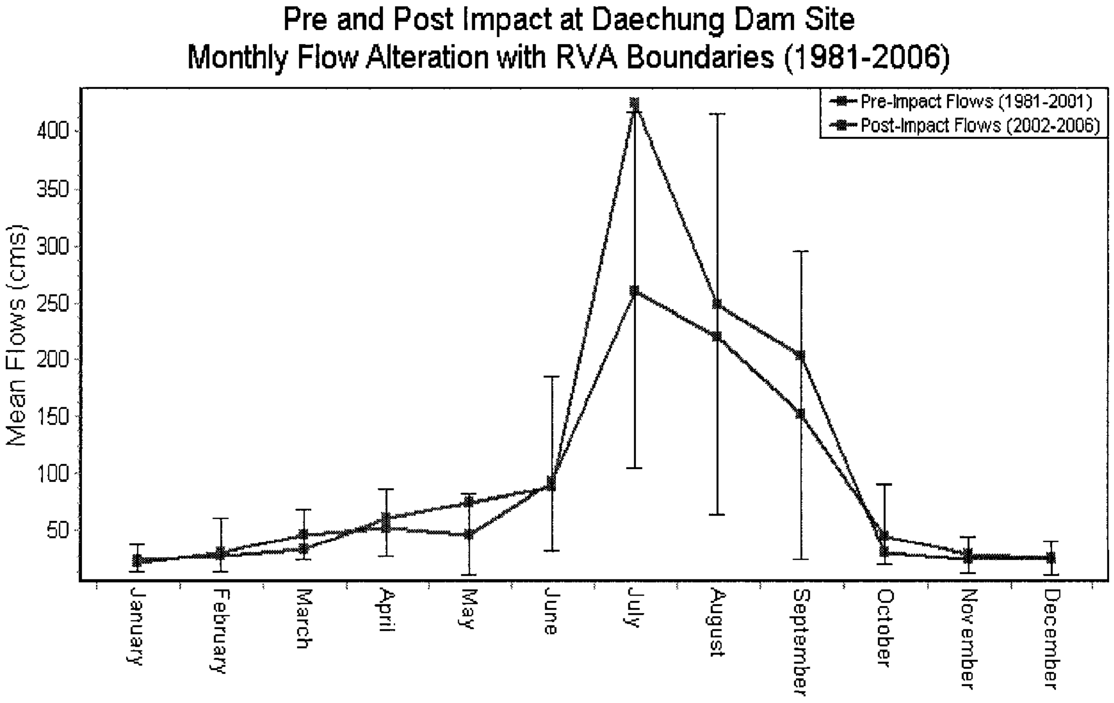


Figure 4.3 Monthly Flow Alterations with RVA Boundaries

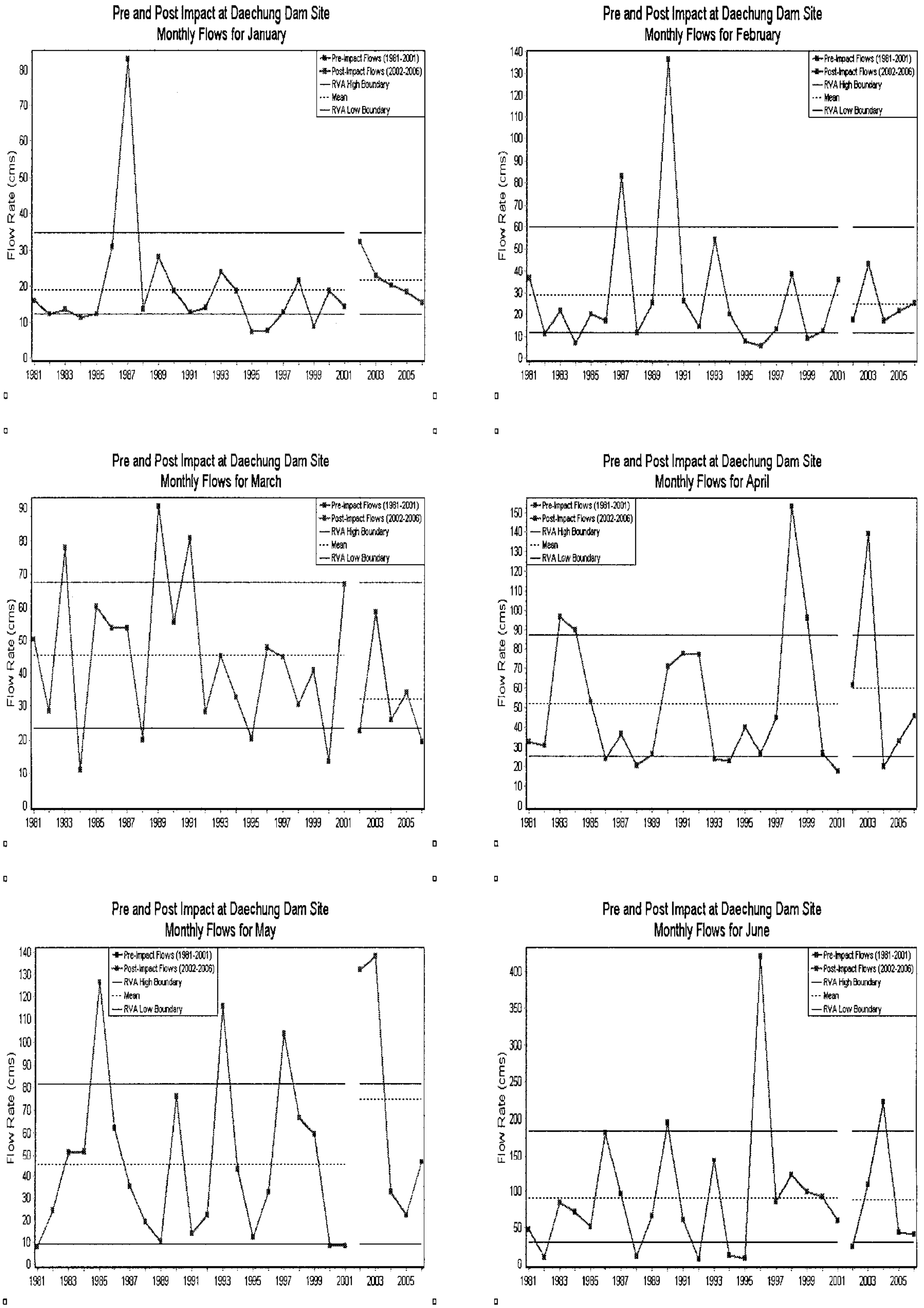
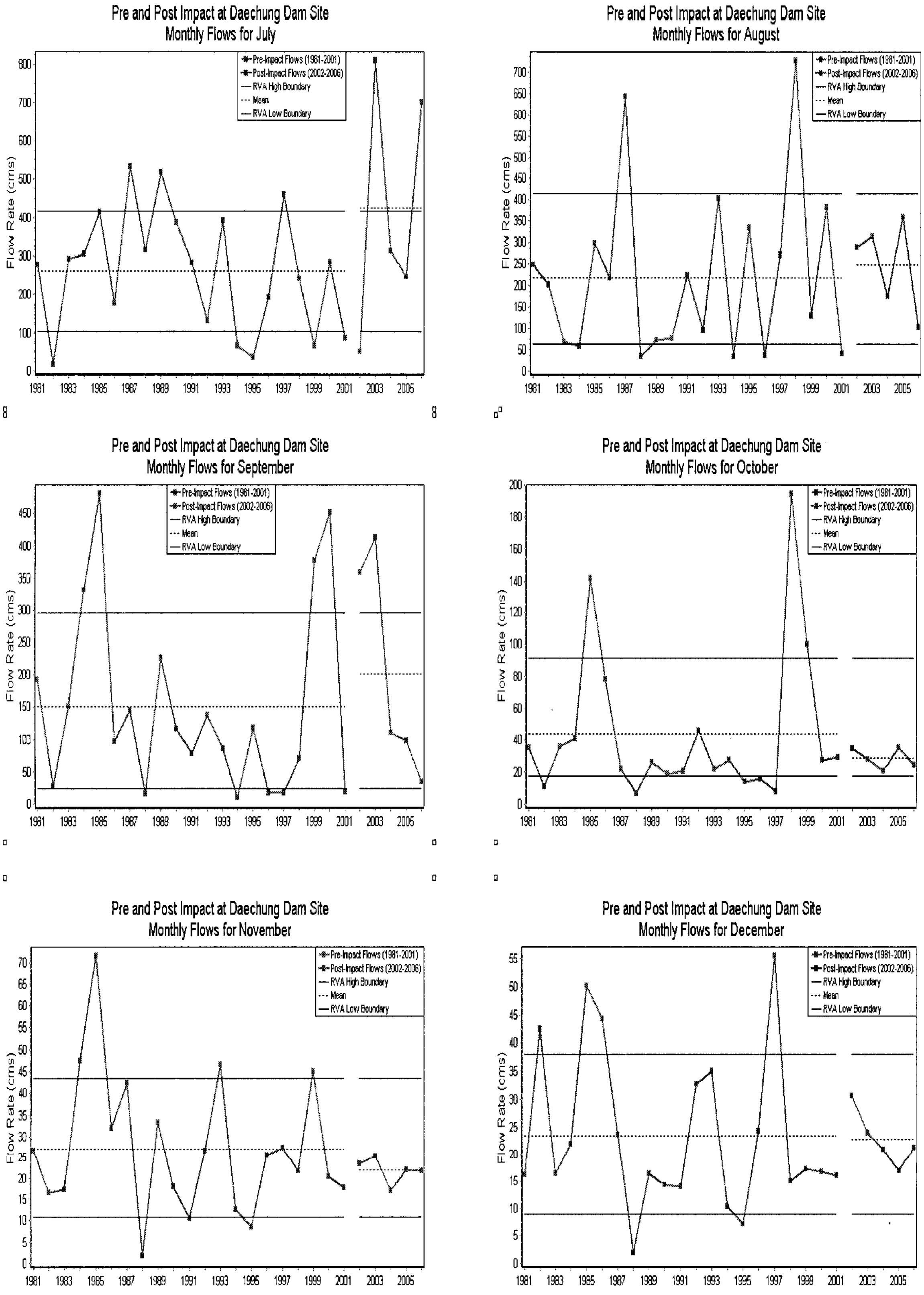


Figure 4.4 Monthly Flow Alterations with RVA Boundaries



Pre and Post Impact at Daechung Dam Site Monthly Flows for July

Pre and Post Impact at Daechung Dam Site Monthly Flows for August

Pre and Post Impact at Daechung Dam Site Monthly Flows for September

Pre and Post Impact at Daechung Dam Site Monthly Flows for October

Pre and Post Impact at Daechung Dam Site Monthly Flows for November

Pre and Post Impact at Daechung Dam Site Monthly Flows for December

Figure 4.5 Monthly Flow Alterations with RVA Boundaries (continued)

4.3.2 Analysis of Yongdam Reservoir Site

4.3.2.1 Historical Data

The Yongdam Reservoir was built in 2001 and has a short historical inflow record for 6 years from 2001 to 2006. The pre-impact data set has therefore been defined as 2001-2006 for the inflow, and the post-impact data set covers 2011-2016 for the outflow for the same period to compare the results of the two periods. The IHA results for the Yongdam reservoir are given in Table 4.4 and illustrated in Figure 4.6 and Figure 4.7. The average and overall degree of hydrologic alterations are 65.52% and 79.12%, respectively. The stream-flow in the pre-impact period ranges from 1.1m^3/s to 25.2m^3/s and the stream-flow in post-impact from 2.4m^3/s to 30.2m^3/s. The lower boundary of RVA was 2.0m^3/s and the upper boundary of RVA was 16.6m^3/s for January. The annual coefficient of variation was 3.0 for the pre-impact and 1.81 for the post-impact. According to the results obtained, low-flow increases in response to the dam construction, while the occurrence frequencies of large and small floods decrease. These hydrologic alterations can affect downstream aquatic conditions and fishery habitats.

Table 4.4 Results of the IHA Method at Yongdam Reservoir Site (Unit: m^3/s)

	Pre-impact (2001-2006)		Post-impact(2011-2016)		RVA Boundaries	
	Minimum	Maximum	Minimum	Maximum	Low	High
January	1.1	25.2	2.4	30.2	2.0	16.6
February	4.3	16.9	2.7	26.4	4.8	16.7
March	2.0	27.7	14.4	27.4	4.6	23.5
April	8.1	58.1	13.8	26.8	8.4	44.7
May	4.0	48.5	5.5	29.2	4.5	38.5
June	7.4	42.8	8.3	31.8	10.7	36.6
July	19.8	220.7	14.5	221.7	34.9	189.6
August	18.5	173.0	12.1	76.9	23.3	140.8
September	4.2	100.3	17.2	98.7	9.4	74.5
October	0.9	15.3	15.3	27.2	1.5	11.7
November	1.0	14.6	14.3	27.6	1.5	10.8
December	0.6	15.3	12.5	25.7	1.5	12.2

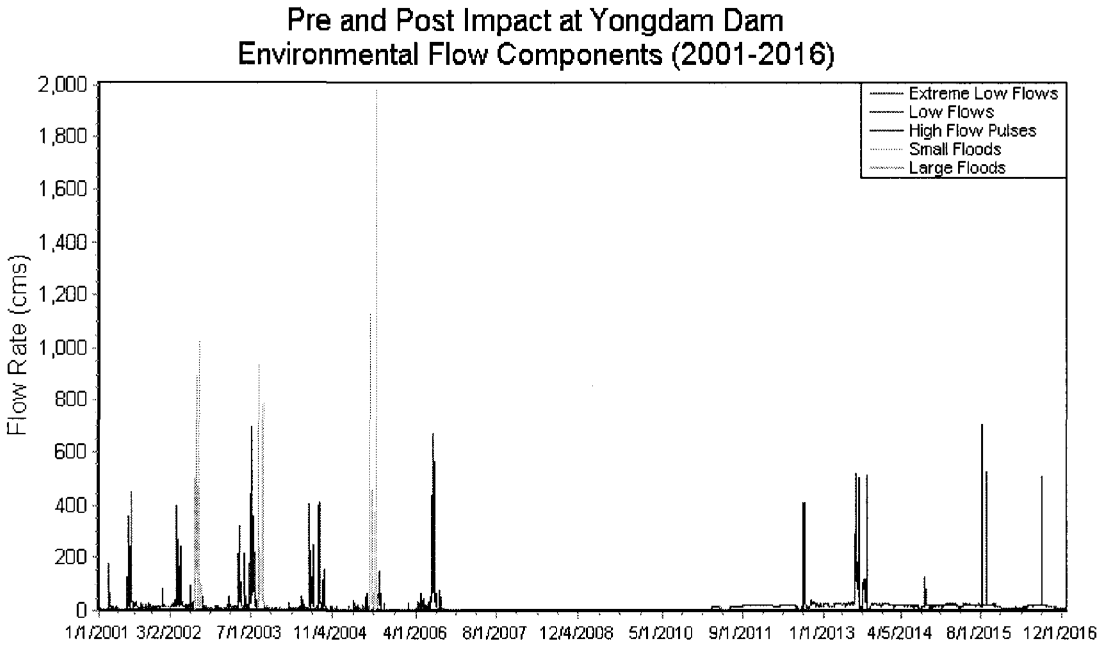


Figure 4.6 Environmental Flow Components at Yongdam Reservoir

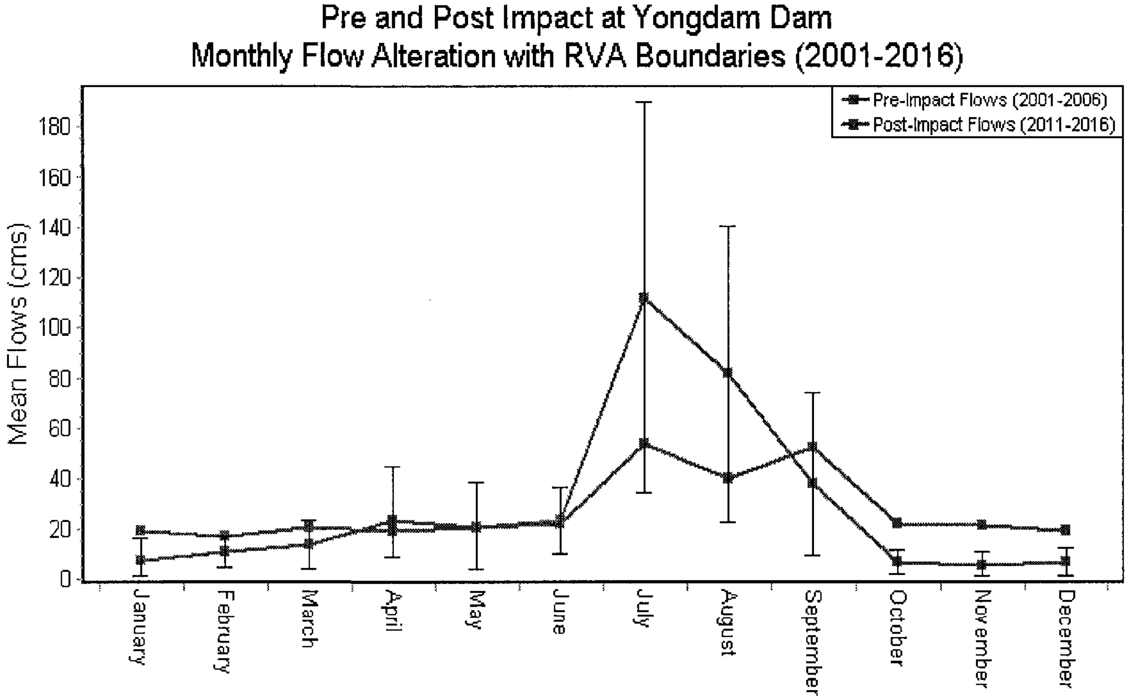


Figure 4.7 Monthly Flow Alterations with RVA Boundaries

4.3.2.2 Simulated Data

In order to estimate the instream flow requirement, a daily data set was simulated by the DAWAST model. The pre-impact data set was defined as 1996-2005 for the inflow and the post-impact data set was 2006-2015 for the release from the reservoir and included instream flow requirements and spills to compare the results of the two periods. The water year was set to begin on 1996-01-01.

The IHA results for the Yongdam reservoir are given in Table 4.5 and Table 4.6 and illustrated in Figure 4.8 through Figure 4.10. The RVA boundaries of stream-flow in January range from 2.26m^3/s to 5.471m^3/s when the instream flow requirement was set as 3m^3/s. The means of stream-flow in January are 3.337m^3/s for the pre-impact period and 3m^3/s for the post-impact period, respectively. The calculated average and overall degree of hydrologic alterations are 69.72 percent and 80.54 percent for the scenarios-2 which was set as 3m^3/s for instream flow requirements for fish and aquatic habitat downstream, respectively, as shown in Table 4.5.

According to the results obtained, increasing the instream flow requirements does not necessarily improve the average and overall degree of hydrologic alteration. In this analysis, the best instream flow requirement obtainable is about 3m^3/s. This means that the presence of the Yongdam Reservoir has significantly affected the downstream hydrologic conditions in the case of the Yongdam Reservoir. The important factor is the trans-basin water supply. In order to meet trans-basin water and downstream instream flow requirements under the given conditions, it is recommended the instream flow requirement is set to 3m^3/s.

Table 4.5 Results of the IHA Method at Yongdam Reservoir Site by Scenarios

	Instream-flow Release (m^3/s)	Average Degree (%)	Overall Degree (%)	Low Flow Threshold (m^3/s)	No. of IHAs		
					Low Alterna-tion	Moderate Alterna-tion	High Alterna-tion
Scenario-1	2	80.40	86.00	2.26	3	7	23
Scenario-2	3	69.72	80.56	2.26	5	10	18
Scenario-3	4	72.22	81.08	2.26	5	9	19
Scenario-4	5	74.22	82.00	2.26	5	8	20
Scenario-5	6	77.33	83.37	2.26	4	9	20

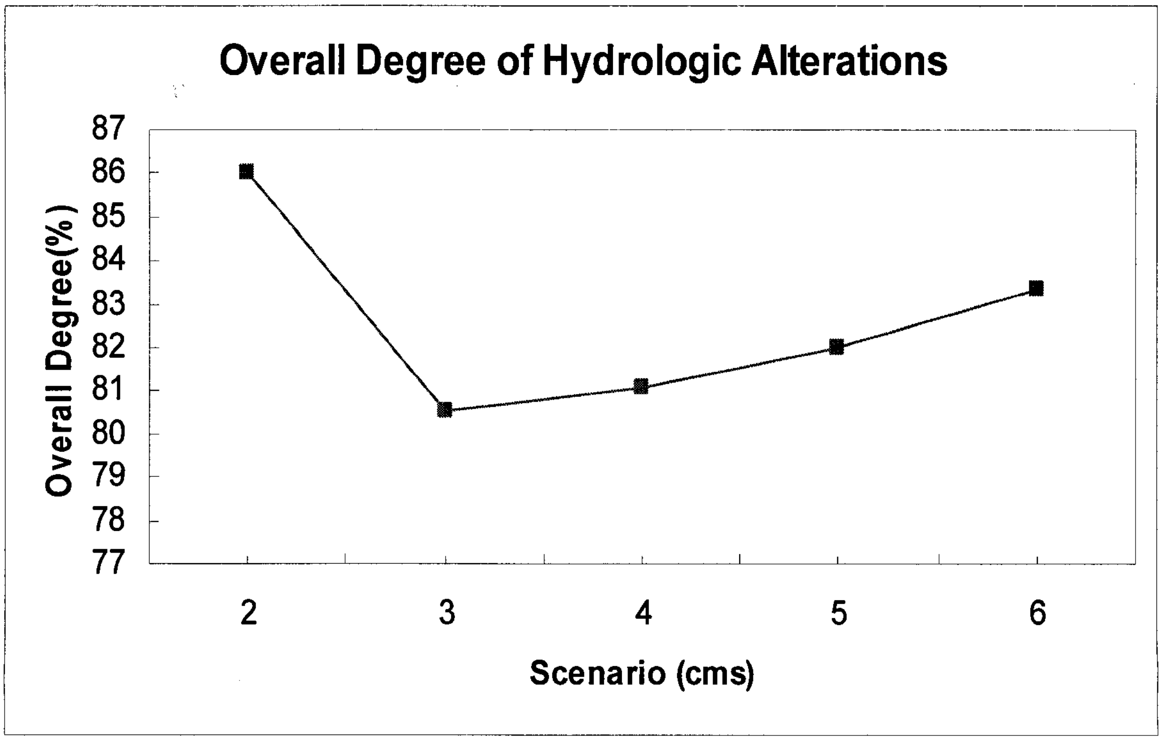


Figure 4.8 Overall Degree of Hydrologic Alterations by Scenarios

Table 4.6 Degree of Hydrologic Alteration (when scenario 3m^3/s)

Indicators of hydrologic alterations	RVA Boundary(m^3/s)		Means(m^3/s)		N_e	N_0	D(%)	Class
	Lower	Upper	Pre-Impact	Post-Impact				
Group 1: January	2.26	5.471	3.337	3	8	10	25.00	L
February	2.26	7.333	3.987	3	9	10	11.11	L
March	2.49	7.661	5.076	3	6	10	66.67	M
April	2.989	30.09	14.63	3	6	10	66.67	M
May	3.143	23.56	12.61	3	6	0	100.00	H
June	6.901	55.66	31.28	4.336	7	1	85.71	H
July	11.75	120.2	65.97	19.01	7	3	57.14	M
August	19.9	119.1	69.52	22.91	6	3	50.00	M
September	5.185	60.52	32.85	7.406	6	1	83.33	H
October	3.275	19.97	9.859	4.136	6	1	83.33	H
November	2.338	25.33	8.3	3	7	10	42.86	M
December	2.26	12.89	6.568	3	9	10	11.11	L
Group 2: 1-day minimum	2.15	2.251	2.194	3	6	0	100.00	H
3-day minimum	2.245	2.26	2.256	3	9	0	100.00	H
7-day minimum	2.26	2.305	2.271	3	9	0	100.00	H
30-day minimum	2.26	2.623	2.35	3	9	0	100.00	H
90-day minimum	2.484	3.786	2.967	3	7	10	42.86	M
1-day maximum	404.4	854.6	629.5	224.1	7	2	71.43	H
3-day maximum	302.7	674.8	488.7	165.3	7	2	71.43	H
7-day maximum	183	379	281	93.6	6	3	50.00	M
30-day maximum	78.68	167.4	123	34.77	6	2	66.67	M
90-day maximum	41.97	91.72	66.84	17.68	8	1	87.50	H
Number of zero days	0	0	0	0	10	10	0.00	L
Base flow condition	0.0756	0.152	0.1138	0.7002	8	1	87.50	H
Group 3: Date of annual Minimum	24.44	237.2	130.8	1	5	0	100.00	H
Date of annual Maximum	184.3	274.3	229.3	110.2	8	5	37.50	M
Group 4: Low-pulse count	0.02505	1.375	0.7	0	5	0	100.00	H
Low-pulse duration	1	1	1		1	1	0.00	L
High-pulse count	4.229	8.571	6.4	1.5	6	1	83.33	H
High-pulse duration	2.343	3.875	3.109	3.119	6	3	50.00	M
Group 5: Rise rate	21.65	38.46	30.06	97.93	7	0	100.00	H
Fall rate	-17.04	-8.95	-13	-83.18	7	0	100.00	H
Flow reversals	57	76.67	66.3	4.9	7	0	100.00	H
Average Degree							**69.72**	**H**
# of Low Alteration								5
# of Moderate Alteration								10
# of High Alteration								18
Overall Degree							**80.56**	**H**

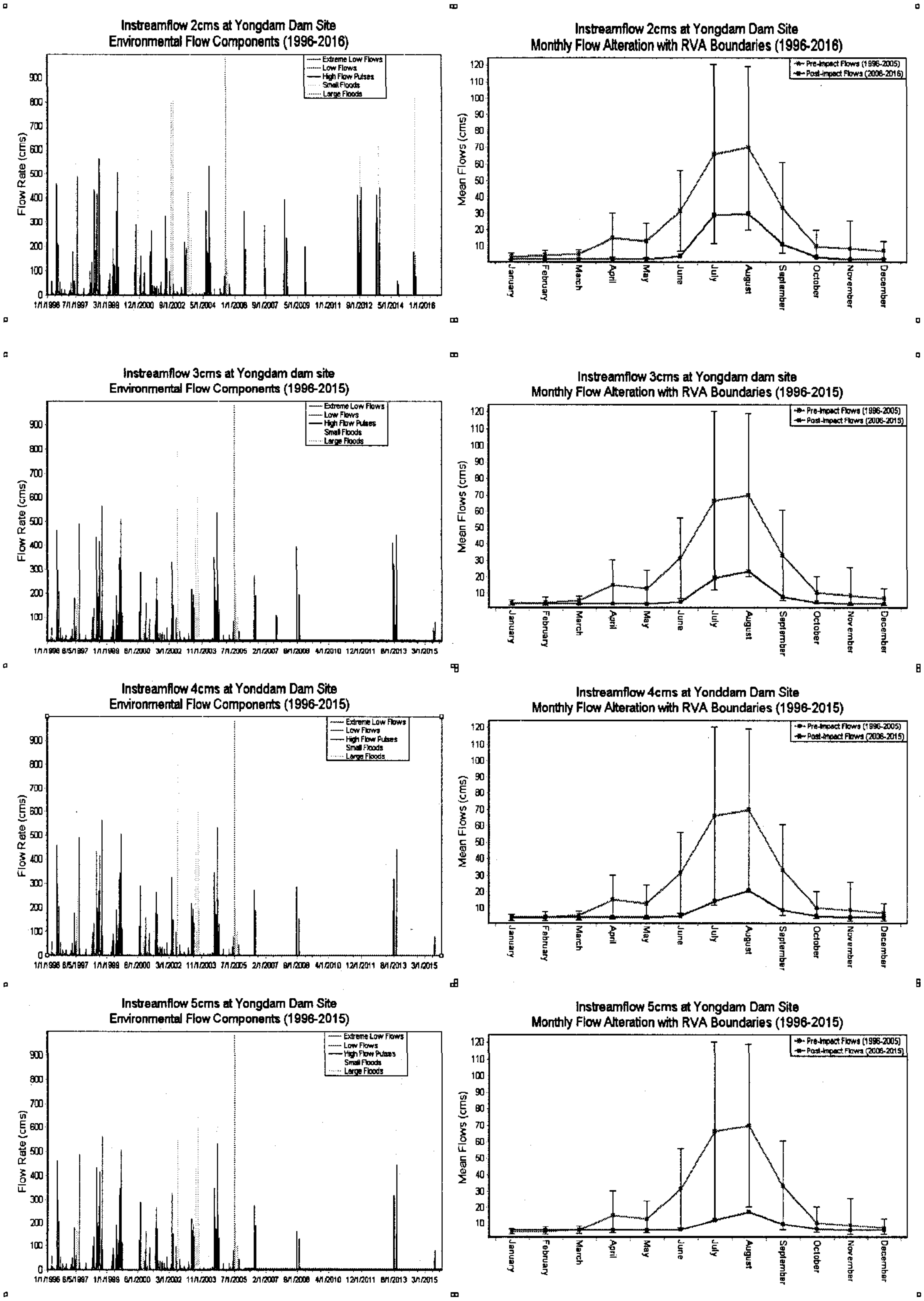


Figure 4.9 Environmental Flow Components and Monthly Flow Alterations with RVA Boundaries by Scenarios

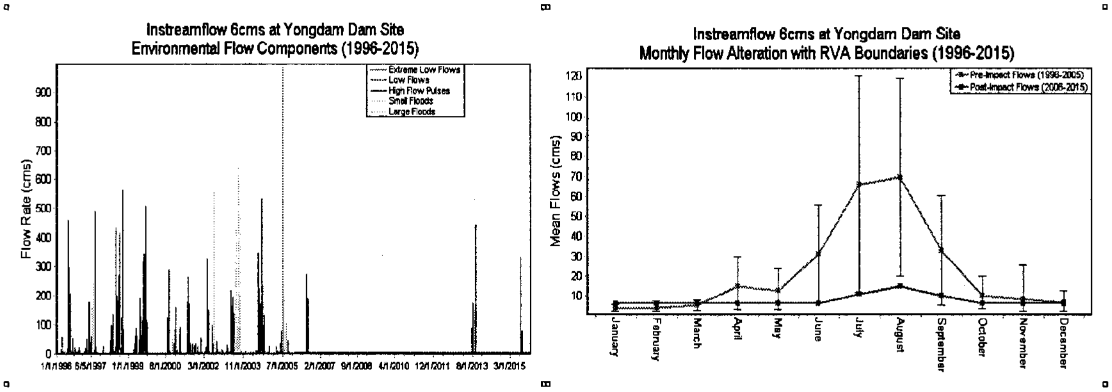


Figure 4.10 Environmental Flow Components and Monthly Flow Alterations with RVA Boundaries by Scenarios (continued)

4.4 Generation of Daily Stream-flow

In this study, steamflow data was generated by using the DAWAST model. The DAWAST model has also functions which can provide estimates of water use and simulate dam operation based on a daily time step. Stream-flow and precipitation of the upstream Daechung reservoir have been observed since the reservoir was completed in 1981, yet the available data of Yongdam reservoir for this study is limited because the reservoir was built in 2001. Therefore, generating daily stream-flow data to analyze the possible instream flow for various water uses was required.

4.4.1 Estimation of Water Use for Irrigation

In order to estimate the irrigation requirements of paddy fields, input data such as evapotranspiration, infiltration, and effective rainfall must be considered in the model. The rate of evapotranspiration is affected by meteorological conditions, such as duration of sunshine, temperature, humidity and wind speed. Infiltration is determined by factors such as soil properties and types and groundwater level. The amounts of water used in cultivating rice and in managing hydraulic facilities are also considered. Paddy water requirements are calculated by multiplying the paddy area, adding decreasing pond depth, subtracting effective rainfall and taking into account additional various losses.

Using the DAWAST model, daily paddy water requirements were estimated in the upstream Yongdam reservoir during the last 10 years from 1996 to 2005. Effective rainfall was considered, ponding depth was specified to 60mm, infiltration depth was 5mm, water use ratio for hydraulic facilities was 15%, and the water use ratio for cultivation management was 20%. Tables 4.7 through 4.8, and Figures 4.11through 4.12 show results of estimated daily paddy water requirements which depend on the annual rainfall. That is, with decreases in annual rainfall, both paddy water requirements and evapotranspiration demands increase. For example, during the drought seasons in 2001, the amount of annual rainfall was 1,027.4mm, pan evaporation was 1,047.0mm (2.9mm/day), evapotranspiration was 976.07mm (5.3mm/day), mean ponding depth was 34.4mm, and paddy water requirements were 33.4MCM for one year. Based on the annual average for the last 10 years from 1996 to 2005, annual paddy water requirements range from 19.3MCM to 33.8MCM. Table 4.8 lists the monthly results of paddy water requirements.

The DAWAST model can also provide estimates of municipal and industrial water use. Municipal water use is estimated by multiplying the number of persons who reside within a sub-watershed by the amount of water used per day per person. Industrial water use is estimated by multiplying the number of workers or the area of an industrial complex within a watershed by the amount of water used per person or per unit area. Figure 4.12 shows the results of estimates for various water uses at the upstream Yongdam reservoir for 10 years from 1996 to 2005.

Table 4.7 Summary of Paddy Water Requirements

Year	Rainfall (mm/yr)	Evaporation (mm/yr)	Evapotrnas-piration (mm/yr)	Average Ponding Depth(mm/day)	Paddy Water	
					Yearly (MCM)	Daily (MCD)
1996	1238.2	1149.3	902.13	34.4	27.5	0.16
1997	1464.6	1210.9	899.48	35.9	30.3	0.18
1998	1736.6	998.4	758.14	37.5	26.9	0.16
1999	1321.1	1056.1	857.15	36.4	26.4	0.15
2000	1053.4	961.6	923.57	33.2	34.7	0.20
2001	1027.4	1047.0	976.07	34.4	33.8	0.20
2002	1661.04	1090.4	879.93	36.4	32.1	0.19
2003	2050.33	813.3	810.26	40.3	19.3	0.11
2004	1392.2	987.5	836.68	37.4	26.0	0.15
2005	1478.2	938.6	866.77	36.2	27.4	0.16
Mean	1442.31	1025.31	871.02	36.21	28.44	0.17

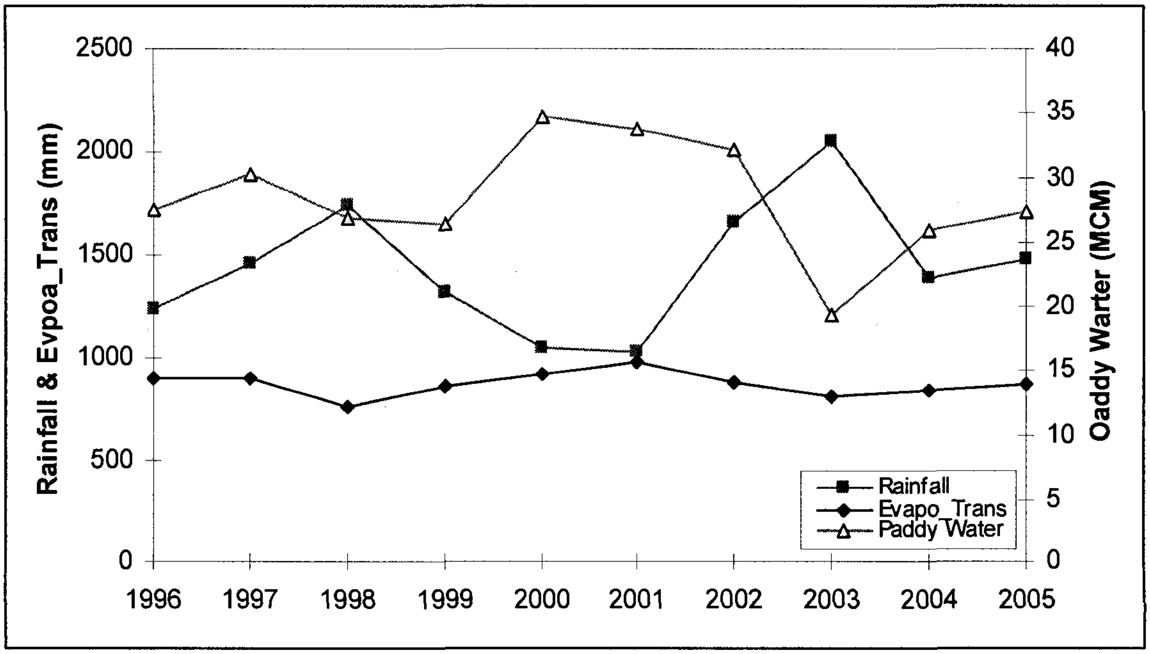


Figure 4.11 Water Paddy Requirements at the Upstream YongDam Reservoir

Table 4.8 Monthly Estimated Water Use for M& I, and Irrigation of the Upstream Yongdam Reservoir

(Unit: MCM)

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	Subtotal	0.2	0.2	0.2	0.8	6.4	4.1	4.7	8.9	4.2	0.3	0.3	0.3	30.6
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.5	6.2	3.8	4.4	8.6	3.9	0.0	0.0	0.0	27.5
1997	Subtotal	0.2	0.2	0.2	0.8	5.8	7.1	3.5	10.3	4.4	0.3	0.3	0.3	33.4
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.6	5.5	6.9	3.2	10.0	4.2	0.0	0.0	0.0	30.3
1998	Subtotal	0.2	0.2	0.2	0.7	6.4	6.5	5.4	5.5	4.2	0.3	0.3	0.3	30.0
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.4	6.1	6.3	5.1	5.2	3.9	0.0	0.0	0.0	26.9
1999	Subtotal	0.2	0.2	0.2	0.7	6.1	8.9	4.8	6.4	1.1	0.3	0.3	0.3	29.4
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.5	5.9	8.7	4.5	6.1	0.8	0.0	0.0	0.0	26.4
2000	Subtotal	0.2	0.2	0.2	0.8	6.5	12.1	9.9	5.1	2.0	0.3	0.3	0.3	37.8
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.6	6.2	11.8	9.6	4.8	1.7	0.0	0.0	0.0	34.7
2001	Subtotal	0.2	0.2	0.2	0.8	6.5	7.7	4.1	11.9	4.3	0.3	0.3	0.3	36.9
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.6	6.3	7.5	3.8	11.7	4.1	0.0	0.0	0.0	33.8
2002	Subtotal	0.2	0.2	0.2	0.7	6.4	10.4	6.5	6.9	2.8	0.3	0.3	0.3	35.2
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.5	6.1	10.1	6.2	6.6	2.5	0.0	0.0	0.0	32.1
2003	Subtotal	0.2	0.2	0.2	0.6	5.1	7.9	0.6	5.1	1.6	0.3	0.3	0.3	22.3
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.4	4.8	7.7	0.3	4.8	1.3	0.0	0.0	0.0	19.3
2004	Subtotal	0.2	0.2	0.2	0.8	5.7	9.2	3.8	5.7	2.5	0.3	0.3	0.3	29.1
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.5	5.4	8.9	3.5	5.4	2.2	0.0	0.0	0.0	26.0
2005	Subtotal	0.2	0.2	0.2	0.7	6.6	7.4	4.7	6.3	3.3	0.3	0.3	0.3	30.4
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.5	6.3	7.1	4.4	6.0	3.0	0.0	0.0	0.0	27.4
Mean	Subtotal	0.2	0.2	0.2	0.7	6.1	8.1	4.8	7.2	3.0	0.3	0.3	0.3	31.5
	M & I	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.1
	Irrig	0.0	0.0	0.0	0.5	5.9	7.9	4.5	6.9	2.8	0.0	0.0	0.0	28.4

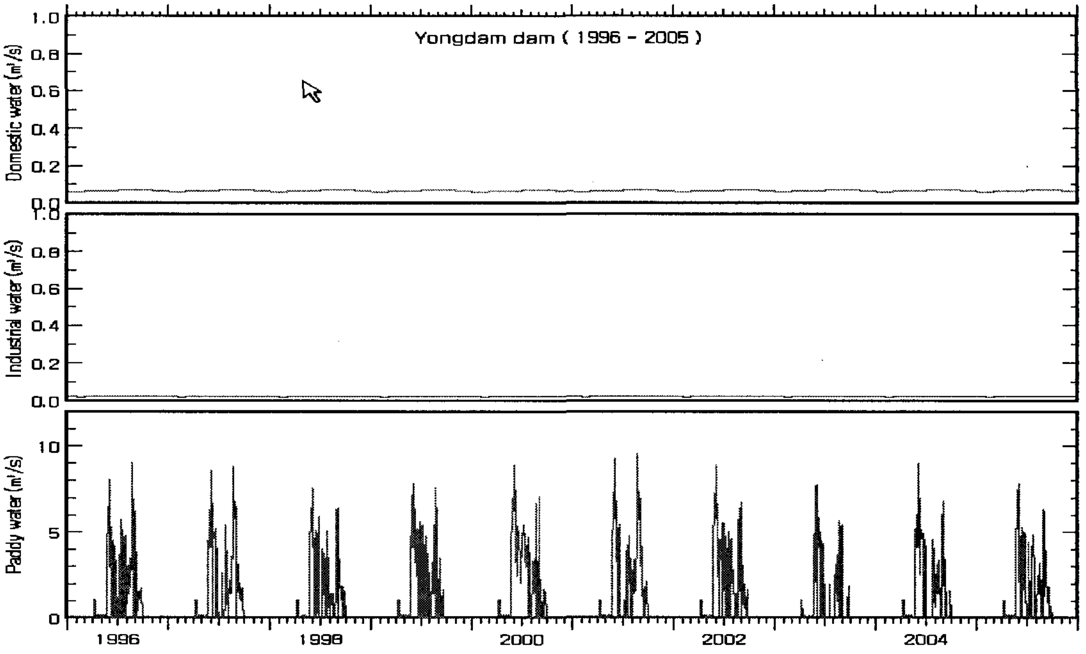


Figure 4.12 Estimation of Various Water Use at the Upstream Yongdam Reservoir

4.4.2 Generation of Daily Stream-flow

In order to analyze instream flow requirements for fish and aquatic habitat by using the RVA method based on daily data, generating daily stream-flow data are required. As stated in section 4.2, the daily stream-flow data for 10 years from 1996 to 2005 were generated by using the DAWAST Model which has the function of considering the return flow from water demands. Five parameter optimization of the DAWAST model (Noh, 1999) was calibrated by using the Simplex method. The ratios of return flow are 65 percent for municipal and industrial water use and 35 percent for irrigation water use which were applied by KOWACO (2000) in the Geum Basin Study. Figure 4.13 and Figure 4.14 show the result of five parameters optimized at the upstream Yongdam site. The values of the five estimated parameters are UMAX 280.2mm, LMAX 22.2mm, FC 141.5mm, CP 0.0142 and CE 0.0074 in the model. The calibration period was assigned as two years from 2002 to 2003, and the verification period was two years from 2004 to 2005. Figure 4.15 shows the daily stream-flow simulated. Stream-flow runoff is simulated by the estimated parameters. For example, the annual observed runoff was 1048.1mm and simulated runoff was 922.1mm when rainfall was 1661.0mm in 2002. The ratio of the simulated runoff to the observed runoff is 88.0 %. This model can relatively simulate the high flows acceptably, but not the low flows. On the whole, the results obtained were relatively good. These obtained results are used to analyze instream flow requirement at an ungaged site in this study.

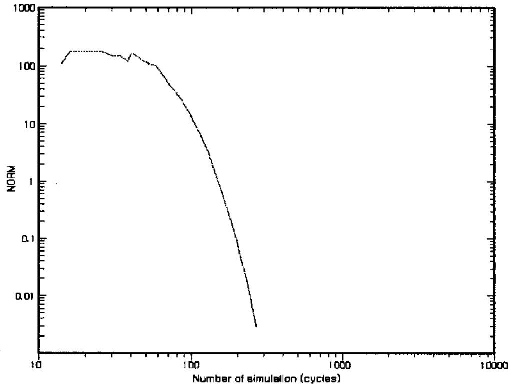


Figure 4.13 Estimation of Five Parameters Considering Various Water Uses

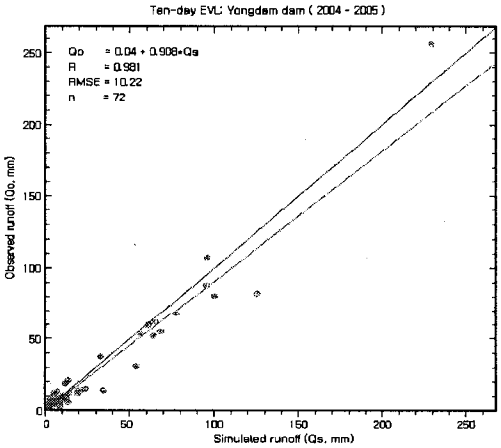


Figure 4.14 Verification between the Observed and the Simulated (2004-2005)

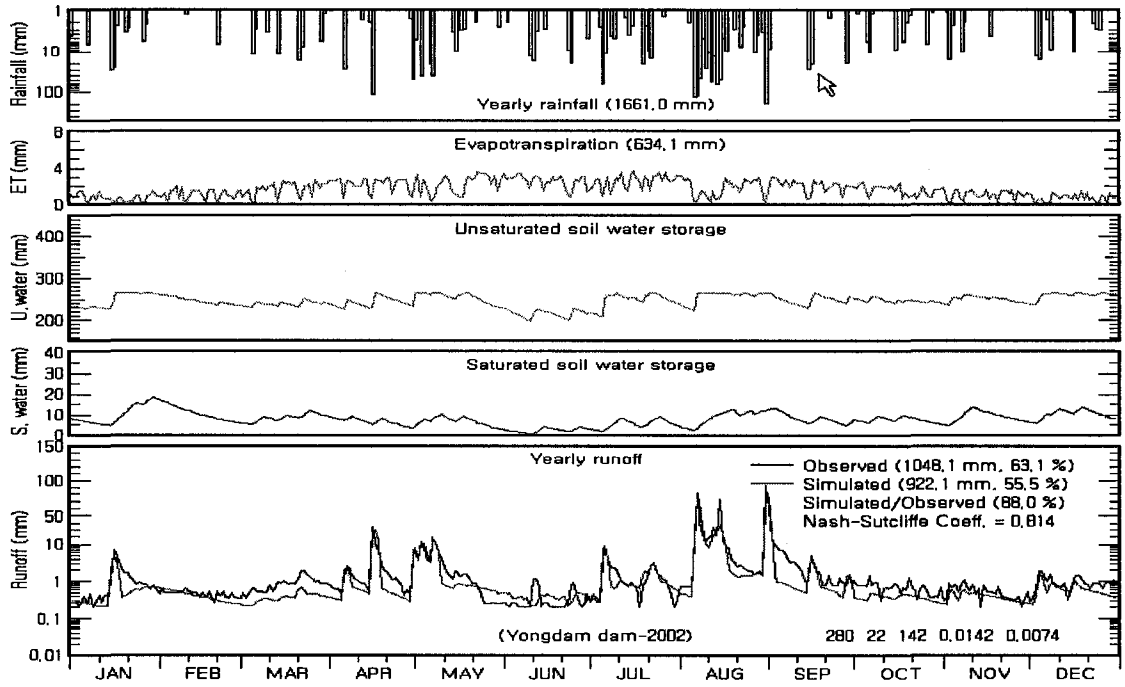


Figure 4.15 Daily Simulated Stream-flow (2002)

4.4.3 Water Storage Simulation in a Reservoir

In order to simulate reservoir operations based on simulated various water uses and stream-flows, the standard operating policy (SOP) is used in the DAWAST. The priority of release from a reservoir is the order of instream flow requirement, and trans-basin water supply. The initial water level was specified as 263.5m, and the restricted water level in the wet season from June to September was 261.5m as specified by KOWACO (2002). Figure 4.16 and Figure 4.17 show daily simulated reservoir operations that met the required instream flow flows when set as 4.1m^3/s. The required instream flow varied with 2m^3/s to 6m^3/s According to the results obtained, if the required downstream instream flow is greater than 4.0m^3/s, a deficit of water supply in the trans-basin transfer occurs. Spill from the reservoir rarely occurred. These results show the construction of the reservoir significantly affected stream-flow conditions. Figure 4.18 shows the results of reservoir operation for ten years

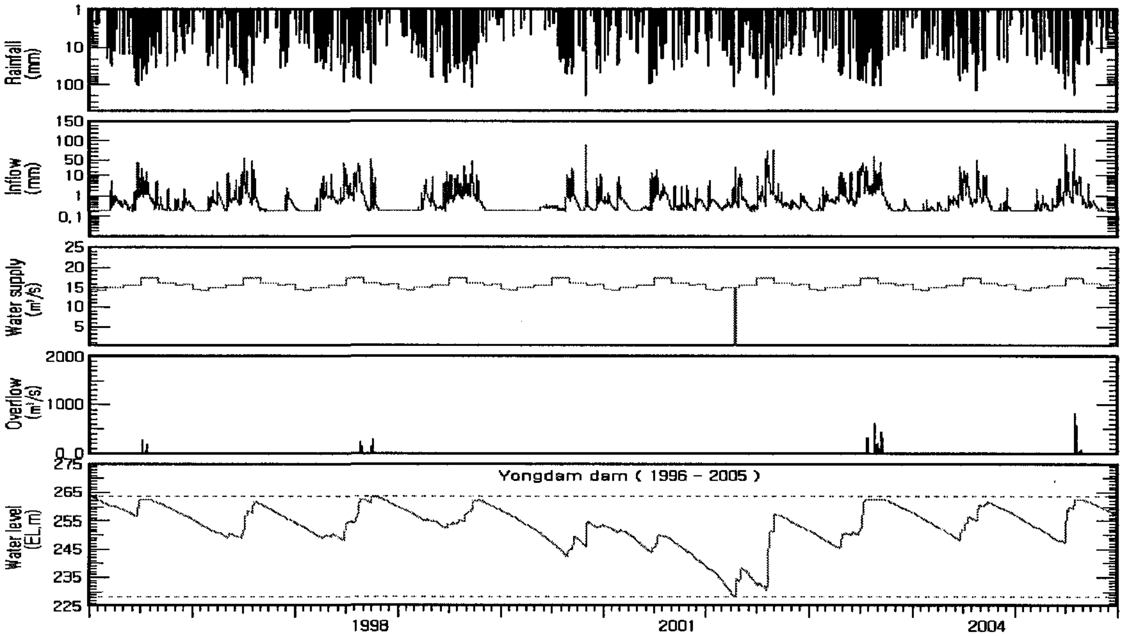


Figure 4.16 Results of Reservoir Operation when Instream flow is 4.1 m^3/s

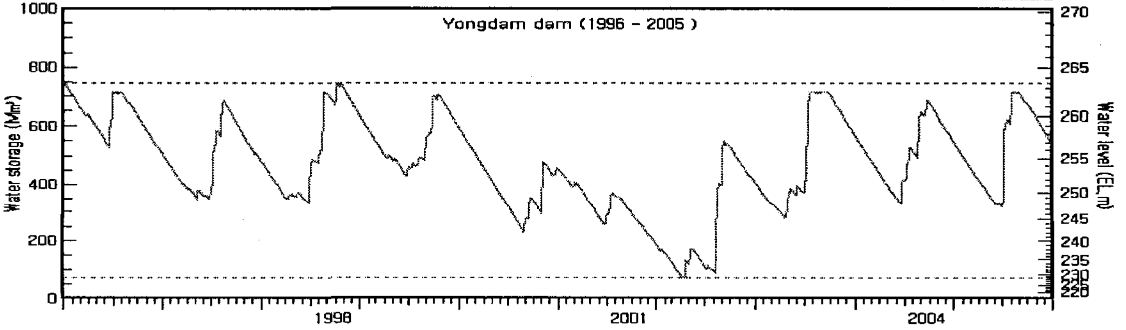


Figure 4.17 Deficit of Water Supply when Instream flow is 4.1m^3/s

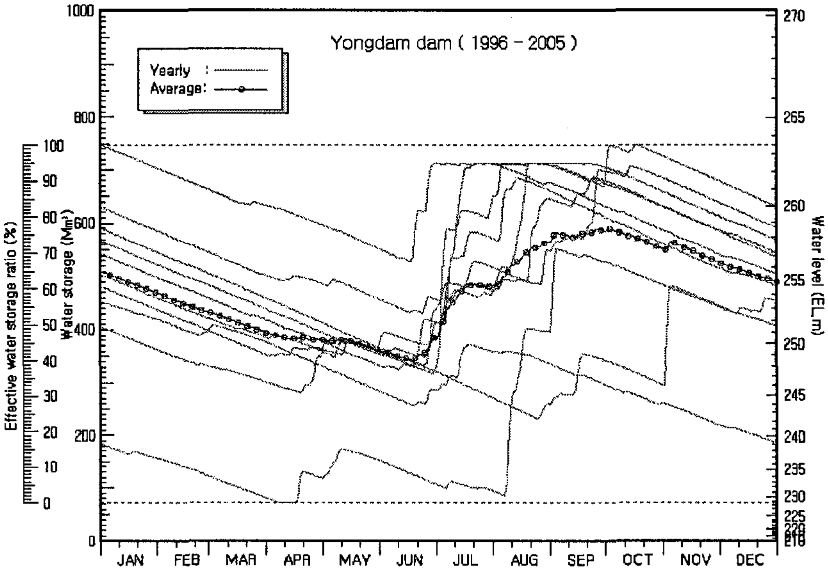


Figure 4.18 Water Level and Storage for Analyzed periods (1996 – 2005)

4.5 Summary

An RVA-based methodology is presented to determine the feasible combinations of flow diversion and downstream in-stream release for an operated reservoir. A feasible combination of flow diversion and instream flow release is defined as one that does not cause severe hydrologic alterations and thus is considered not to seriously disturb the riverine environment.

In order to estimate the instream flow requirements using the RVA method, it is necessary to simulate the daily stream-flow at an ungaged site and the DAWAST model was used.

Under the given conditions, Yongdam reservoir has the potential of high ecological impacts according to the results of the overall hydrologic alteration. The main factor of hydrologic alteration is trans-basin water supply. In order to meet the water supply and downstream instream flow requirements for fish and aquatic habitat, the downstream instream flow requirement for ecologic health is about $3m^3/s$ based on simulated data.

CHAPTER 5

OPTIMIZING CONJUNCTIVE MANAGEMENT SYSTEMS

5.1 Introduction

This chapter evaluates conjunctive use management using a multi-objective optimization model that considers water supply, instream flow requirements for fish and aquatic habitat, trans-basin diversion, withdrawal for groundwater and surface waters. In order to meet this purpose, response matrix coefficients for stream depletion must be developed by using MODFLOW for transient conditions and a multi-objective linear optimization model must be developed by using the CPLEX software.

5.2 Response-Matrix Technique for Stream-Aquifer System

5.2.1 Response-Matrix Technique

To evaluate the sustained yield of a set of pumping wells in stream-aquifer systems, the optimization method is based on a commonly applied technique called the response matrix technique. This technique assumes that the rate of stream-flow depletion at each constraint stream reach is a linear function of the rates of groundwater withdrawal at wells near the stream. By assuming linearity, it is possible to determine total stream depletion at a constraint site by summation of the individual stream-flow depletions induced by each well.

The response-matrix approach for ground-water management modeling has been well established in the literature. Descriptions and applications of the approach are given by Maddock (1972, 1975), Morel-Seytoux and Daly (1975), Illangasekare and Morel-Seytoux (1982), Mueller and Male (1993), Ahlfeld and Heidari (1995), and Ahlfeld and Mulligan (2000).

The technique is valid as long as 1) the saturated thickness and transmissivity of the aquifer do not vary substantially with changes in withdrawal rates and 2) other nonlinear effects simulated by the transient model, such as head-dependent boundary conditions, do not substantially affect the linear relation between groundwater withdrawals and stream-flow depletions.

Implementation of the response matrix technique requires calculation of how stream-flow depletion responds to simulated unit withdrawals for each well. To calculate the characteristic responses, the unit withdrawal rate is specified for one of the wells. The amount of stream-flow depletion resulting from the unit withdrawal (Qw_i) is determined by subtracting stream-flow rates calculated by the model with the unit withdrawal active from those calculated by the model with the unit withdrawal inactive. Stream depletion response to the unit withdrawal is defined as $Qsd_{j,t}$. Stream depletion response coefficients ($r_{j,i,t}$) are then given by;

$$r_{j,i,t} = \frac{Qsd_{j,t}}{Qw_i} \tag{5.1}$$

Where, $r_{j,i,t}$ are the response coefficients which are dimensionless and range from 0.0 to 1.0, $Qsd_{j,t}$ is the stream-flow depletion due to the unit withdrawal, and Qw_i is the unit withdrawal.

Because of the assumed linearity of the system, total stream depletion, $Qsd_{j,t}$, at each constraint site j and for each month t can be calculated with the response coefficients by summation of the individual stream-flow depletion caused by each well in each month. Stream depletion due to the pumping of wells, equation (5.1) can be rewritten to replace $Qsd_{j,t}$ with $r_{j,i,t}\,Qw_{i,t'}$, so that the resulting modified expression is given;

$$Qsd_{j,t} = \sum_{i=1}^{NW} \sum_{k=1}^{12} r_{j,i,k}\, Qw_{i,k'} \tag{5.2}$$

where,

$$k' = t - k + 1, \quad \mathit{for}\ t - k + 1 > 0$$
$$k' = 12 + (t - k + 1), \quad \mathit{for}\ t - k + 1 \leq 0\,.$$

The two-part definition of *k'* is required as a series of the annual cycle of withdrawal. For example, stream-flow depletions at the present time (t = 1) can be affected by withdrawal at the previous time (t = 12).

For the assumption of linearity to be valid, the values of response coefficients for each well/stream-constraint-site pair must remain constant for all simulated and hydrologic conditions. In coupling the simulation and optimization model, the response coefficients are incorporated directly into the constraint set of the linear program for conjunctive use management.

5.2.2 Development of Response Coefficients

This section evaluates the response coefficients of stream depletion due to the pumping wells near a stream. The positions of pumping wells were hypothetically assumed, as shown in Chapter Three. In order to compare two results with or without withdrawal, the development of the MODFLOW model under the condition without withdrawal is needed as a control before withdrawal is considered.

The active area of the model was surrounded laterally by no-flow boundaries. No-flow boundaries were specified along the finite valley assumed. The flow boundaries on the northern and southern ends of the model were set up as specified-flux in stress for the transient simulations. The rate of pumping for each well is 640m^3/s, and the hydraulic conductivity is 50m/day.

The agricultural area with 18 sites is 13.6km^2 in the study area. The average area of agricultural area is approximately 0.8km^2 shown in Table 5.1. In the conceptual model of MODFLOW, a sample site size is assumed as 2.4 km^2 including uplands in order to develop the response coefficients. The total number of pumping wells in the conceptual model is estimated to be 20 wells, considering wells of agricultural lands in the vicinity of Yeoju and Incheon (Cha, 2007).

The response coefficients of stream depletion for this sample site from the conceptual model of MODFLOW are given in Table 5.2 and shown in Figure 5.1. Figure 5.1 illustrates that the response decreases with time and the largest value is 0.270. This value occurs close to the pumping start time. This means that the interaction between aquifer and stream is strong and the two water sources are fully hydraulically interconnected. These response coefficients were calculated from spatially distributed aquifer characteristics and complex boundary conditions.

Table 5.1 Average Well-pumping Site Area and Well Numbers

Items	Area or Well Number
Stream-aquifer Analysis Area - Total Agricultural Lands - Average Land	 13,605,000 km^2/18 sites 755,800 m^2/ste
Wells - Yeoju Area - Incheon Area	 18 wells/km^2 22 wells/km^2
Well Numbers Applied in the Study Area	20 wells/km^2

Source: Cha (2007)

Table 5.2 Response Coefficients of Stream Depletion by Multi-pumping Wells

Month	1	2	3	4	5	6	7	8	9	10	11	12
K=25m/day	0.153	0.121	0.087	0.070	0.059	0.052	0.046	0.041	0.037	0.033	0.029	0.026
K=50m/day*	0.270	0.158	0.111	0.087	0.070	0.056	0.046	0.037	0.030	0.024	0.020	0.016
K=70m/day	0.339	0.178	0.122	0.090	0.067	0.050	0.037	0.028	0.021	0.015	0.011	0.008

Note: * The results obtained for K = 50 m/day are applied in this study

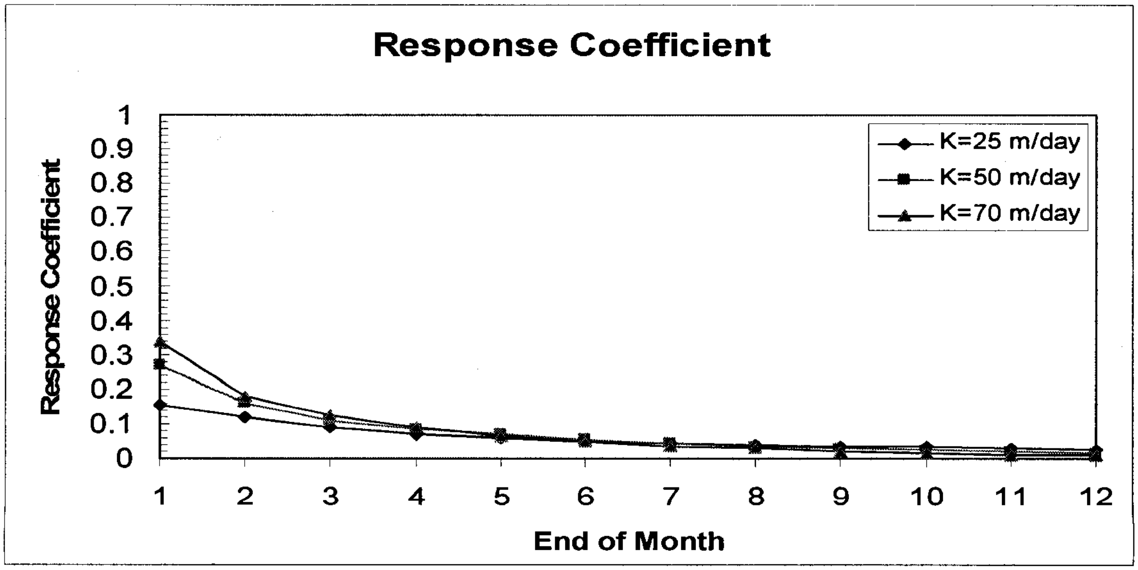


Figure 5.1 Response Coefficients for the Study Area

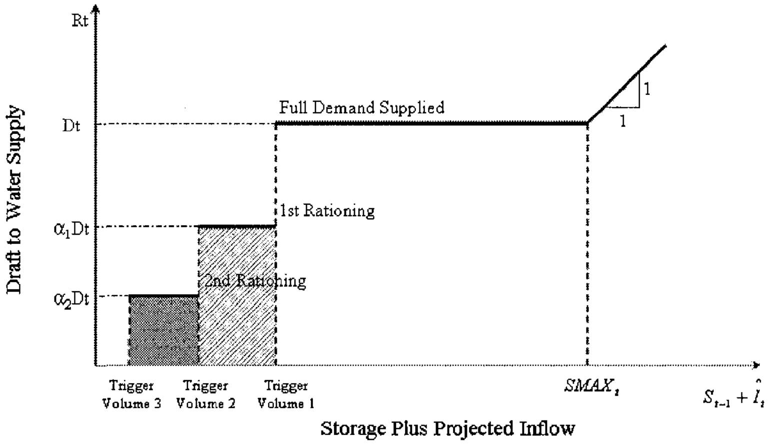
5.3 Model Formulation for Stream-Aquifer-Reservoir System

5.3.1 Discrete Hedging Rule

In general, multi-purpose reservoirs are operated by a set of predetermined rules formulated based on historical inflow, design storage capacity, safe yield criteria, trans-basin water supply, flood control, hydropower generation, and instream flow requirements for fish and aquatic habitats. Reservoir operations are expected to meet all these demands and rules. Safe yield operation is generally adequate under normal conditions but is unlikely to be sufficient during critical periods such as prolonged droughts, other extreme weather conditions, regional climate patterns, and sudden changes in water demand patterns. During such periods, standard operating procedures may result in single periods of severe short supply or sequences of consecutive short supplies, either of which may induce additional damages and irreversible consequences. To secure against unexpected risk of either brief extreme shortages or lengthy smaller shortages during critical periods, additional reliability criteria must be identified.

Hashimoto et al. (1982) presents the resilience concept that can be a measure of the probability of being in a period of no failure for a given time period given that there was a failure in the last period. A resilient system is capable of recovery from a deficit state to normal operation in a short time; that is, the resilience characterizes how quickly the system returns to a normal state once failure has occurred. According to Hashimoto et al., vulnerability is a measure of the significance of failure.

Shih et al. (1995) present a mixed integer programming model to operate a water supply reservoir through discrete rationing phases. The model determines the volumes of reservoir storage plus expected inflow that trigger the phases of rationing under the objective of maximizing months without rationing given a limit on the number of months with phase two rationing. Figure 5.2 illustrates these triggers and their corresponding rationing phases of the reservoir. For a particular month, if the water availability which is the previous month's storage plus the expected inflow for this month is greater than V_{1p}, all demands can be released from the reservoir without rationing. If the water availability is greater than V_{2p} but less than V_{1p}, phase one rationing will occur for the coming month as demands will be allowed to reduce only α_1 fraction of normal demands. If the water availability is less than V_{2p} but greater than V_{3p}, phase two will be initiated as demands will be reduced to only α_2 proportion of normal demands. Trigger volumes depend on hydrologic conditions of inflows and water savings that result from the various reduction measures.



Source: Shih et al. (1995)

Figure 5.2 Discrete Hedging Rule

5.3.2 Objective Function

As a water resources system composed of reservoir storage approaches full utilization, the management of demand and operation for the system becomes especially important, particularly during drought and incipient drought. During droughts, water managers strive to reduce overall damages associated with an inability to meet normal demands to the greatest extent possible.

The objective function for a single reservoir system was developed by using mixed integer programming based on the hedging rule for reservoir operation. The mathematical form is written as follows;

$$\begin{aligned} Min = \; & cof_1 \sum_{t=1}^{T} (QM_{c,t} + QG_{s,t} + QT_{r,t}) + w \sum_{p=1}^{12} (V_{1p} + V_{2p} + V_{3p}) \\ & - cof_2 \sum_{t=1}^{T} y_{1t} + cof_3 \; (QMX + GMX + TMX) \\ & - cof_4 \sum_{t=1}^{T} QGW_{s,t} - cof_5 \sum_{t=1}^{T} QSW_{s,t} \end{aligned} \tag{5.2}$$

where, $cof_1, w, cof_2, cof_3, cof_4, cof_5$: weighting factors.

$QM_{c,t,}$ $QG_{s,t}$, $QT_{r,t}$: total deficits of instream flow requirements, irrigation water use, and trans-basin diversion, respectively.

V_{1p}, V_{2p}, V_{3p} : trigger volumes depending on phases.

y_{1t} : 1 if full demand is available during period t; otherwise 0.

QMX, GMX, TMX : maximum deficits of instream flow requirements, irrigation water use, and trans-basin diversion, respectively.

$QGW_{s,t}$: groundwater pumping rate for the irrigation water use at sites and the time interval of month.

$QSW_{s,t}$: surface water pumping rate for the irrigation water use at sites and the time interval of month.

The first term on the right side of equation (5.2) minimizes the sum of deficits during the entire time horizon at the control and the irrigation sites, and trans-basin diversion, the second term is used to determine the trigger volumes V_{1p} , V_{2p}, and V_{3p} for the different rationing phases in all months, the third term represents the number of success of reservoir water supply for all demands during time horizon, the fourth term minimizes the maximum deficit of instream flow, irrigation water use and trans-basin diversion; and the last two terms maximize surface and ground waters for irrigation water use. The time interval used to determine the overall tradeoff between surface and ground waters in this analysis was a month.

5.3.3 Reservoir System Constraints

In general, water supply reservoirs are operated by a set of predetermined rules formulated on the basis of historical inflow, design storage capacity, and safe yield criteria. Reservoir operations with these rules are anticipated to meet the target demand. Reservoir operation rules developed based on the safe yield concept are generally adequate under normal conditions but are unlikely to be sufficient during critical periods such as prolonged droughts, other extreme weather conditions, and sudden changes in water demand patterns. During such periods, standard operating procedures may result in single periods of severe short supply or sequences of consecutive short supplies, either of which may induce additional damages and irreversible consequences. To secure against unexpected risk of either brief extreme shortages or lengthy smaller shortages during critical periods, additional reliability criteria must be identified.

The constraints of the model in this study were adopted from Shih et al. (1995) and Park (2002): in addition, trans-basin diversion constraints were added to measure all demands. The following constraint set for the reservoir, in nonstandard form, is listed and discussed below.

$$y_{1t} \geq \frac{(S_{t-1} + \hat{I}_t) - (V_{1p} - \varepsilon)}{M} \qquad \forall t, p \qquad (5.3)$$

$$y_{1t} \leq 1 - \frac{V_{1p} - (S_{t-1} + \hat{I}_t)}{M} \qquad \forall t, p \qquad (5.4)$$

$$y_{2t} \geq \frac{(S_{t-1} + \hat{I}_t) - (V_{2p} - \varepsilon)}{M} \qquad \forall t, p \qquad (5.5)$$

$$y_{2t} \leq 1 - \frac{V_{2p} - (S_{t-1} + \hat{I}_t)}{M} \qquad \forall t, p \qquad (5.6)$$

$$S_t = S_{t-1} + I_t - R_t - W_t - DIV_t \qquad \forall t \qquad (5.7)$$

$$S_t \leq C \qquad \forall t \qquad (5.8)$$

$$S_0 \leq S_T \qquad \forall t \qquad (5.9)$$

$$R_t = (1.0 - \alpha_1) \cdot D \cdot y_{1t} + (\alpha_1 - \alpha_2) \cdot D \cdot y_{2t} + \alpha_2 \cdot D \qquad \forall t \qquad (5.10)$$

$$U_t \leq S_t / C \qquad \forall t \qquad (5.11)$$

$$W_t \leq M \cdot U_t \qquad \forall t \qquad (5.12)$$

$$V_{1p} \geq (1 + \beta_1) \cdot V_{2p} \qquad \forall t \qquad (5.13)$$

$$V_{2p} \geq (1+\beta_2)\cdot V_{3p} \qquad \forall t \tag{5.14}$$

$$V_{3p} \geq \alpha_2 \cdot D \qquad \forall t \tag{5.15}$$

$$S_{t-1} + \hat{I}_t \geq V_{3p} + \varepsilon \qquad \forall t \tag{5.16}$$

$$y_{1t-1} + y_{1t+1} \leq 1 + y_{1t} \qquad \forall t \tag{5.17}$$

$$y_{1t} \leq y_{2t+1} \qquad \forall t \tag{5.18}$$

$$y_{1t} + RM_t = 1 \qquad \forall t \tag{5.19}$$

$$\sum_{t=1}^{T} RM_t \leq p_r \qquad \forall t \tag{5.20}$$

$$\sum_{t=1}^{t+Nc} RM_t \leq N_r \qquad \forall t \tag{5.21}$$

$$DIV_t \leq DIV\max \qquad \forall t \tag{5.22}$$

$$IDV_t \leq DIV_t \,/\, DIV\max \qquad \forall t \tag{5.23}$$

$$R_t - IDV_t \cdot M \leq 0 \qquad \forall t \tag{5.24}$$

$$DIV_t + QT_t = DIV\max \qquad \forall t \tag{5.25}$$

$$QT_t - TMX \leq 0 \qquad \forall t \tag{5.26}$$

$$R\min \leq R_t \leq R\max \qquad \forall t \tag{5.27}$$

$$R_t \geq R\max \cdot U_t \qquad \forall t \tag{5.28}$$

$$S\min \leq S_t \leq S\max \qquad \forall t \tag{5.29}$$

where,

t : month in the time horizon (1…120).

$p \in \{1,2,\cdots,12\}$, corresponding to different month $p = t - 12\cdot\left(\frac{1}{12}(t-1)\right)$

y_{1t} : 1 if full demand is available during period *t*; 0, otherwise; unknown.

y_{2t} : 1 if we are in phase one rationing or better; 0, otherwise; unknown.

S_t : storage in the reservoir at the end of period t; unknown.

S_0 : storage in the reservoir at the beginning of period, known.

S_T : storage in the reservoir at the end of analysis, unknown.

C : reservoir capacity; known.

V_{1p} : value of storage and inflow above which no restrictions on water use are placed; unknown.

V_{2p} : value of storage and inflow below which phase two is implemented for month p; unknown.

V_{3p} : the lower bound of storage plus inflow for month p; known.

I_t : inflow in period *t*; known.

$\hat{I}_t$: projected inflow in period *t*; known.

W_t : spill in period *t*; unknown.

D : demand, assumed known and the same throughout the year.

U_t : 1, if reservoir is full at the end of period *t*; 0, otherwise; unknown.

M : big number: given.

ε : small number; given

α_1 : percentage of demand that obtains during phase one rationing; known.

α_2 : percentage of demand that obtains during phase two rationing; known.

β_1 : fractional separation value, used here as 0.05.

β_2 : fractional separation value, used here as 0.05.

p_r : total number of periods of deficit at the reservoir; known.

N_r : maximum number of the consecutive periods of shortage in the reservoir that is allowed; known.

RM_t : integer variable indicating the reservoir failure to supply all demands if y_{1t} is one

DIV_t : trans-basin diversion of reservoir in period t; unknown.

$DIV\max$: maximum trans-basin diversion of reservoir; known.

IDV_t : 1 if diversion equals to maximum diversion; 0, otherwise.

QT_t : trans-basin diversion deficit in period t; unknown.

TMX : maximum trans-basin diversion deficit for the entire time; unknown.

$R\min$, $R\max$: minimum and maximum release from reservoir.

$S\min$, $S\max$: minimum and maximum storage of reservoir.

The reasons for these constraints are the following. Constraint (5.3) in combination with the integer requirements says that if the storage at the end of last period plus the projected inflow to the reservoir is greater than or equal to the trigger volume V_{1p} , then y_{1t} must be one and no rationing is needed. Constraint (5.4) in combination with the integer requirements requires that y_{1t} be zero if the available water is less than V_{1p} , which means the full demand is not available and rationing is required. If there were no ε in constraint (5.3), when $S_{t-1} + \hat{I}_t = V_{1p}$, the variable y_{1t} could be zero or one. To correct this, ε is incorporated into the constraint (5.3) so that when $S_{t-1} + \hat{I}_t = V_{1p}$, the variable y_{1t} must be equal to 1, meaning again that no rationing is needed. Constraint (5.5) in combination with the integer requirements indicate that if the storage at the end of the previous time period plus projected inflow is greater than or equal to trigger volume, V_{2p}, then y_{2t} will be equal to one. Constraint (5.6) forces y_{2t} to zero if the end storage plus projected inflow is less than V_{2p}. Constraint (5.7) is the mass balance equation of inflow and outflow in the reservoir during each time period t. There are many ways to express this mass balance. Constraint (5.8) is the capacity restriction on each storage volume and insures the modeled reservoir is not storing more water than physically possible. Constraint (5.9) ensures that through the period of operation, water is not drawn from the initial storage. Constraint (5.10) sets the release equal to the full demand if y_{1t} and y_{2t} are both unity. It decreases the release to $\alpha_1 \cdot D$ if only y_{2t} is one, and it decrease the release to $\alpha_2 \cdot D$ if neither y_{1t} nor y_{2t} is one. The fraction α_2 of water demand is always released. Constraints (5.11) and (5.12) are incorporated into the model to ensure that spill can only happen when the reservoir is at capacity. Constraint (5.11) says that if the storage at the end of time period t is less than the reservoir capacity, then U_t will be zero, indicating the reservoir is not full to capacity. Constraint (5.12) forces the reservoir spill to be zero when U_t is zero, ensuring no spillage occurs when the storage is less than the capacity. If the right hand side of constraint (5.11) equals one meaning the storage is equal to the capacity, then the right hand side of constraint (5.12) is a large number, and the spill is constrained to that level. Constraints (5.13) and (5.14) are set to separate the trigger volumes of phase one and two and the trigger volumes of phase two and phase three by at least some percentages, β_1 and β_2. Constraint (5.15) ensures that the trigger volume V_{3p} is at least greater than α_2 proportion of the demand. Constraint (5.16) says that the storage at the end of the previous time period plus the projected inflow should be at least greater than V_{3p} in order to release α_2 percent of water demand. This implies that $\alpha_2 \cdot D$ (the minimum release) can always be provided. Constraint (5.17) says that if the release in period *t-1* and the release in period *t+1* are both at full demand, then the current period must have a release of full demand as well. Constraint (5.18) says that if full demand is released in period *t* then at least α_1 fraction of water demand must be released in period *t+1*. Constraint (5.19) represents the status of reservoir release failure that if y_{1t} is zero, RM_t must be one. Constraint (5.20) sets the maximum number of deficits allowed for the entire simulation time. Constraint (5.21) sets the maximum number of consecutive periods of shortage that is allowed at the reservoir; this value p_r is known and constrains the value of the sums of RM_t. Constraints (5.22) through (5.24) control trans-basin diversion. If IDV_t is 1, the reservoir will provide some water to trans-basin diversion before downstream demand. Constraint (5.25) determines the deficit of diversion QT_t at time *t*. Constraint (5.26) determines the maximum deficit of the trans-basin diversion for the entire time period *TMX* based on QT_t. Constraint (5.27) sets the range of downstream release. Constraint (5.28) says that when the storage of the reservoir is greater than the capacity, maximum release except spill will be occurred. Constraint (5.29) sets the minimum and maximum reservoir storage.

5.3.4 Stream-Aquifer System Constraints

In the stream-aquifer system, stream-flow is regulated by multi-purpose reservoir managers for purposes with the objectives of maintaining water quality; satisfying municipal, industrial water, and irrigation demands; and satisfying instream flow requirements for fish and aquatic habitats. Stream-flow constraints for streams requested in the optimization model are based on the various water demands and instream flow requirements at the given model nodes.

Stream-flow constraints are specified in terms of the minimum amount of flow required at the primal nodes representing the modeled nodes. The constraint set for a stream-aquifer system, in non-standard form, is the following.

$$QRE_t = R_t + \mathrm{W}_t \qquad \forall t \qquad (5.30)$$

$$QSTR_{1,t} = QRE_t + QL_{1,t} - QSD_{1,t} - QSW_{1,t} \qquad \forall t, s = 1 \qquad (5.31)$$

$$\begin{aligned} QSTR_{s,t} &= QSTR_{s-1,t} + QL_{s,t} - QSD_{s,t} - QSW_{s,t} \\ &\quad + 0.35 \cdot \left\{ \sum_{i=1}^{nw} QGW_{s-1,i,t} + QSW_{s-1,t} \right\} \end{aligned} \qquad \forall t, s = 2 \cdots n-1 \qquad (5.32)$$

$$QSD_{s,t} = \sum_{i=1}^{nw} \sum_{t=1}^{12} r_{s,i,t} QGW_{i,t'} \qquad (5.33)$$

where,

$$t' = tp - t + 1, \; for \;\; tp - t + 1 > 0$$
$$t' = 12 + (tp - t + 1), \; for \;\; tp - t + 1 \le 0$$

$$\sum_{i=1}^{nw} QGW_{s,i,t} + QSW_{s,t} = QAW_{s,t} \qquad \forall t, s \qquad (5.34)$$

$$QAW_{s,t} + QG_{s,t} \ge QAD_{s,t} \qquad \forall t, s \qquad (5.35)$$

$$QG_{s,t} - GMX \le 0 \qquad \forall t,s \qquad (5.36)$$

$$\left(QGW_{s,i,t}\right)_{\min} \le \left(QGW_{s,i,t}\right) \le \left(QGW_{s,i,t}\right)_{\max} \qquad \forall\, i = 1,\ldots.,nw, \forall t = 1,\ldots,12 \qquad (5.37)$$

$$QSTR_{c,t} = QSTR_{s,t} + QL_{c,t} + \; 0.35 \cdot \left\{ \sum_{i=1}^{nw} QGW_{s,i,t} + QSW_{s,t} \right\} \qquad \forall t,s,i \qquad (5.38)$$

$$QSTR_{c,t} + QM_{c,t} \ge QISF_c \qquad \forall t,c \qquad (5.39)$$

$$QM_{c,t} - M \cdot IM_{c,t} \le 0 \qquad \forall t,c \qquad (5.40)$$

$$QM_{c,t} - QMX_c \le 0 \qquad \forall t,c \qquad (5.41)$$

$$\sum_{t=1}^{T} IM_{c,t} \le p_c \qquad \forall t,c \qquad (5.42)$$

$$\sum_{t=1}^{t+Nc} IM_{c,t} \le N_c \qquad \forall t,c \qquad (5.43)$$

where,

QRE_t : total release from reservoir including spill; known.

W_t : spill from the reservoir in period t; unknown.

$QSTR_{st}$: stream-flow at site s in period t; unknown.

$QL_{s,t}$: lateral inflow at site s in period t; known.

$QSD_{s,t}$: stream depletion due to pumping well near a stream at site s in period t; unknown.

$QSW_{s,t}$: diverted surface water for the irrigation at site s in period t; unknown.

$r_{s,i,t}$: response coefficients for stream-aquifer system due to pumping well at site s, and well i, in period t

$QGW_{s,i,t}$: amount of groundwater pumping by well i at reach s in period t; unknown.

nw : the number of pumping wells; known

$QAD_{s,t}$: irrigation demand to be needed at site s in period t; known.

$QAW_{s,t}$: irrigation water use at site s in period t; unknown.

$QG_{s,t}$: irrigation water shortfall at site s in period t ; unknown

GMX : maximum irrigation water shortfall at site s in entire period; unknown.

$(QGW_{s,i,t})_{\min}, (QGW_{s,i,t})_{\max}$: minimum and maximum amount of groundwater to be pumped by the wells at site s, for the well I, in period t; known

$QSTR_{c,t}$: stream-flow at a control point in period t; unknown.

$QL_{c,t}$: lateral inflow at a control point in period t; known.

$QISF_c$: required stream-flow (which is instream flow) at a control point; known

$QM_{c,t}$: water shortfall at a control point in period t; unknown

QMX_c : maximum shortfall at a control point in entire period; unknown.

$IM_{c,t}$: 1 if the shortfall is occurred at a control point ; otherwise, 0; unknown.

M : big number; known

p_c : total number of periods of deficit at a control point; known.

N_c : maximum number of consecutive periods of shortage at a control point that is allowed; known.

Constraint (5.30) sets the total release from the reservoir. Constraints (5.31)-(5.32) represent the mass balance equation of inflow and outflow in the model stream during each time period *t*. When the site number of the node considered is equal to one, stream inflow is composed of reservoir release and lateral inflow, when the site number is greater than or equal to two, reservoir release is exempted because the stream is not directly connected to the reservoir. Outflow from the node is composed of stream depletion due to pumping wells near the stream, diverted surface water, and downstream stream-flow. Constraint (5.33) determines stream depletion due to pumping wells near a stream. By assuming stream-aquifer system is linear, the total stream-flow depletion $\left(QSD_{s,t}\right)$ at a site *s* and for each specified period, tp, can be calculated with the response coefficients by summation of the changes in stream-flow caused by pumping at each individual well, which is the product of each unit response coefficient and the pumping rate at each well $(r_{s,i,t}QGW_{i,t_i})$. The two-part definition of *t'* is required as a consequence of the annual cycle of withdrawals. For example, stream-flow depletion in January (*tp*=1) can be affected by withdrawals in December (*tp*=12). Constraint (5.34) defines the available irrigation water as the combination of groundwater and surface water from a stream and/or an aquifer. Constraint (5.35) sets the deficit for irrigation water use at each site and time period *t*. Constraint (5.36) determines the maximum deficit, GMX, from the irrigation water shortfall found in the entire time horizon. Constraint (5.37) sets the minimum and maximum pumping rate for each well. Constraint (5.38) is the mass balance equation at a control point node in the stream model including the return flow of all demands at the previous site. The return coefficient is assumed to be 0.35 for the return flow at a proceeding site. Constraint (5.39) says established *QISF* as the requirement for instream flow at a control point. When QM_t is 1, constraints (5.40) through (5.41) indicate that a deficit in instream flow has occurred. Constraint (5.42) declares the known maximum number of deficit periods allowed at the control point. Constraint (5.43) limits the number of consecutive periods of shortages at the control point.

5.4 Model Application for the Case Study

A linear optimization model was developed in this study to evaluate the effects of conjunctive management considering reservoir operation, surface and groundwater withdrawal, and stream depletion. The response coefficient of stream depletion due to pumping wells near a stream is incorporated into this model to analyze the effects of pumping. In order to solve the mixed integer linear optimization problem, CPLEX software was used, and the user interface based on Excel software was developed.

The model is formulated on a monthly time step to determine the required releases from the reservoir and the required withdrawal from surface and ground waters to irrigate agricultural lands confined by various constraints.

5.4.1 Model Flow Chart

A model developed using CPLEX software was used to perform the calculations to solve the multi-objective linear problem of this study. The basic calculation structure of the model is shown in Figure 5.3. The model reads the initial objectives and constraints, and uses them to solve the given mixed integer problem. To obtain the optimal solution, the model is used iteratively until a solution within the given convergence tolerance of 0.05 determined.

The CPLEX software is used to determine the pattern of releases to optimally operate the reservoir-stream-aquifer system to best satisfy demands during droughts.

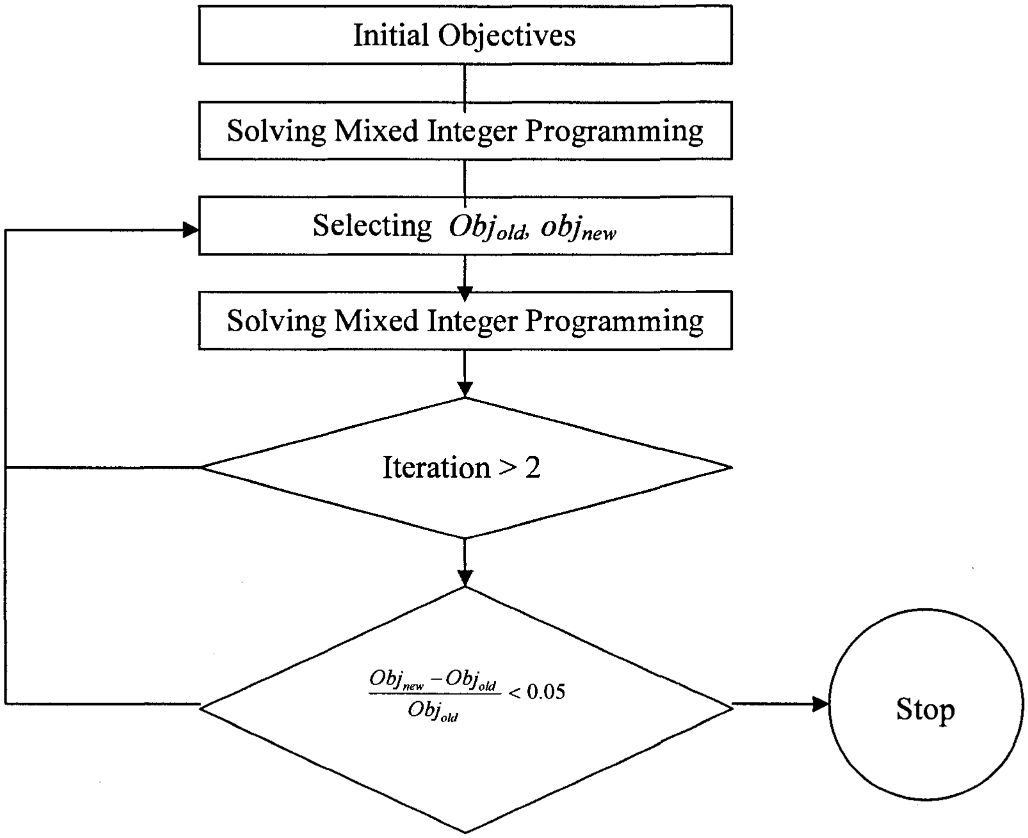


Figure 5.3 Overall Process for Conjunctive Management

5.4.2 Water Demand

The water demand data used in this case study is given in Table 5.3. These demands include municipal and agricultural demands for two sites downstream of the Yongdam reservoir, the trans-basin diversion for municipal water in the Mankyung River basin, and instream flow for the Geum River as shown in Table 5.3. The largest demand in the study area is for the trans-basin diversion to the Jeonju area, the second largest is the instream flow, the third largest is for agricultural use, and the smallest is for municipal use. In development of the conjunctive management system in this study, all water uses were considered except municipal use which was assumed negligible. Water demand is plotted on monthly totals Figure 5.4. Figure 5.5 shows the case study site including the Yongdam and Daechung reservoirs, trans-basin diversion, and areas of agricultural water use.

Table 5.3 Water Demand and Tran-Basin Diversion in the Upper Region of the Yongdam Reservoir

(Units: MCM)

Month	M & I Water		Agricultural		Total Sum	Trans-basin diversion	Min.flow
	Subbasin 1	Subbasin 2	Subbasin 1	Subbasin 2			
Jan	0.173	0.773	0.000	0.000	0.946	41	12.96
Feb	0.173	0.773	0.000	0.000	0.946	41	12.96
Mar	0.180	0.804	0.046	0.273	1.304	41	12.96
Apr	0.180	0.804	0.049	0.289	1.322	41	12.96
May	0.197	0.879	0.128	0.754	1.957	41	12.96
Jun	0.206	0.921	0.954	5.632	7.713	41	12.96
Jul	0.221	0.984	0.628	3.706	5.539	41	12.96
Aug	0.233	1.037	0.546	3.225	5.041	41	12.96
Sep	0.235	1.048	0.364	2.150	3.797	41	12.96
Oct	0.221	0.984	0.003	0.016	1.224	41	12.96
Nov	0.180	0.804	0.000	0.000	0.985	41	12.96
Dec	0.173	0.773	0.000	0.000	0.946	41	12.96
Sum	2.373	10.585	2.717	16.045	31.719	492	155.52
Max	0.235	1.048	0.954	5.632	7.713	41	12.96

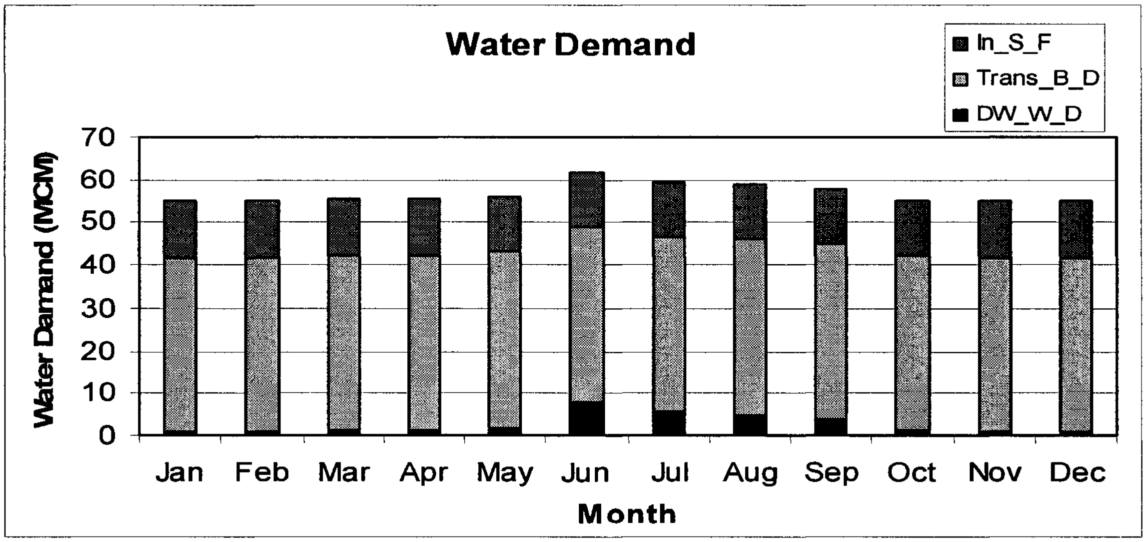
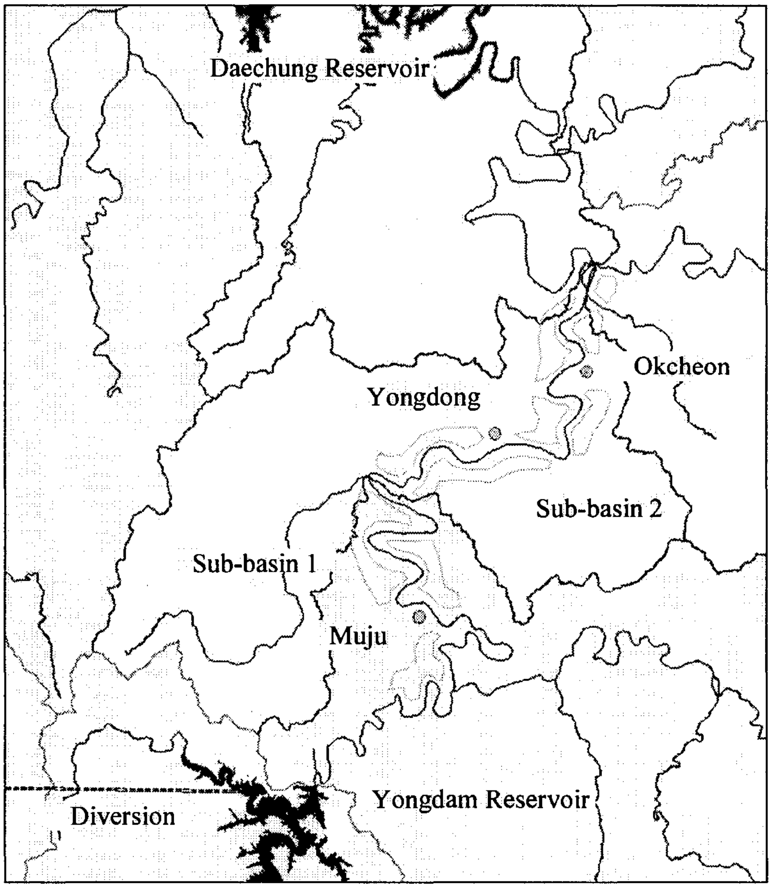


Figure 5.4 Monthly Water Demand in Geum River Basin



Source: Cha (2007)

Figure 5.5 Water Supply System of Case Study in Geum River Basin

5.4.3 Instream flow Requirements

Instream flow requirements at each node were specified by using the ratio of sub-basin area to the area of the Daechung reservoir based on the results analyzed in Chapter Four. Table 5.4 presents the instream flow requirements at each node including the control point downstream. According to the detailed design report of the Yongdam Multi-purpose Dam, the downstream instream flow requirement was established as $5m^3/s$. The release for the downstream instream flow requirements at Yongdam reservoir were therefore varied from $2m^3/s$ to $6m^3/s$ to figure out the effect of conjunctive water use, considering varied constant release policies from the reservoir. The instream flow requirements of sub-basin 1 and 2 are constantly applied as the mean value in Table 5.4, but the instream flow requirements of Yongdam reservoir were assigned as $5m^3/s$ that were established in the detailed design report of the Yongdam Multi-purpose Dam.

Table 5.4 Instream flow Requirement at Each Point

Site	Basin area (km^2)	Accumulated Area (km^2)	RVA Boundary (m^3/s)		
			Low	High	Mean
Yongdam Reservoir	930.0	930.0	2.26	5.47	3.87
Sub-basin 1	663.7	1596.7	4.70	13.18	8.94
Sub-basin 2	489.7	2083.4	6.14	17.23	11.68
Daechung Reservoir	4134.0	4134.0	12.18	34.19	23.19

5.4.4 Sensitivity Analysis of Surface and Ground Waters

In general, water supply management in Korea ignores the effects of and on groundwater. Groundwater is only recognized an alternative of emergency water supply during severe drought seasons but it is constantly impacted by withdrawals due to the thin physical structure and high transmissivity of aquifers, as discussed in Chapter Three. This compartmentalized management leads to a misunderstanding of connectivity between groundwater and surface water.

To achieve effective conjunctive water use, two different water supply policy priorities were investigated. The first step is applied to the following order to water supplies from the Yongdam reservoir;

1) The trans-basin diversion to Jeonju which must be met because this diversion was the basic purpose of the Yongdam Reservoir construction;
2) Downstream instream flow requirements for fish and aquatic habitat and conservation of stream environment;
3) Downstream water use for irrigation
4) Municipal and industrial water uses were assumed to be negligible and will not be considered.

The second order to water supplies from the Yongdam reservoir is the following;

1) Downstream instream flow requirements for fish and aquatic habitat and conservation of stream environment;
2) The trans-basin diversion to Jeonju that must be met
3) Downstream water use for irrigation
4) Municipal and industrial water uses which is ignored because it is assumed to be negligible.

Various uncertainties of the weighting factors are related to priority of groundwater and surface water, priorities among trans-basin diversion, instream flow and downstream water demand. To evaluate the effects of parameters, a sensitivity analysis was used. These uncertainties were estimated by performing a sensitivity analysis on the weighting factors of model parameters.

The weighting factors of objectives were applied as suggested by Moy and Others (1986), and Park (2002) where the maximum deficit is assigned a value of 1, and the total deficits is 0.01. The weighting factors for this case study were set up as shown in Table 5.5. It is assumed that the weighting factor of the total deficit is 1, the maximum deficit is 100, the trigger volume is 0.1, and the success of reservoir is 1. The weighting factors for water supply are considered to evaluate water deficits for trans-basin diversion, instream flow requirements, and water use for irrigation. The sensitivity of the weighting factors for each objective is not considered. The weighting factors of surface and ground waters are only considered.

Table 5.5 Weighting Factors for the Alternatives

Item	Trigger Volume			No. of Reservoir Success	Deficit		Source	
	TV 1	TV 2	TV 3		Max	Total	Surface Water	Ground water
Surface Water	0.1	0.1	0.1	1	100	1	1	-
Conjunctive Water	0.1	0.1	0.1	1	100	1	1 or 1.2	1 or 1.2

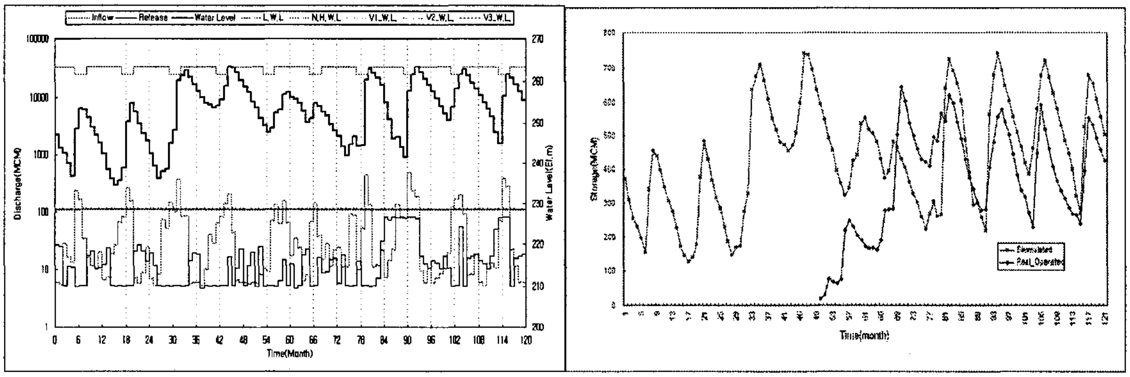
Allocation Policy 1: Priority of trans-basin diversion, instream flow and irrigation water use

Surface water alone was used to meet the various water initially in this allocation policy and assigned of one opposed to the zero assigned to groundwater; these weighting factors were then varied to introduce the effects of groundwater supply. In following model simulation, trans-basin diversion is not included in the reservoir operation, that is, the reservoir must provide the trans-basin diversion prior to instream flow and irrigation water use. Table 5.6 shows the results generated for water demand when water supply orders are described above. The trans-basin diversion has no deficit because it has first priority to water supplies and then is no deficit of instream flow requirements in this allocation method. Deficits in irrigation water, however, did occur in this method but was dependent on how the groundwater was treated in the model. When hedging is used to ration water supply to demands, the downstream instream flow requirements and irrigation water use were applied. According to the results analyzed, for example, when the reservoir constantly releases instream flow requirement of $5m^3/s$ and the management setup is forced only on the use of surface water, the total deficit of irrigation water is 11.6 MCM during the analysis period from 1996 to 2005, the objective value is 141.03, and the number of model iteration is 200. When the weighting factor for the groundwater is considered, however, the total deficit of irrigation water ranges from 0.0MCM to 3.58MCM. This illustrates the effect of the connection between surface and ground waters in Korea and stresses the importance of their conjunctive use. The effect of conjunctive water use can result in the reduction of total deficit for irrigation water use. With increasing downstream instream flow requirement, the total deficit of the irrigation also increases. With an increasing groundwater weighting factor, the total deficit of irrigation water use decreases. With increase in instream flow requirements, the number of reservoir failures increases from 0 to 69. When instream flow requirement is varied from $2m^3/s$ to $6m^3/s$, the inflection point of the total deficit in irrigation water use occurs around $5m^3/s$. When instream flow requirements increases greater than $5m^3/s$, total deficits for irrigation water use are reduced due to the effect of second rationing which frequently takes place in reservoir system to reduce deficits as shown in Figure 5.6 and Figure 5.7.

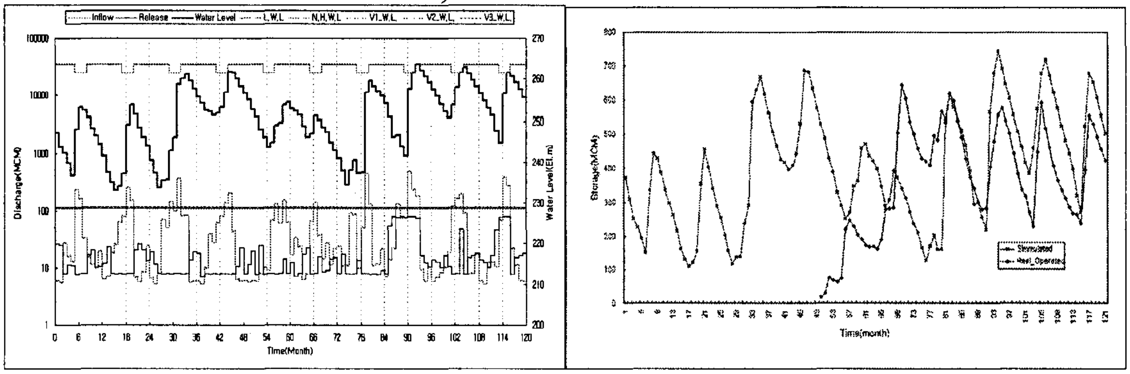
Table 5.6 Results of Model Application by Setting Different Weighting factors (Units: MCM or number)

When setting the weighting factors as groundwater = 0, and surface water = 1							
Item			S_2cms	S_3cms	S_4cms	S_5cms	S_6cms
Trans-basin Diversion Deficit			0.00	0.00	0.00	0.00	0.00
Instream flow Deficit		Sub_Basin1	0.00	0.00	0.00	0.00	0.00
		Sub_Basin2	0.00	0.00	0.00	0.00	0.00
		Control Point	0.00	0.00	0.00	0.00	0.00
Irrigation Water Use	Sub_Basin 1	Surface Water	27.18	27.18	25.60	25.50	25.42
		Groundwater	0.00	0.00	0.00	0.00	0.00
		Deficit	0.00	0.00	1.58	1.68	1.76
		Total	27.18	27.18	27.18	27.18	27.18
	Sub_Basin 2	Surface Water	160.45	160.45	151.84	150.53	150.93
		Groundwater	0.00	0.00	0.00	0.00	0.00
		Deficit	0.00	0.00	8.61	9.92	9.52
		Total	160.45	160.45	160.45	160.45	160.45
Reservoir		Trigger Volume 1	30.61	45.91	742.64	2484.12	4107.56
		Trigger Volume 2	27.83	41.74	55.65	595.50	1349.36
		Trigger Volume 3	25.30	37.95	50.59	63.24	75.89
		No. of Failure	0	0	16	42	65
Running Results		Obj. Value	-303.71	-299.05	-200.40	141.03	318.14
		Status	Optimal	Optimal	Optimal	Optimal	Optimal
		Iteration	97	96	102	200	110
When the weighting factors as groundwater = 1, and surface water = 1							
Item			S_2cms	S_3cms	S_4cms	S_5cms	S_6cms
Trans-basin Diversion Deficit			0.00	0.00	0.00	0.00	0.00
Instream flow Deficit		Sub_Basin1	0.00	0.00	0.00	0.00	0.00
		Sub_Basin2	0.00	0.00	0.00	0.00	0.00
		Control Point	0.00	0.00	0.00	0.00	0.00
Irrigation Water Use	Sub_Basin 1	Surface	23.72	23.72	24.04	23.31	22.70
		Ground	3.46	3.46	3.14	3.51	4.48
		Deficit	0.00	0.00	0.00	0.36	0.00
		Total	27.18	27.18	27.18	27.18	27.18
	Sub_Basin 2	Surface	139.78	140.06	142.56	146.70	141.51
		Ground	20.67	20.39	17.89	13.72	18.94
		Deficit	0.00	0.00	0.00	0.03	0.00
		Total	160.45	160.45	160.45	160.45	160.45
Reservoir		Trigger Volume 1	30.61	45.91	741.92	2802.65	4162.08

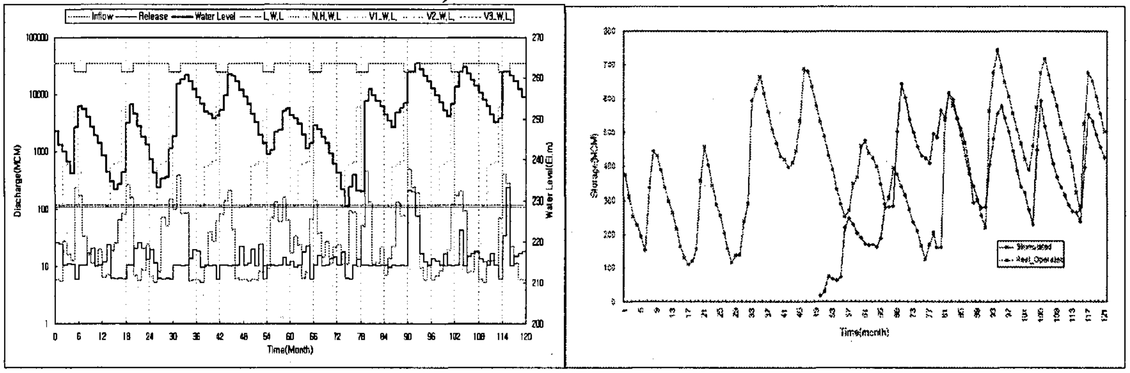
		Trigger Volume 2	27.83	41.74	55.65	292.10	1258.23
		Trigger Volume 3	25.30	37.95	50.59	63.24	75.89
		No. of Failure	0	0	16	47	66
Running Results		Obj. Value	-303.72	-299.07	-210.67	89.44	304.19
		Status	Optimal	Optimal	Optimal	Optimal	Optimal
		Iteration	126	126	221	438	222
When the weighting factors as groundwater = 1, and surface water = 1.2							
Item			S_2cms	S_3cms	S_4cms	S_5cms	S_6cms
Trans-basin Diversion Deficit			0.00	0.00	0.00	0.00	0.00
Instream flow Deficit		Sub_Basin1	0.00	0.00	0.00	0.00	0.00
		Sub_Basin2	0.00	0.00	0.00	0.00	0.00
		Control Point	0.00	0.00	0.00	0.00	0.00
Irrigation Water Use	Sub_Basin 1	Surface	27.18	27.18	25.60	25.13	26.28
		Ground	0.00	0.00	1.58	1.13	0.90
		Deficit	0.00	0.00	0.00	0.92	0.00
		Total	27.18	27.18	27.18	27.18	27.18
	Sub_Basin 2	Surface	160.45	160.45	151.84	146.61	152.69
		Ground	0.00	0.00	8.61	11.18	7.76
		Deficit	0.00	0.00	1.81	2.66	0.00
		Total	160.45	160.45	162.26	160.45	160.45
Reservoir		Trigger Volume 1	30.58	45.91	742.64	2955.44	4163.77
		Trigger Volume 2	27.80	41.74	55.65	219.20	1259.61
		Trigger Volume 3	25.27	37.95	50.59	63.24	75.89
		No. of failure	0	0	16	44	66
Running Results		Obj. Value	-341.26	-336.57	-246.08	71.31	268.71
		Status	Optimal	Optimal	Optimal	Optimal	Optimal
		Iteration	91	91	114	219	130
When the weighting factors as groundwater = 1.2, and surface water = 1							
Item			S_2cms	S_3cms	S_4cms	S_5cms	S_6cms
Trans-basin Diversion Deficit			0.00	0.00	0.00	0.00	0.00
Instream flow Deficit		Sub_Basin1	0.00	0.00	0.00	0.00	0.00
		Sub_Basin2	0.00	0.00	0.00	0.00	0.00
		Control Point	0.00	0.00	0.00	0.00	0.00
Irrigation Water Use	Sub_Basin 1	Surface	0.00	0.00	14.05	12.45	7.80
		Ground	27.18	27.18	13.13	14.73	19.38
		Deficit	0.00	0.00	0.00	0.00	0.00
		Total	27.18	27.18	27.18	27.18	27.18
	Sub_Basin 2	Surface	0.00	0.00	79.79	71.70	43.82
		Ground	160.45	160.45	80.66	88.75	116.63
		Deficit	0.00	0.00	0.00	0.00	0.00
		Total	160.45	160.45	160.45	160.45	160.45
Reservoir		Trigger Volume 1	30.61	45.91	744.52	2689.34	4431.54
		Trigger Volume 2	27.83	41.74	55.65	415.64	1179.14
		Trigger Volume 3	25.30	37.95	50.59	63.24	75.89
		No. of failure	0	0	16	50	69
Running Results		Obj. Value	-341.15	-336.46	-229.14	34.74	299.04
		Status	Optimal	Optimal	Optimal	Optimal	Optimal
		Iteration	117	117	105	107	285



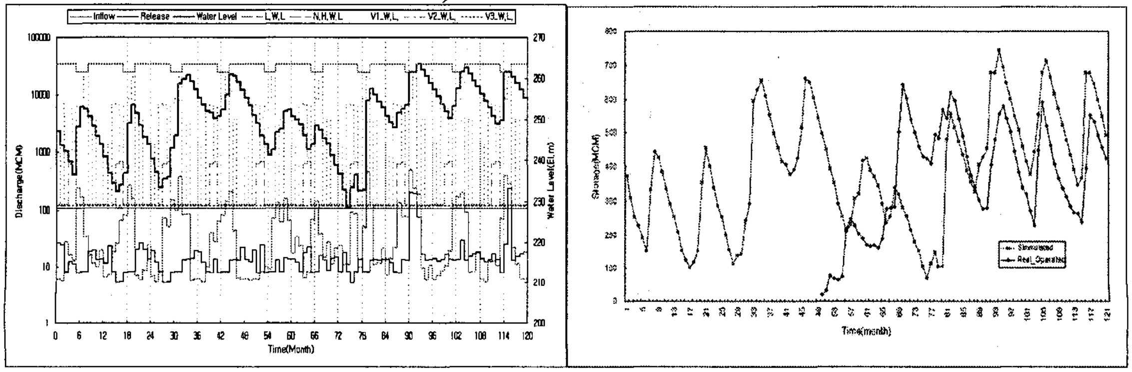
a) Instream flow = 2cms



b) Instream flow = 3cms

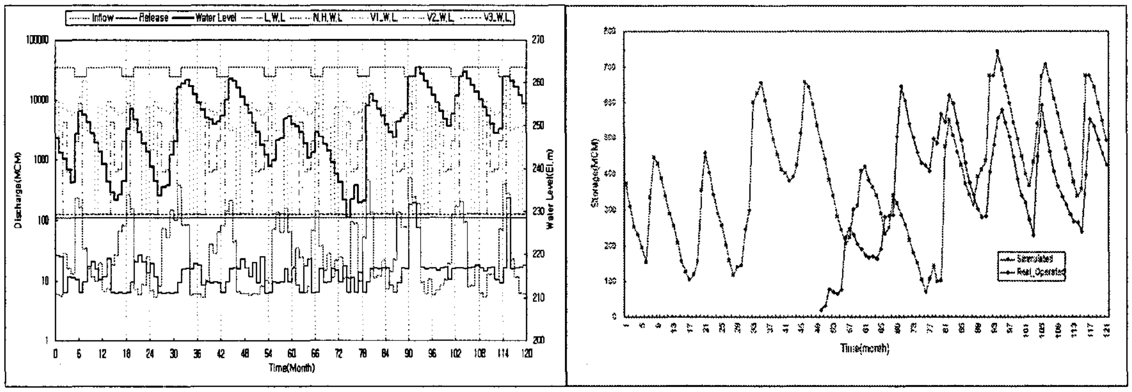


c) Instream flow = 4cms



d) Instream flow = 5cms

Figure 5.6 Results of Reservoir Operation by Varying Instream flow (when setting the priority of water supply such as trans-basin diversion, instream flow, and irrigation water use, and groundwater = 1, and surface water =1 for the weighting factor)



e) Instream flow = 6cms

Figure 5.7 Results of Reservoir Operation by Varying Instream flow (when setting the priority of water supply such as trans-basin diversion, instream flow, and irrigation water use, and groundwater = 1, and surface water =1 for the weighting factor) **(continued)**

Allocation Policy 2: Priority of instream flow, trans-basin diversion, and irrigation water use

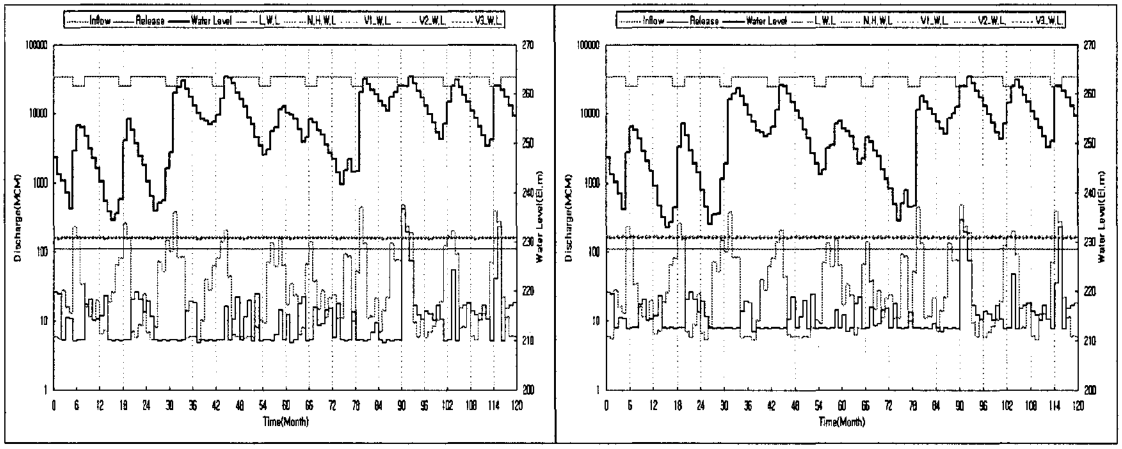
In the second allocation setup, the reservoir must provide instream flow requirements prior to trans-basin diversion and irrigation water use. Therefore, there is no deficit of instream flow requirements for the entire period of analysis. In applying the hedging rule for reservoir operation, all demand are considered, but instream flow requirements are released from a reservoir under the constraint that there is no deficit at any site including the control point. The consecutive number of deficit and the total number of deficits periods are set up as 3 and 16 in reservoir system. Table 5.7 and Figure 5.8 illustrate the results for each scenario. According to the results obtained, when the reservoir constantly releases an instream flow requirement of 5m^3/s and water demands are satisfied only through surface water, the total system deficit is 13.7 MCM during the analysis period of 120 months, and the maximum deficit is 6.3 MCM for all demands. When the weighting factors of one for surface water and groundwater are used, the total system deficit is reduced to 2.1 MCM. This again illustrates the effectiveness of conjunctive water use. In this allocation setup, when the downstream instream flow requirement increases, the total deficit in the irrigation water and trans-basin diversion also increases. When the groundwater weighting factor is increased, the total deficit of irrigation water use decreases.

As shown in the results of the two water allocation policies presented in this case study, the order in which the instream flow requirement, trans-basin diversion, and irrigation water use are considered produces impacts on the rest of the system. A good order of allocations will result in fewer deficits and higher system reliability. This case study also illustrates that demands were satisfied more effectively when the connection between groundwater and surface water was considered.

Table 5.7 Results of Model Application by Setting Different Weighting factors for surface and groundwater

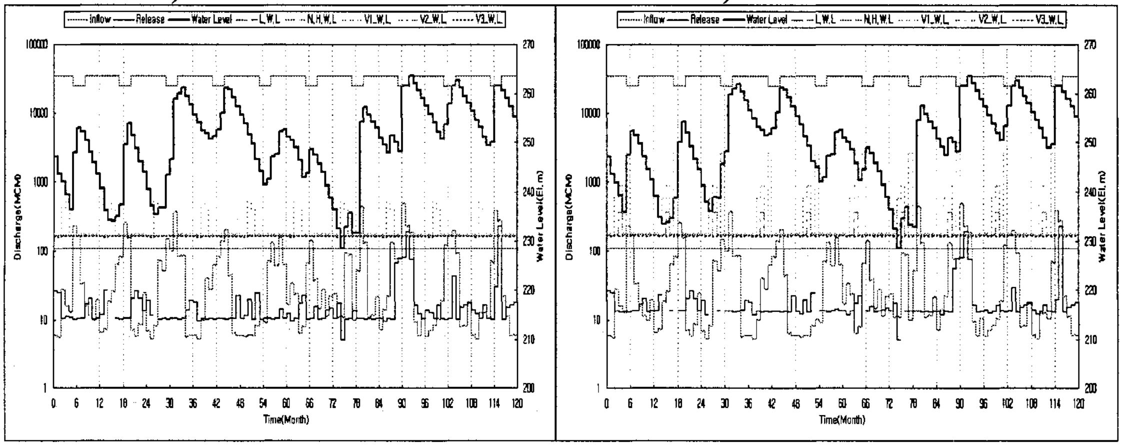
(Unit: $10^6 m^3$)

Item			2cms				3cms				4cms				5cms				6cms			
Weighting Factor		Surface water	1	1	1.2	1	1	1	1.2	1	1	1	1.2	1	1	1	1.2	1	1	1	1.2	1
		Ground water	0	1	1	1.2	0	1	1	1.2	0	1	1	1.2	0	1	1	1.2	0	1	1	1.2
Reservoir		TV 1	269.8	269.8	269.8	269.8	285.1	285.1	285.1	285.1	563.4	529.9	544.3	572.7	1031.7	1031.7	1031.7	1264.3	1570.7	1354.8	1692.0	1496.2
		TV 2	245.2	245.2	245.2	245.2	259.1	259.1	259.1	259.1	273.1	273.1	273.1	273.1	287.0	287.0	287.0	287.0	300.9	300.9	743.0	300.9
		TV 3	222.9	222.9	222.9	222.9	235.6	235.6	235.6	235.6	248.2	248.2	248.2	248.2	260.9	260.9	260.9	260.9	273.5	273.5	273.5	273.5
		Total_TV	737.9	737.9	737.9	737.9	779.8	779.8	779.8	779.8	1084.7	1051.2	1065.6	1094.0	1579.5	1579.5	1579.5	1812.2	2145.1	1929.2	2708.5	2070.6
		No. of Failure	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	7.0	7.0	8.0	16.0	16.0	16.0	16.0	20.0	20.0	20.0	20.0
TransBasin Diversion		W_Supply	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4929.4	4929.4	4929.4	4931.6	4879.6	4868.6	4870.1	4869.1
		D_Total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	2.1	2.1	0.0	51.9	63.0	61.4	62.4
		Total	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.6	4931.5	4931.5	4931.5	4931.5
		D_Max	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.0	3.5	4.5	4.4	3.9
		D_No	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.0	13.0	13.0	0.0	15.0	14.0	14.0	16.0
Instream flow Deficit	Sub_Basin1	ISF	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9	1639.9
		D_Total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		D_Max	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub_Basin2	ISF	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7	2806.7
		D_Total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		D_Max	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Control Point	ISF	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7	3689.7
		D_Total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		D_Max	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Irrigation Water Use	Sub_Basin 1	Surface	27.2	23.6	27.2	0.0	27.2	23.6	27.2	0.0	27.2	24.1	26.8	5.2	25.5	21.0	25.5	11.0	25.5	22.3	25.5	15.0
		Ground	0.0	3.6	0.0	27.2	0.0	3.6	0.0	27.2	0.0	3.1	0.3	21.9	0.0	6.2	1.7	16.2	0.0	4.9	1.7	12.2
		D_Total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	1.7	0.0	0.0	0.0
		Total	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2
		D_Max	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.5	0.0	0.0	0.0
	Sub_Basin 2	Surface	160.5	139.0	160.5	0.0	160.5	139.3	160.5	0.0	160.5	142.2	159.1	30.6	150.6	98.6	150.6	63.2	150.9	120.5	150.9	86.4
		Ground	0.0	21.4	0.0	160.5	0.0	21.1	0.0	160.5	0.0	18.3	1.3	129.8	0.0	61.9	9.9	97.3	0.0	39.9	9.6	74.1
		D_Total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	0.0	0.0	0.0	9.5	0.0	0.0	0.0
		Total	160.5	160.4	160.5	160.5	160.5	160.5	160.5	160.5	160.5	160.5	160.4	160.4	160.5	160.5	160.5	160.5	160.4	160.5	160.5	160.5
		D_Max	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	0.0	0.0	0.0	5.6	0.0	0.0	0.0
Running Results		Obj_V	-238.5	-238.5	-276.0	-275.9	-233.8	-233.8	-271.3	-271.2	-195.1	-199.4	-235.2	-224.5	-107.3	-115.1	-154.1	-136.9	336.0	417.9	448.1	354.9
		Status	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS
		Iter	80.0	126.0	82.0	114.0	80.0	125.0	82.0	114.0	101.0	215.0	115.0	415.0	215.0	199.0	198.0	112.0	98.0	125.0	264.0	127.0
Total_Deficit			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.7	2.1	2.1	0.0	63.1	63.0	61.4	62.4
Total_Max			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	2.1	2.1	0.0	51.9	63.0	61.4	62.4
Max			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.3	0.2	0.2	0.0	9.6	4.5	4.4	3.9



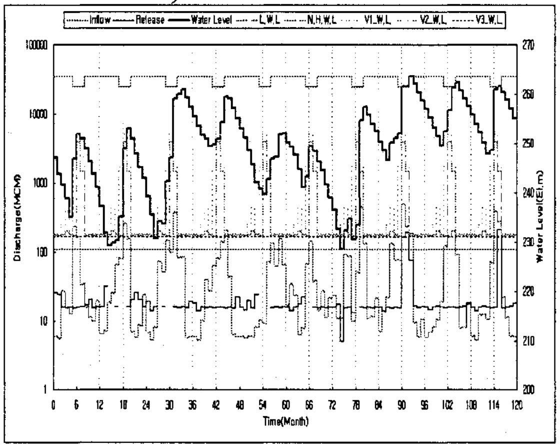
a) Instream flow = 2cms

b) Instream flow = 3cms



c) Instream flow = 4cms

d) Instream flow = 5cms



e) Instream flow = 6cms

Figure 5.8 Priorities of Water Supply for Reservoir Operation by Varying Instream flow (when setting the priority of water supply such as instream flow, trans-basin diversion, and irrigation water use, and groundwater = 1, and surface water = 1 for the weighting factor)

5.4.5 Performance Measures

Hashomoto (1982) defines reliability as the probability that no failure occurs within a fixed period of time. Reliability, which was originally the measure of risk of failure, is generally expressed as the expected number of failures per time interval. For the purpose of this study, reliability is a count of the number of deficit periods divided by the total number of periods, a measure of frequency and probability of failure. Magnitudes of deficits are not often considered in terms of reliability. A reliable reservoir is one that has very few failures during the period of analysis.

Resilience is considered to be the probability of recovery from failure to some acceptable state within a specified time interval. Resilience can be a measure of the probability of being in a period of no failure this period given that there was a failure in the last period. A resilient system is one that is capable of recovering from a deficit state to normal operation in a short time. In this study, a resilience measure is used as the maximum number of consecutive periods of shortages that occur prior to recovery. The larger this number, the less resilient the reservoir. A criterion based on the maximum number of consecutive periods of shortage can provide a benchmark for the comparison of different modes of reservoir operation.

Vulnerability is a measure of significance of failure. Measurement of average release may be adequate for long term performance evaluation but is insufficient and inadequate to account for the infrequent and extreme events that a reservoir will experience in its economic life. In this study, the vulnerability criterion used the magnitude of the largest deficit during the period of operation.

Tradeoff Analysis Between Reliability Objectives

The three risk objectives are to minimize the total number of deficits periods, the maximum deficit, and the maximum number of consecutive deficits. Tradeoff curves between the maximum deficit (vulnerability) and the number of deficit periods (reliability) for different values of the maximum number of consecutive periods of deficits (resilience) are shown in Table 5.8 and Figure 5.9. These results were obtained by running 31 simulations of the model while varying the total number of deficits and the consecutive number of deficits for the reservoir. When the total number of deficits and the consecutive number of deficits increase, the maximum deficits decrease. According to the results, the total number of deficits and the consecutive number of deficits of reservoir are greater than 16 and 4 to meet all demands when the downstream instream flow requirements is set at $5m^3/s$. These results are not binding when the total deficit number is less than 10. The maximum deficit for the system was 8.4 MCM, and the total deficit was 67.4MCM for 10 years at the consecutive deficit number, 1, and the total deficit number, 10.

Tradeoffs between maximum deficit (vulnerability) and the maximum number of consecutive deficits (resilience) are shown in Figure 5.10. For each of the curves shown, as the number of deficit periods decreases, the maximum deficit increases. The relative change of the maximum deficit value is not a linear relationship with the number of deficit periods. The tradeoffs among all objectives are shown in the three-dimensional surface in Figure 5.11.

To mitigate the damage of droughts, reservoir rationing for all demands is necessary, and conjunctive water use must also be considered as was seen in the results of the case study.

Table 5.8 Values of Objectives and System Maximum Deficit for Each Scenario

Div.	Reservoir Constraints		System Water Deficit		Model Results		
Order	No. of Deficit Periods	No. of Consecutive Deficits	Total	Max	Objective Value	Status	No. of Iteration
1	16	4	0	0	-115.9027	OPTIMAL SOL	142
2	16	3	2.1387743	0.1645211	-115.085	OPTIMAL SOL	199
3	16	2	2.5707747	0.1977519	-112.2149	OPTIMAL SOL	198
4	16	1	7.0242199	0.530622	-56.64984	OPTIMAL SOL	280
5	15	7	10.766062	0.8281586	-41.05373	OPTIMAL SOL	190
6	15	6	10.334061	0.7949278	-31.46847	OPTIMAL SOL	181
7	15	5	10.766062	0.8281586	-41.05373	OPTIMAL SOL	190
8	15	4	10.766062	0.8281586	-41.05373	OPTIMAL SOL	188
9	15	3	11.198062	0.8927464	-15.5563	OPTIMAL SOL	410
10	15	2	15.530772	1.294231	3.256692	OPTIMAL SOL	190
11	15	1	16.392277	1.490207	48.97901	OPTIMAL SOL	204
12	14	6	19.786977	1.812495	79.23213	OPTIMAL SOL	293
13	14	5	23.726064	1.977172	80.77088	OPTIMAL SOL	287
14	14	4	24.158064	2.013172	86.02623	OPTIMAL SOL	287
15	14	3	24.489355	2.226305	126.032	OPTIMAL SOL	296
16	14	2	28.49077	2.59007	144.8279	OPTIMAL SOL	326
17	14	1	24.057352	2.587032	127.3828	OPTIMAL SOL	291
18	13	5	27.626775	3.119128	207.1445	OPTIMAL SOL	322
19	13	4	27.626775	3.119128	207.1445	OPTIMAL SOL	355
20	13	3	27.194775	3.119128	203.9626	OPTIMAL SOL	477
21	13	2	27.19477	2.719477	175.6146	OPTIMAL SOL	354
22	13	1	32.74698	3.274698	228.4761	OPTIMAL SOL	362
23	12	4	40.58677	4.058677	313.9138	OPTIMAL SOL	374
24	12	3	40.58677	4.058677	307.4694	OPTIMAL SOL	363
25	12	2	40.58677	4.058677	303.9497	OPTIMAL SOL	362
26	12	1	40.58677	4.058677	303.9497	OPTIMAL SOL	351
27	11	3	53.978778	5.997642	497.4235	OPTIMAL SOL	361
28	11	2	53.978778	5.997642	497.4235	OPTIMAL SOL	361
29	11	1	53.978778	5.997642	497.4235	OPTIMAL SOL	362
30	10	2	62.174064	7.771758	715.918	OPTIMAL SOL	355
31	10	1	67.370776	8.421347	744.0106	OPTIMAL SOL	365

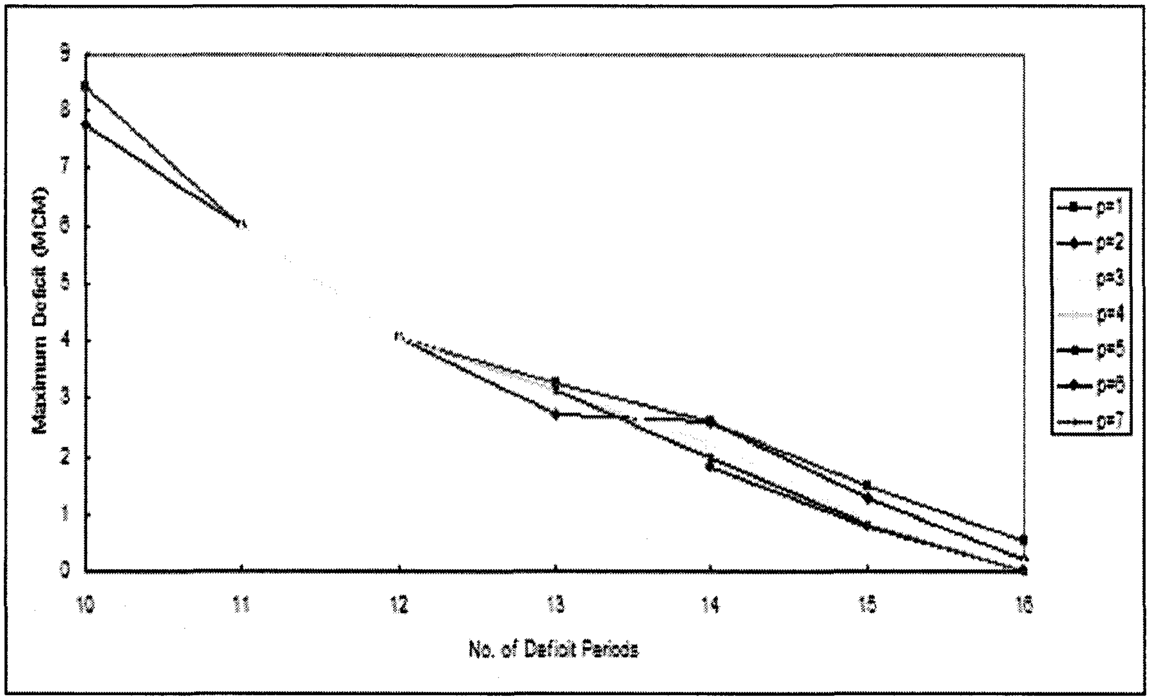


Figure 5.9 Tradeoff: Vulnerability vs. Reliability

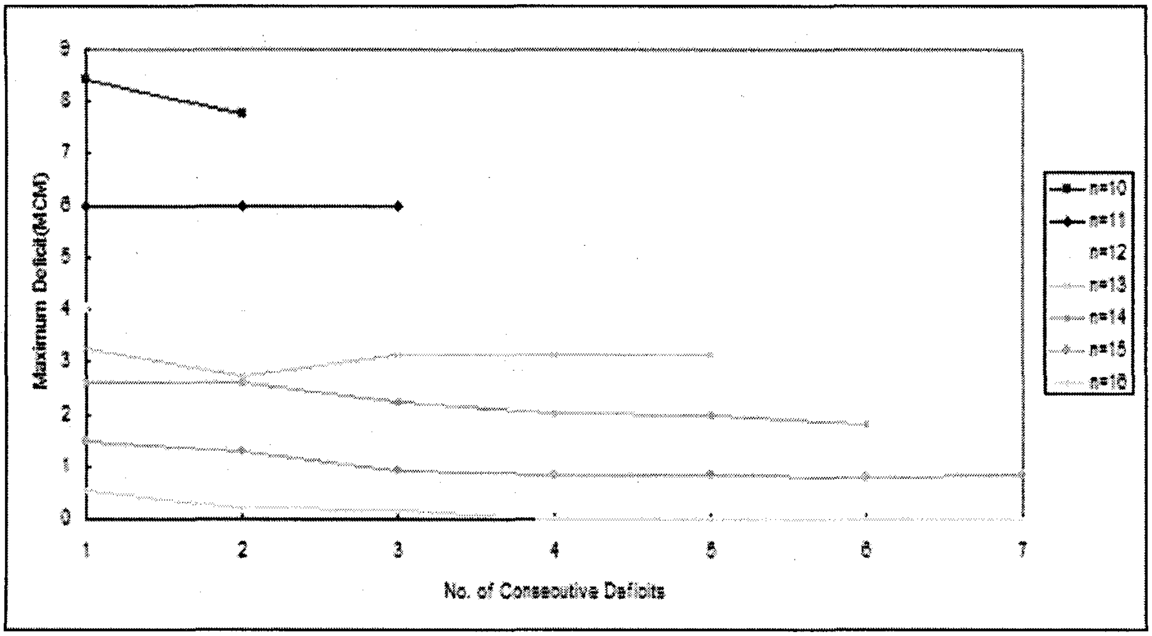


Figure 5.10 Tradeoff: Vulnerability vs. Resilience

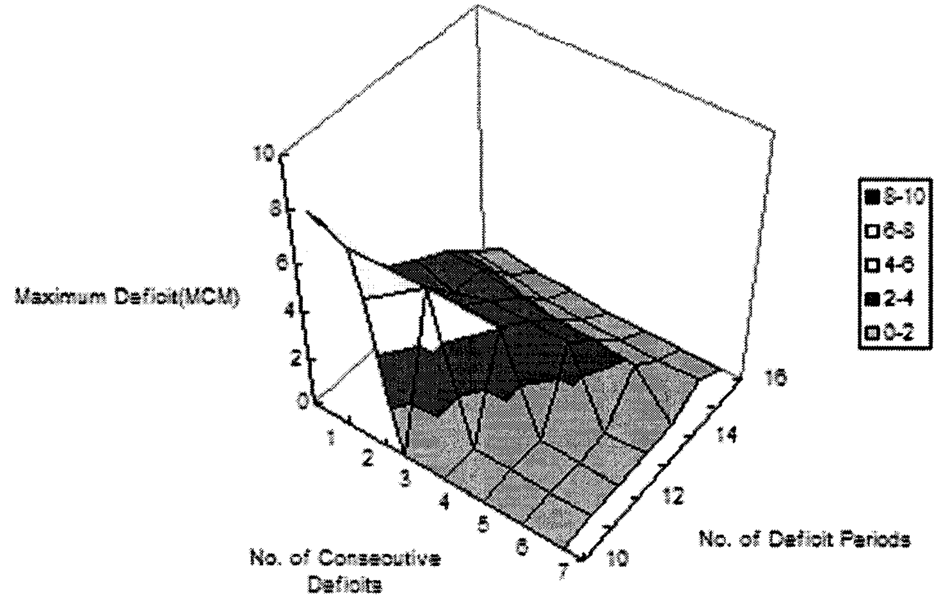


Figure 5.11 Three-dimensional Tradeoff Surface

5.5 Summary

Through running the conjunctive model, we see that the use of both surface and ground waters is viable in satisfying demands even though the thickness of aquifers developed along river courses are relatively thin. A better understanding of connection between groundwater and surface water allows the water manager to better manage these limited water resources.

In the sensitivity analysis, the weighting factors were assumed as the total deficit was 1, maximum deficit was 100, trigger volume was 0.1, and success of reservoir was 1. The weighting factors for water supply are also considered to evaluate water deficits for trans-basin diversion, instream flow requirements, and water use for the irrigation. The sensitivity of the weighting factors for each objective is not considered. The weighting factors of surface and ground waters are only considered.

When allocation policy one was modeled with an instream flow requirement of $5m^3/s$ from the reservoir, and the use of only the surface water to satisfy water demands, and the hedging rule for instream flow and irrigation water use was employed, the total deficit of irrigation was 11.6MCM during the analysis period from 1996 to 2005. However, when the weighting factor for the groundwater was considered, the total deficit of the irrigation water use ranged from 0.0MCM to 3.58MCM. This illustrates the effect of connection between surface and ground waters and how this connection can be used for more effective water management. The effect of conjunctive water use can also represent the reduction of total deficit for irrigation water use.

When allocation policy two was modeled with an instream flow requirement of $5m^3/s$ from the reservoir, and the use of surface water was only considered along with a hedging rule for all demands, the total system deficit was 13.7MCM during the analysis period of 120 months, and the maximum deficit was 6.3MCM for all demands. However, when the weighting factors of one for both of surface and groundwater were employed, the total system deficit was reduced to 2.1MCM.

According to the comparison of these allocation policies for reservoir operation, the order in which the order of instream flow requirements, trans-basin diversion, and irrigation water use demands and water considered impacts water availability for other users and illustrates that the conjunctive use of water resources in the form of surface and groundwater results in more effective use in this case study.

In measure performance, three measures were used as reliability, resilience, and venerability. Reliability is a count of the number of deficit periods divided by the total number of periods, a measure of frequency and probability of failure. A resilience measure is used as the maximum number of consecutive periods of shortages that occur prior to recovery. The larger this number, the less resilient the reservoir. Vulnerability is a measure of significance of failure. Measurement of average release may be adequate for long term performance evaluation but is insufficient and inadequate to account for the infrequent and extreme events that a reservoir will experience in its economic life.

CHAPTER 6

MANAGEMENT STRATEGY FOR CONJUNCTIVE USE AND INSTREAM FLOW

6.1 Introduction

This chapter describes institutional arrangements to implement conjunctive management. It addresses the existing organizations, water right systems, instream flow requirements, and data management. Water issues such as over-allocation, instream flow, and water quality are affected by institutional arrangements in implementing a project or solving a practical problem. In this chapter, institutional arrangements in Korea are compared to a limited extent with those at the federal level and in two states of the United States, California and Colorado. The comparisons enable a perspective to be drawn about arrangement of appropriate institutions in Korea.

In terms of technical issues, as stated earlier, aquifers near a stream in Korea are hydraulically interconnected, notably in the mountainous areas, and the movement of water can have significant water management implications. The hydrologic alteration occurred due to the construction of dams. Conjunctive use with these aquifers can help reduce deficits during drought periods, but its effect will be small.

The study led to recommendations about conjunctive management of surface water and groundwater in Korea based on a gap analysis and comparative analysis. In this chapter, the laws, regulations, data management and management arrangements for managing these highly connected systems in Korea will be analyzed to show how to make a conjunctive use strategy work.

6.2 Framework of Analysis

In terms of institutional arrangements, a framework for conjunctive water management of surface water and groundwater must include a systematic and iterative way to identify and control the factors. The framework can help water managers, water authorities, policy makers, watershed groups, industry groups and others learn about water management priorities and requirements and can facilitate coordinated results. The framework needs a simple check list of activities in a logical order to provide the opportunity to evaluate and revise priorities within an overall scheme of sustainable water management.

For one system of analysis, Grigg (2004) presents a list of five key questions about the institutional elements;

1) who has control?: designated authorities and stake holders (mainly organizations)
2) what are the laws and controls?: legal framework and control mechanisms (laws, regulations, decision requirements, enforcements mechanisms)
3) what are the incentives?: ownership, property rights, and incentives
4) who has what role: roles, responsibilities, and relationships between stakeholders
5) what is the management culture?: management practices, customs and ways of doing business (informal institutions).

He also presents the framework for institutional analysis including;

1) a conceptual model of how the management and control system work (what

goes on here?)

2) identification of the key issues in each category of institutional element (what process need adjustment?)
3) identification of institutional practices that should lead to improvement (what ought to go on here?)
4) three-step process leads to results through analyzing gap analysis which is a comparison of an existing status with a desired status.

The framework represents a general process that can be followed for conjunctive management regardless of the size and ownership of a watershed or the water issues that need to be considered. In this chapter, the framework suggested by Grigg (2004) will be used to evaluate the implementation issues of conjunctive water use management.

6.3 Water Right System-Ownership of the Rights to Use Water

6.3.1 Current Water Right System in Korea

Water Right System

The water rights systems in Korean acts and laws are diverse. Two kinds of water rights exist; the customary water right defined as water use right in public water area in Articles 221-236 in Korean Civil Law and water rights under the permit system stipulated in the River Act. The River Act was enacted in 1963 to contribute to public welfare and management of the river by the appointment, management, use and conservation of the river to prevent the damages from the river flow, increase the benefit of the water use, and improve and preserve its environment.

Prior to the River Act, a water right was the customary water right, and designated as the permitted water right by classifying it. In 1966 the Specified Multi-purpose Dam Act was enacted to handle dam construction and management, and the Dam Use Right emerged. The vested water right was defined, and then modified by establishing the dam use right. In a practical sense, types are now classified as the customary and vested water right, dam use right, and the permitted water right. Figure 6.1 shows the overall history of water rights as to surface water by the introduction year. Appendix C.1 illustrates the various acts related to water management in Korea.

For groundwater, the Groundwater Act was passed in 1993 to provide detailed regulations regarding the master plan, permission and report on development and utilization, designation of groundwater preservation area, prevention and measurement of water contamination, registration of construction businesses to development and utilize groundwater, groundwater impact investigation agency and groundwater purification business. Various other acts concerning groundwater exist in Korea such as the Spring Act, Laws of Management for the Share Surface of the Water, etc. The Groundwater Act included a permitting system for groundwater, but it did not consider interaction between streams and aquifers.

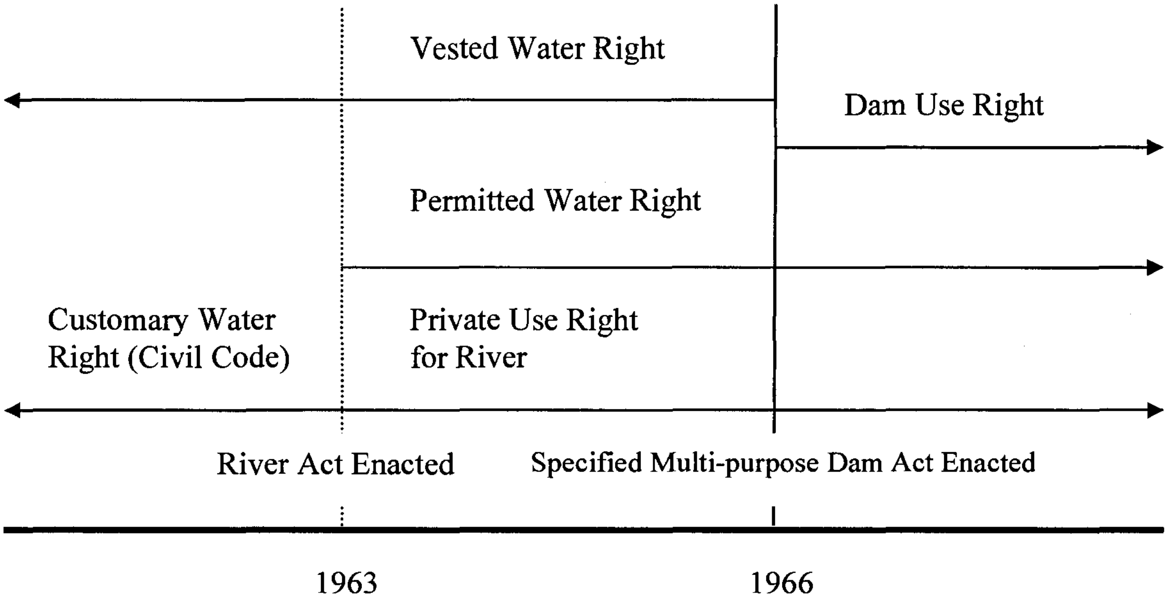


Figure 6.1 Water right of surface water in Korea by the year of the introduction

River Water Administration

According to the River Act and the Small Stream Maintenance Act, rivers are classified as: 1) national rivers managed by the central government: 2) local rivers managed by the local government: and 3) small streams managed by the local government. Therefore, in issuing permits for water use in a stream, Korea has a dual system.

The Flood Control Office (FCO) under the Ministry Of Construction and Transportation (MOCT) at the basin level is authorized to issue permits of surface water appropriations in national rivers, and local governments have authority to issue permits of water use in local rivers. Figure 6.2 shows an example for river management dependent on river classification. As shown in Figure 6.3, when an applicant applies for water use in national streams by each purpose, the FCO should negotiate with the Regional Construction Management Office (RCMO) under the MOCT and municipalities about the usage of the stream and facilities to be installed. Also, it should review technical parts such as the water budget and downstream impacts due to withdrawals. Therefore, the main and related agencies are directly and indirectly involved in permitting water use.

Meanwhile, when an applicant applies for water use in a 1st or 2nd class local stream, the local government should issue the permit of water use after reviewing whether a new appropriation can injury senior water users. The local government should also consider the implementation of stream management and the stream maintenance master plan.

Local governments with jurisdiction also have the authority to issue groundwater rights. The procedure of permitting water rights is similar to that of surface rights, but the local government must negotiate with the FCO about the stream depletion due to a pumping well if a well location is within 300m from a stream.

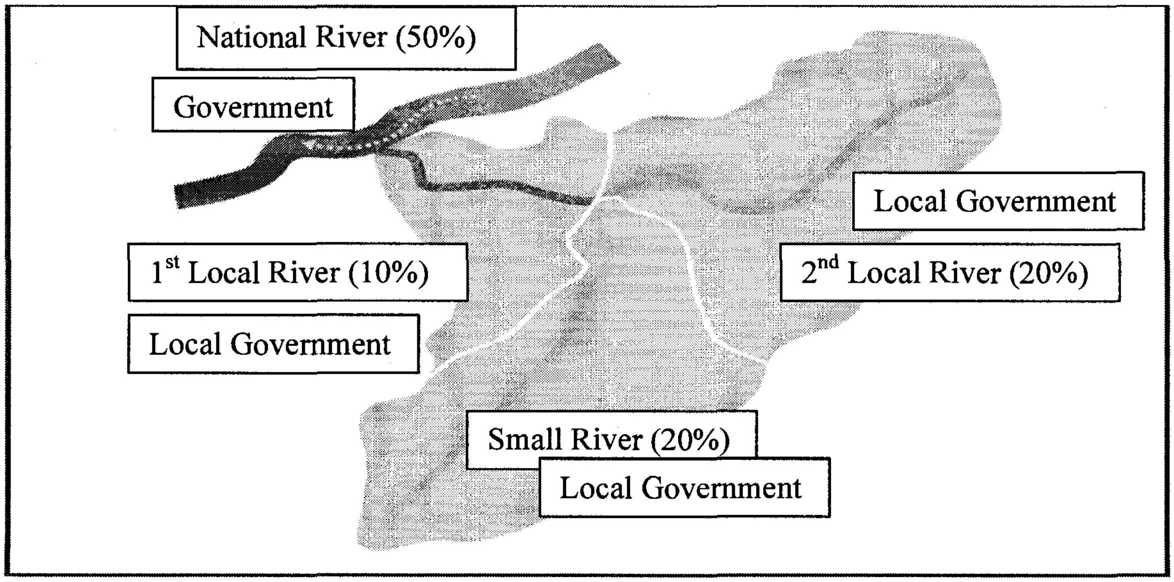


Figure 6.2 Example of River Management Depending on Jurisdiction

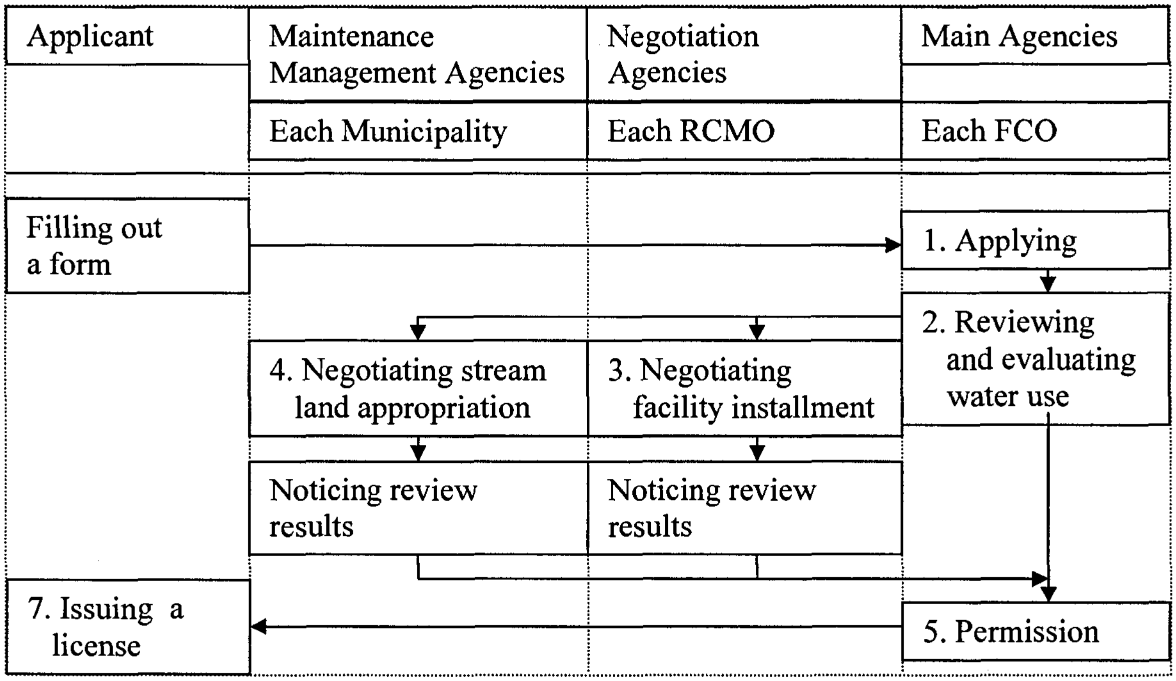


Figure 6.3 Procedure of Permitting the Water Use in Stream

6.3.2 Water Right System at the State Level (Colorado, California)

Colorado has followed a system of water allocation known as the prior appropriation doctrine[5]. Under the doctrine, the first appropriator of water has a senior right to that water, and that right must be satisfied before any subsequent rights junior to that can receive water. The Water Rights Determination and Administration Act of 1969 was passed in response to the state Supreme Court's finding concerning tributary wells and surface water. The act required that surface water and groundwater rights be administered together as an integrated unit. Through integrated administration of surface

---

[5] The prior appropriation doctrine is often referred to as the priority system or "first in time, first in right." An appropriation is made when an individual physically takes water from a stream or well(when legally available) and puts that water to some type of beneficial use. The first person to appropriate water and apply that water to use has the first right to that water within a particular stream system. This person, after receiving a court decree verifying their priority status, then becomes the senior water right holder and that water right must be satisfied before any other water rights are filled. (Guide to Colorado well permits, water rights, and water administration, March, 2006)

and groundwater (also known as conjunctive use), junior right holders appropriating water (that is, tributary wells[6]) can not injure the vested rights of a senior appropriator.

Water rights in Colorado are established through a water court system. There are seven water courts, one for each major river basin, which adjudicate water rights across the state. Each water court has an appointed water judge and water referee who hear all water related matters within their jurisdiction. The State Engineer administers and distributes the state's waters. The State Engineer is also responsible for issuing and denying permits to construct wells and divert groundwater, but these permits do not constitute rights to groundwater. The Colorado Ground Water Commission is a regulatory and an adjudicatory body authorized to manage and control designated groundwater resources.

California laws recognize separate bases for establishing rights to the use of groundwater and surface water under a hybrid doctrine that includes riparian and appropriative rules.

For surface water, riparian rights are the rights of landowners to the use of the flow of a stream that crosses or borders their land. These riparian rights are not quantified and thus are not governed by a permit process. Water use by riparian owners is limited only by the doctrine of "reasonable and beneficial use". The doctrine of prior appropriation is followed with respect to most other uses of surface water resources. The California Water Resources Control Board (CWRCB) is authorized to issue permits for

---

[6] Tributary water means water that is hydrologically connected to a natural stream either by surface or underground flows. Conversely, Non-tributary ground water is ground water located outside the boundaries of any designated groundwater basin, where the withdrawal of this ground water by a well will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal (Guide to Colorado well permits, water rights, and water administration, March, 2006)

diverting and using specific quantities of water per year.

Groundwater rights are recognized and allocated by a multifaceted and complex set of rules. Underground stream-flow may be a hydraulically connected portion of the flow of a stream and is treated as if it were surface water through the permit application process. Use of percolating groundwater is not within the jurisdiction of any state agency, and no statewide procedure exists for water use. Instead, rights to use are by a form of common law, developed and enforced by the courts.

Even though Colorado and California have separate acts about surface and ground waters, they manage them as a single source. As mentioned above, acts or laws as to surface water and ground water in Korea were enacted separately even though they are fully interconnected as a single source. Korea needs to revise those acts or laws with respect to water in terms of efficiently and effectively utilizing limited water.

Table 6.1 illustrates the status of water right systems between Colorado and California in the United States and Korea.

Table 6.1 Summary of the Water Rights in Colorado, California and Korea

Division		Colorado	California	Korea
Surface water right system		Appropriation	Hybrid	Mixed
Exception		-	Pueblo Rights	Customary Rights
Permit System	Surface water	Yes	Yes	Yes
	Groundwater	Yes	No	Yes
Court approval (Permit)	Surface water	Yes	No	No
	Groundwater	No	No	No
	Buying/selling	Yes	Yes	No
Legislative activity		Yes	Yes	Yes

Source: selected and revised from AWWA (1990)

In Colorado, the tributary groundwater account for the interaction between surface and ground waters, whereas in California, percolating ground water represents the connection of surface and ground waters. Table 6.2 illustrates the status of the relationship between surface and ground water in Colorado, California and Korea.

Table 6.2 Relationship between Groundwater and Surface Water

Division	Colorado	California	Korea
Surface water	Tributary Groundwater	Underground water	Seeping water
Groundwater	No-tributary Groundwater	Percolating Groundwater	Filling or Flowing water
Others	Designated[1]	-	Preserved[2]

Note: 1. Ground water that, in its natural course, is not available to or required for the fulfillment of decreed surface rights, or ground water in areas not adjacent to a continuously flowing natural, wherein groundwater withdrawals have constituted the principal water usage for at least 15 years preceding the date of the first hearing on the proposed designation of the basin, and which is within the geographic boundaries of a designated ground water basin.

2. Ground water is necessary to be preserved by the various purpose such as; Areas at the upper reaches of a stream which is connected hydraulically to the lower reaches where groundwater is consumed; Areas having an aquifer abundant with groundwater serving as a main water supply source; Areas whose water quality is likely to be lowered as the facilities, etc..

6.4 Organization (Korea vs. the United States)

6.4.1 Water Management Organizations and Roles in Korea

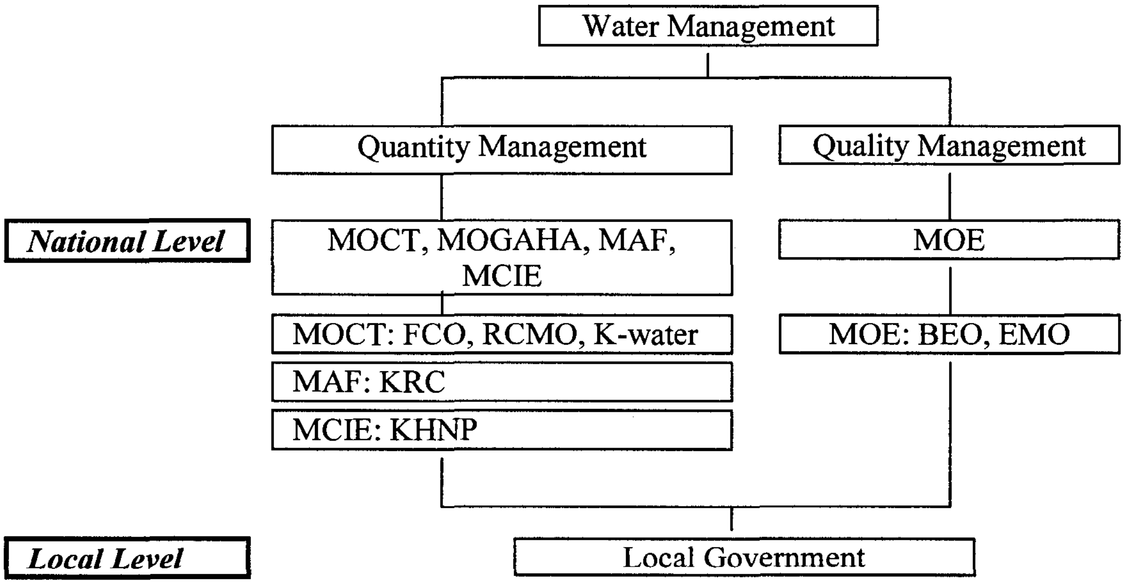
Water management in Korea is comprehensive considering water quantity, which contains flood control, new development of water resources, allocation of water resources, etc., and water quality which includes ecosystem conservation, drinking water etc.. Administrative agencies of water management are classified in three major categories as the central government, its affiliated agencies, and local governments. At the central government level, there are five ministries related to water management. Table 6.3 illustrates the assigned businesses related to water management by each ministry. Figure

6.4 shows overall structure of agencies related to water management. The water management system in Korea is complicated. The Ministry Of Construction and Transportation (MOCT) is generally authorized to administer and develop the businesses of water management in terms of water quantity, whereas the Ministry of Environment (MOE) has authority to regulate and manage water quality. In aspects of water supply, the MOCT manages the allocation of streams and dams for municipal, industrial and irrigation water use at the national level, the Ministry of Government Administration and Home Affairs (MOGAHA) takes charge of water supply to local areas at the local level, the Ministry of Agriculture and Forestry (MAF) manages various facilities for the irrigation such as weirs, pumping stations, dams etc., and the Ministry of Commerce, Industry and Energy (MCIE) controls dams to produce hydropower. The working organizations to execute national water policy are mostly local governments and affiliated agencies under each ministry. Accordingly, water management organizations in Korea are classified as central and local governments, with each basin management agency under each ministry.

As stated in Chapter Three, flood control and water allocation is of interest because the precipitation is relatively great. Most water organizations and their functions are concentrated on these two components. Therefore, the working organizations under ministries with groundwater management are not separated. The organizations are affiliated with the main organizations or agencies dependent on surface water management.

Table 6.3 Water Management Organizations and Roles in Korea

Division	Roles and Assigned Business
Ministry of Construction and Transportation (MOCT)	- National stream management - Storage management - Groundwater management - Flood control - Multi-regional water supply system - Multi-purpose dam
Ministry of Environment (MOE)	- Sewerage management - Groundwater and surface water quality - Stream purification - Local water supply system - Dam water quality measurement
Ministry Of Government Administration and Home Affairs (MOGAHA) (including Local Governments)	- Water source area management - Local water supply system - 1st and 2nd class local stream management
Ministry of Agriculture and Forestry (MAF)	- Irrigation dam management - Irrigation estuary management - Irrigation groundwater management
Ministry of Commerce, Industry and Energy (MCIE)	- Hydropower dam management



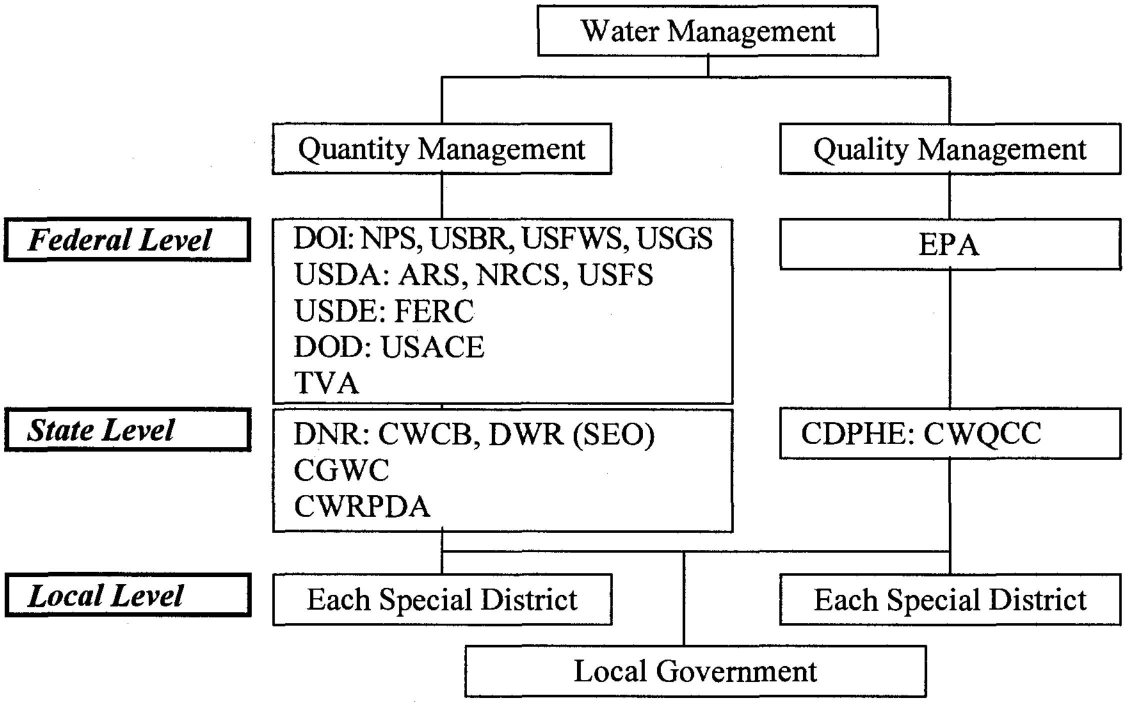
Note: FCO: Flood Control Office, RCMO: Regional Construction Management Offices, KRC: Korea Rural Community & Agriculture Corporation, KHNP: Korea Hydro & Nuclear Power Co. Ltd., BEO: Basin Environmental Office, EMO: Environmental Management Office

Figure 6.4 Water Management Organizations in Korea

6.4.2 Water Organizations in the United States

At the Federal Level

Numerous bureaus, agencies and commissions within the federal government have concerns and responsibility in areas of water supply and quality regulation. Appendix C.2 represents the summary of the major federal agencies and their roles. Figure 6.5 shows the overall organization of water management in the United States. At the state and local level, an example of Colorado's organizations is presented.



Note: DNR: Colorado Department of Natural Resources, CWCB: Colorado Water Conservation Board, DWR (SEO): Division of Water Resources (or State's Engineer's Office), CGWC: Colorado Ground Water Commission, CWRPDA: Colorado Water Resources and Power Development Authority, CDPHE: Colorado Department of Public Health and Environment, CWQCC: Colorado Water Quality Control Commission

Figure 6.5 Overall Water Management Organizations in USA

At the State Level (California and Colorado)

In California, the state government supports water management by the creation of local special-purpose districts and agencies, by providing information on water conditions, and by operating the State Water Project (Blomquist et al., 2004).

The California Water Resources Control Board (WRCB) and the California Department of Water Resources (DWR) are two prominent state agencies with respect to the allocation and management of water supplies. The WRCB administers the surface water right permit process, but also includes a system of Regional Water Quality Boards with authority to issue rulings, orders, and fines concerning land or water uses that may impair water quality. The DWR operates the State Water Project and conducts studies of water conditions and hydrogeologic properties of water resources. All other water supply management organizations in California are local.

In Colorado, no single state agency is responsible for water management. Water quantity management, planning, and administration fall under the authority of the Colorado Department of Natural Resources (DNR), while water quality is the domain of the Colorado Department of Public Health and Environment (CDPHE). The State Engineer administers and distributes the state's waters. The State Engineer is also responsible for issuing and denying permits to construct wells and divert groundwater, but these permits do not constitute rights to groundwater. The Colorado Ground Water Commission is a regulatory and an adjudicatory body authorized to manage and control designated groundwater resources. Finally, the Colorado Water Conservation Board (CWCB) oversees conservation and development in the state and is responsible for the state's instream flow program (Wolfe, 2005). Appendix C.3 illustrates Colorado's organization and its roles in detail.

6.4.3 Lesson for Korea

Water management does not operate in a vacuum; it is devised and administered by organizations, and water management choices and activities emerge through the interaction of organizations. The involvement of multiple organizations with differing interests and responsibilities raises coordination issues. Coordination would be especially vital for conjunctive management where multiple jurisdictions and specialized organizations are employed to take advantage of surface and ground water. At the same time, coordination entails negotiation.

In case of the United States, either federal or state organizations administer and manage surface and ground waters as a single source based on the river basin regardless of quantity and quality. Table 6.4 and Table 6.5 illustrate conjunctive management institutions and organizations in Colorado and California. In implementing conjunctive management, the two states took account of surface and ground waters as a single source. Colorado mainly used a water rights system, while California used organizational arrangements and coordination. These facts offer Korea, which faces tough challenges to advance into more efficient and effective management of water resources including groundwater, an opportunity to coordinate between organizations and revise the related institutions.

Table 6.4 Comparison of Conjunctive Management Institution and Organizations

Items	Colorado	California
Water-Rights System		
- integrated ground and surface water rights	✓	
- state law quantifies groundwater rights	✓	
- state defines to recharge and recover stored groundwater	✓	
- state permits local-level institutions to define rights to groundwater		✓
Organizational Arrangements		
- state agencies approve locally organized conjunctive management projects	✓	
- private organizations and individuals participate in conjunctive management projects	✓	Rarely
- sub-state governments, including municipalities, countries participate in conjunctive management	Rarely	✓
- organizations proving conjunctive management coordinate around basin boundaries		✓

Source: Boomquist et al. (2004)

Table 6.5 Summary of Water Management Organizations

Division	Colorado	California	Korea
Water Management	Decentralized (7 divisions)	Centralized (DWR)	Centralized (MOCT, MOE)
Water Regulation	Centralized (Division Engineers)	Decentralized (SWCB)	Centralized (MOCT, MOE)
No. of Agency	87 (80 districts and 7 divisions)	2,850 (districts and agencies)	24 (MOCT: 11, MOE: 13)
Conflicts	- Minimal time taken to resolve conflicts by courts (relatively) - More conflicts	- Negotiations required extended time frame (relatively) - Fewer conflicts	- Being short time in past - Currently longer time - More expected conflicts

Source: Boomquist et al. (2004) and results discussed with Grigg

6.5 Instream flow Requirements

Korea

Maintenance stream-flow was introduced in 1967 in order to protect plains from saltwater intrusion at the mouth of a river in water resources development and utilization plans by MOCT. With realizing its importance to preserve ecosystem, since then, the notion of instream flow has changed so that it is environmental flow to maintain stream purity. However, there is expressly no definition of instream flow. Appendix C.4 illustrates the evolution of maintenance stream-flow in major rules or regulations issued by MOCT.

In Article 20 of the River Act revised in 1999, maintenance stream-flow is defined as minimum flow to maintain the normal function and status of stream. The Act states that the maintenance stream-flow should be notified through the deliberation of the Central River Management Committee. Estimating maintenance stream-flow and selecting the principal points on a stream course are also stipulated. In Article 13 of its Enforcement Ordinance, it states regulations defining guideline of stream-flow and criteria of selecting major points. MOCT prepared the guideline of maintenance stream-flow in order to expressly establish the notion of maintenance stream-flow and define the detailed methodology. Here is the procedure of estimating maintenance stream-flow based on the guideline:

1) understanding of stream environment and characteristics
2) dividing river reaches and choosing main points
3) analysis and estimation of low flow and water needs by item
4) defining maintenance stream-flows by reach

5) reviewing and establishing maintenance stream-flows at main points or reaches

Pursuit to Article 20 of the River Act and Article 13 of its Enforcement Ordinance, it only describes facts concerning estimating methodology and notification of estimated stream-flow including major points, yet does not represent relevant and detailed particulars about agency, administration or management even though the FCO has authority to calculate and notify the instream flow. Table 6.6 illustrates participation in instream flow water rights creation, administration and ownership as compared with US Western States and Korea. The River Act does not recognize water rights for instream flow requirements relied on the available water in a stream, but designated and notified by needs. Because the shortage of stream-flow data, no-expertise of officials, and incredible water budget analysis are obstacles for reasonable water allocation in a stream.

Table 6.6 Participation in Instream flow Water Rights Appropriations or Transfers

State or Country	Who Can Appropriate ISF Water Rights	Who Can Transfer Existing Water Rights to ISF Use
California	Not allowed	Any water right holder can transfer a right to ISF purpose if established criteria are met
Colorado	Colorado Water Conservation Board	Any person, including government entities or organizations, can transfer rights to the CWCB for conversion to ISF
Korea[1]	Ministry of Construction & Transportation (MOCT) or FCO	Not stipulated

Note: 1. Instream flow which is notified by the FCO is not a water right in Korea.

Colorado and California

In Colorado, water rights to in-stream uses were introduced in a statutory program and established in 1973. Beneficial uses of instream flow in Colorado are followed with four uses such as 1) fish, 2) other aquatic organisms, 3) riparian areas, and 4) environmental protection. The Colorado Water Conservation Board can appropriate instream flow water rights as stated in the earlier section. Any person, including governmental entities or organizations, can transfer rights to the CWCB for conversion to in stream-flow. CWCB also has the authority to appropriate, monitor and protect instream flow, and the water court adjudicates all water rights and the Division of Water Resources administers all water rights. CWCB provides legal protection by reviewing every water rights application filed in the state water court for potential impacts to existing instream flow water rights. If potential injury is identified, the CWCB staff files a statement of opposition with the water court and seeks protective terms in that decree. This protection through the filling of statements of opposition has allowed junior instream flow water rights to gain relevance in the prior appropriation system. CWCB performs monitoring and enforcement and provides physical protection for instream flows largely with the use of gages. If flows fall below the in-stream right and water is available given the seniority of the right, CWCB can place a call to meet its flow requirements

In California, instream flow water rights were established in 1991. New instream flow water rights are not granted but conditions placed on other water rights and permits to leave flows in streams for in-stream purposes (through water rights can be transferred to instream flow purposes). Beneficial uses of instream flow in California are followed with eight uses such as 1) fish, 2) other aquatic organisms, 4) wildlife, 5) riparian areas, 6) aesthetics, 7) navigation, and 8) water quality. California requires periodic review of instream flow rights. Transferred rights are subject to review, but it is important to note that review applies to all water rights, not only instream flows. This review is generally flow set to establish whether the need and purpose of the instream flow are still valid if there is still sufficient water available to meet that need. Any water rights holder can transfer a right to instream flow purposes if established criteria are met. The State Water Resources Control Board (SWRCB) authorizes and administers the instream flow water rights.

Table 6.7 Explicitly Recognized Beneficial Uses of Instream flow

Items	Colorado	California	Korea[1]	Items
Fish	●	●	●	Fish
Other Aquatic Organization	●	●	●	Groundwater
Wild life		●		
Riparian Areas	●	●	●	Salt Water Intrusion
Recreation		●	●	River Mouth Closure
Aesthetics		●	●	Scenic Views
Environmental Protection	●		●	Ecosystem Protection
Navigation		●	●	Water Source & Facilities
Channel Maintenance			●	Channel Maintenance
Water Quality		●	●	Water Quality

Note: 1. Korea has different criterion on the instream flow including saltwater intrusion, rivermouth closure, water sources and its facility protection, and groundwater level protection

Table 6.8 Tools Available for Instream flow Protection

State or Country	Tools for Instream flow Protection
California	- California Wild and Scenic Rivers Act - Administrative review of new and existing water permits resulting in protective conditions for ISF - Conversion of existing right to ISF purposes
Colorado	- Instream flow water right obtained through new appropriation - Acquisition and conversion of existing rights through grant, purchase, donation, bequest, devise, lease, exchange, or other contractual agreement - Short-term loan or lease of water right from private individual or water bank to the CWCB
Korea	- Minimum flows set through administrative rule-making procedure

6.5.1 Current Trends in Instream flow

Most instream flow programs specify a single, minimum value of stream flow that is required to 1) meet a legal standard or 2) sustain an endangered species or some other flow-dependent resources. However, current trends in instream flow programs moving away from these single values and towards comprehensive river science. For example, instream flow hydrology and hydraulics now include the hydrologic regimes with seasonal and inter-annual variation and not only a minimum flow value; biological aspects account for aquatic and riparian ecosystems and not just a single-species target species. In addressing stream flows across this broad range of ecosystem conditions and processes, scientists now consider a fuller range of stream flow conditions beyond minimum instream flow needs.

Instream flow is a simple notion with the difficult task of balancing conflicting uses for river water. To date, four trends in instream flow science have marked its evolution:

1) from single, minimal flows to flow regimes;
2) from a single-species focus to a focus on whole ecosystem;
3) from the study of the stream channel to the study of riparian and floodplain areas; and
4) from a hydrology dominated field to an interdisciplinary field that includes hydrologist, biologists, lawyers, geomorphologists and water quality experts.

Implementing an instream flow recommendation requires a skillful balance in apportioning water among disparate and competing uses. This balance between human and ecosystem needs is considered in finding a flow regime that conserves fish and wildlife and human uses of water. Allocating water for a range of water needs and uses is a challenge in many places across the nation. Furthermore, situations exist that disrupt this delicate balance, such as the groundwater withdrawal, rapidly changing land uses, many reservoirs, over-appropriated rivers compared to rivers where water remains available.

Groundwater is a critical aspect of instream flow. Springs and seeps contribute a significant portion of the total water that flows in many of rivers and streams and illustrate how groundwater and surface water function as a single hydrologic system in many instances. Well pumping can influence groundwater discharge to rivers and streams, with the potential to alter base flow conditions. Even though significant, unregulated withdrawals from aquifers could affect instream flows in significant ways, the system for allocation of surface and groundwater resources in Korea is legally separate. This discontinuity between the single physical property of surface and groundwater systems and the diverged allocation system for surface water and groundwater raised some questions about the efficacy of instream flow recommendations that may be affected by groundwater withdrawal.

6.6 Data Management

Accurate and comprehensive water resources data are important to planners and decision-makers at all levels of government, researchers, developers and business community. Now more than ever, the increasing need to manage our precious water resources is driving the need for more detailed water data for many domains of the nation.

At this time, governmental agencies, municipalities, institute and universities collect and maintain extensive water resources data. However, some of these data are not readily available to others, datasets may be missing information which decrease their usefulness to other agencies, or access and retrieval are time consuming or cumbersome. As a result, planning and management efforts, such as development of Nation Water Plan, become difficult. Many agencies are starting to address the data issue by providing data directories and data downloading capabilities through their Internet websites. It is anticipated that the Internet will be the most significant tool for improving data sharing capabilities in the future.

Improved data development, collection, management, coordination and sharing in water resources allow the Nation to make direct and indirect benefits. For example, decision-makers, planners, regulators and the public can become better informed which may lead to improved decisions, and future Nation Water Plan can be improved. Also, improved data access and sharing between agencies can result in reduced duplication of efforts, thereby saving money to be needed in collecting, managing and storing data.

For purposes of water resources, data are classified as three types: temporal, spatial and textual data. Temporal data are those data related to a particular point in time or period of time. Examples include stream-flows, groundwater levels, and precipitation data. Spatial data are those data related to space which can be shown on a map, and are mainly maintained by Geographic Information Systems (GIS). GIS is a computer system for assembling, storing, manipulating, and displaying spatial data which includes information on the physical locations (geographic coordinates) of features and information about those features. Textual data compose of text-based information such as directories, library inventories, etc..

Metadata, or information about data in a dataset, is an important component of information management. With metadata, the characteristics of a dataset are documented so that potential users can determine the appropriateness of the data for their particular purpose. Metadata can include a variety of information such as the agency responsible for the data; measurement, collection and laboratory methodologies; and data accuracy.

Collection, Management and Distribution of Data for Surface Water

Data for the quantity of the surface water are collected by three major agencies; MOCT's Flood Control Office (FCO); MOCT's Korea Water Resources Corporation (K-water); MAF's Korea Rural Community & Agriculture Corporation (KRC). FCO mainly collects water levels and discharge at principle stations of national streams, water rights, and water use in national streams. K-water collects reservoir levels and storages data, water use, and precipitation related to reservoir operation upstream the reservoir. KRC mainly collects water data related to the irrigation such as agricultural reservoir levels and storages. But most stream-flows data are collected by FCO and K-water which play important roles in the national water management. The 676 rainfall gauging stations have been operated by FCO and K-water, and 506 of them operate in the telemetry system. Table 6.9 and Table 6.10 illustrate the status of rainfall and stream gauging stations in Korea. Most of the other agencies collect limited water quantity data on a project-specific basis and store the data in internal, project-specific databases. These data are available in a variety of ways, depending on the agency.

Table 6.9 Summary of Rainfall Gauging Stations in Korea.

Agency		Total	Non-real Time	Real Time
Total		676	170	506
MOCT	Han River	154	33	121
	Nakdong River	142	37	105
	Geum River	71	14	57
	Seomjin River	48	4	44
	Youngsan River	19	-	19
K-water		157	-	157
KRC		9	6	3
KMA		157	-	157

Source: http://hrfco.go.kr/YearCD/2005/rain/index.html

Table 6.10 Summary of Stream-flow Gauging Stations in Korea.

Agency		Total	Non-real Time	Real Time
Total		423	49	374
MOCT	Han River	87	15	72
	Nakdong River	74	14	60
	Geum River	64	3	61
	Seomjin River	39	4	35
	Youngsan River	33	-	33
K-water		110	-	110
KRC		16	13	3

Source: http://hrfco.go.kr/YearCD/2005/water/index.html

Flood Control Office

MOCT's Flood Control Office is the national agency primarily responsible for collecting and sharing data on water availability and use. In particular, the FCO is the main collector of stream-flow data, which measures the volume of water flowing through a stream using streamgages. FCO collects data through its national streamgage network, which continuously measures the level and flow of rivers and streams at 283 stations nationwide except gage stations upstream the reservoir. It makes these data available to the public via the Internet. FCO combine its data, together with the Korea Meteorological Administration's data, to forecast water supplies and floods.

Korea Water Resources Corporation (K-water)

The MOCT's Korea Water Resources Corporation is the primary agency that is responsible for collecting and sharing data on water availability and use. In particular, the K-water is one of the main collectors of stream-flow data, which measures the volume of water flowing trough a stream using stream-gages. K-water collects data through its own stream-gage network, which continuously measures the level and flow of rivers and streams at 110 stations nationwide upstream the reservoir. It makes these data available to the public via the Internet. K-water is also a major collector of water use data.

Korea Rural Community & Agriculture Corporation (KRC)

The MAF's Korea Rural Community & Agriculture Corporation is the primary agency that is responsible for collecting and sharing data on the irrigation water use. But activities of measuring and collecting water data are limited in the domain of irrigation water supply.

Korea Meteorological Administration (KMA)

Precipitation data are also important in determining how much water will be available for use, as well as in predicting floods. The Korea Meteorological Administration is primarily the agency response for collecting and sharing data through the nationwide network. KMA provides its data to other agencies which need precipitation data to effectively or safely manage or operate their facilities.

In 1999, the government recognized the need to effective manage various types of data in order to improve national competitiveness through sharing data available so that established the master plan of Water Information System. As a result, Water Management Information Networking System (WINS) has been developed and operated by MOCT since 1999. WINS include a variety of data related to water produced by many agencies such as water use, water facilities for the irrigation, groundwater levels, precipitation, spatial data and water quality. The number of agencies is 13 including Korea Meteorological Administration, Ministry of Commerce, Industry and Energy, Ministry of Agriculture, and Ministry of Environment, and the number of the item of sharing data 34. This system was developed based on the data-centered approach. Under the long term plan of water information, MOCT has also developed the Water Management Information System (WAMIS) to effectively manage water data, provide real-time data to users and make an improved decision of water policies to decision-makers or planners. This program has been participated by agencies related to water data. The agencies under the government, universities, institutes and the public can easily access, and retrieval data through each agency, WINS, or WAMIS Web pages.

Collection, Management and Distribution of Data for Groundwater

The Groundwater Act in 1993 contains regulations with respect to the groundwater monitoring network construction and management to effectively and efficiently manage the valuable groundwater sources. The groundwater monitoring network for measuring the groundwater quantity and quality in Korea was, thereby, designed and managed by the central and local government.

Four types of monitoring stations have been established: National Groundwater Monitoring Station (NGMS) under the MOCT: Groundwater Quality Monitoring Station (GQMS) under the MOE: Subsidiary Groundwater Monitoring Station (SGMS) under the local governments: and Seawater Intrusion Monitoring Station (SIMS) under MAF. The MGMSs and GQMSs are part of the primary groundwater stations, and the SGMSs and SIMSs part of the secondary groundwater stations.

The monitoring objective of the NGMSs focuses on long-term trends of groundwater levels and quality, and serves the general information as a key station. The MGMSs were installed and completed about 320 groundwater monitoring stations across the nation in 2003.

The GQMSs have been operated since 1992 to collect the groundwater samples form the installed wells. The total number of the GQMSs is 1,965, of which 781 monitoring wells are managed directly by the Local Environmental Office and 1,194 monitoring wells are managed by the local governments. At these monitoring stations, water samples are collected twice a year, spring and fall, and 15 items are tested for collecting quality data.

The SGMSs which is to support the NGMSs should be installed by the local governments. The projected total number of these monitoring wells will be 10,000 by 2011. To date, the number of the SGMSs constructed is just 318.

The SIMSs are installed to observe the groundwater levels and quality along costal areas where is a high possibility of sea water intrusion. By 2001, the number of the SIMSs is 87. The items monitored include groundwater temperature, electric conductivity and water levels.

For the NGMSs, real-time groundwater data and relevant information from monitoring stations are retrieved from the database and are available to the public on the Web (which is called the Groundwater Information and Management Service (GIMS)). The MOCT and Kwater publish an annual report on monitoring data every year, and the report distributed to research institute, central and local governments, and others.

6.7 Gaps within the Existing Water Management System

In this section, gaps in the existing water management system of Korea are identified. This uses a gap analysis, which is a comparison of an existing situation with a desired situation (Grigg, 2004). It is used to identify problems that require solutions such as management or organization problems. The gap analysis represents the differences between answers about two questions such as "what goes on here?" and "what ought to go on here?"

There are some gaps in water management organization, policies, responsibilities, problem identification, decisions, and actions that are required to implement conjunctive management. No institutional framework exists with financial and technical resources and/or legal and moral authority to examine integrated approaches to the conjunctive management of the available surface and groundwater resources. Instead, decisions concerning water use and resource management are made by a variety of ministries, local governments, and agencies, which for the most part are each narrowly focused and knowledgeable only on water issues within their local boundaries. Also, each organization tends to be singularly concerned with one or the other type of water supply, and not their conjunctively managed use. Water planning at these organizations reflects their limited view of the problem and range of solutions they consider.

In terms of water allocation such as trans-basin diversion, instream flow requirements and irrigation water use, gaps of water management in Korea include those that follow;

1) Problems related water allocation organization

- Problems related water allocation organization: The FOC has an authority to do the permit business of national rivers while local governments have the mandated power to permit water rights of 1st and 2nd class local rivers in the River Act and the small stream in the Small River Maintenance Act. But most local governments do not have ability to review and allocate among users considering an entire basin. This means that the existing water rights are infringed by issuing a new water right. Sometimes, local governments allow water users to use water without permitting in the drought horizons. Because jurisdictions are different within a basin, it is very difficult to judge comprehensively whether water right is permitted or not. Furthermore, local governments are empowered to issue ground water right. But the management agencies are different such as KRC which develop and manage the pumping wells for irrigation, and K-water which manage information about the existing and wasted wells. Table 6.11 illustrates the current status of Korea agencies on water management depending on the water body objects.

Table 6.11 Korea Organizations on Water Body Objects

Div.	**Rivers**	**Lakes**	**Groundwater**
Central Gov. (Branch or Affiliated)	MOCT[1] - FCO[5] - K-water[6] MOE[2] MAF[3]	MOCT - Branch - K-water MOE - Branch MAF - Branch	MOCT - K-water MAF - KRC[7]
Local Gov.	Each	Each	Each

Source: www.pwa-web.org/data/Republic%20of%20Korea.pdf

Notes: 1. Ministry of Construction and Transportation
2. Ministry of Environment
3. Ministry of Agriculture and Forestry
4. Ministry of Maritime Affairs and Fisheries
5. Flood Control Office
6. Korea Water Resources Corporation
7. Korea Rural Community & Agriculture Corporation

- Problem related water conflict coordination system: The way of dispute arrangements in water use is based on Section 3 in the River Act and the River Management Committee is empowered for the coordination of water use conflict. According to the Article 41 of the River Act, dam owner, applicant of water use, vested right owner, local government and other stakeholders related water use can apply a petition for water conflict coordination. A written application form is submitted to the River Management Committee with a clear purpose and detailed description of a case. The River Management Committee must notify the counterpart of the case and then start coordination. While the committee is processing the case, if the parties to the case take a legal processing, the counterpart can call for the halt of processing of conflict mediation according to the Article 42 of the River Act. This means that if one party to a case takes a legal process, then administrative process is stopped and even if the committee draw a reasonable solutions, any parties to the case do not reach the agreement, and it is impossible to make a resolution. Current mediation of the Committee is just recommendation and no binding power, therefore, sometimes it come into time consuming and usefulness of administrative efforts. Furthermore, the Ground Act does not stipulate the function of the coordination system. When water users apply groundwater right for relevant local governments, if a well location is within 300m from a stream, an agreement with senior water right for the surface is required to issue a new water right.

2) Vagueness of legal status of current water use right in water allocation law and institution

The legal status of current water right in Korea is very vague. The Civil Law, River Act, Dam Act and Ground Act have its own provision for water use right collide each other even though there exists some procedure to adjust conflict. For example, the provision of customary water use rights in the Civil Law collides with permit water use right in the River Act and the Ground Act. Also, the permitting system for water use in the Ground Act can infringe the permitted water rights in the River Act. That is, the permitted waters through the River Act and the Groundwater Act are not accounted based on the available water in a basin. The amount of permitted water use can be accounted as a double

3) Unclear permit criteria instream flow requirements

The River Act does not have clear permit criteria for permission of water use. It is difficult to judge whether the water use is reasonable. For example, the FCO has an authority to designate the instream flow requirements based on the low flow and environmental needs. But the permitted water rights in the River Act and the Ground Act can injury the designated instream flow during the drought periods. Furthermore, the designated instream flow is not a water right.

4) Shortage and inaccuracy of observed stream-flow and groundwater level data

- Currently, we do not have observed stream-flow data at the level of small and local rivers, and also at the level the national rivers observed data is insufficient and inaccurate due to insufficient budget constraints for collecting and investigating. For example, 60 stations among the 300 stream-flow gauging stations have produced useful data for the recent ten years. It can make water use improper and not provide opportunities to apply more advanced methodology. The ground water level data is the similar situation.
- The lack of stream-flow data is one of the obstacles for water use permit system. River authorities do not take account of the influence of senior water rights while they issue a new water right. Even though they consider senior water rights, it is very subjective so that it will ultimately cause another conflict. It also makes rivers drier during the drought periods, and injuries the existing water rights.
- No such nationwide monitoring networks for monitoring groundwater and surface water levels together exist in Korea. Because monitoring networks of stream-flow and the ground water level were separately performed.

The gaps described above must be filled by using adaptive and iterative management. In terms of institutional arrangements, acts or laws should recognize the connection between surface and ground water in allocating water each purpose water use. In the next section, options to implement conjunctive management will be addressed.

6.8 Conjunctive Use Management Options

Understanding of the interaction between surface water and groundwater can be viewed by water management policy and practice in the watershed.

In Korea, it has been managed that traditional institutional separation of surface water and from groundwater has made fundamental communication obstacles that severely limit the implementation of a conjunctive approach. These obstacles hinder the understanding of the processes and results of surface-groundwater interaction on the water policy and management. Such separation is evident throughout policy development and operational management, research and development, and even water users as mentioned earlier. Organizational change such as combining groups that make management decision for groundwater and surface water resources is necessary.

The options that can effectively achieve the goals of conjunctive use management are described in sub-sections below.

6.8.1 Organization Coordination

There are overlaps as well as gaps in the water resources management functions of different ministries, agencies and local government to implement conjunctive management. In many cases these ministries, agencies and local government do not communicate with one another and they do not see the larger water resources as "joint problem" that should be addressed by the various groups working together.

Coordination is needed with regard to policy and legislation, data and information management, water resources planning, operational programs, conjunctive management, and emergency response. At the governmental level this will involves such things as development of a more coordinated strategy for water resources sector, approval of budgets, approval of investment projects and river basin management plans, and improved communication and dispute resolution between sectors and major water users.

It will likely be necessary to build coordination in both a "top-down approach" to establish policies and processes for coordination at the ministry level and a "bottom-up approach" to establish coordination between local and water users at the basin level.

In an aspect of the "top-down approach", although many of the responsibilities for water resources management have been centralized in the central government, it will be important to develop policy recommendations through an open process in which all ministries, agencies and local government with an interest in the issue are able to participate. This participation can be promoted through such things as inter-ministry working groups. It will also be important for water users and other stakeholders to be consulted throughout the process to ensure that their views and information are taken into account and that awareness, consensus and ownership are developed.

In an aspect of the "bottom-up approach", a new river basin management organization will be required to efficiently and effectively manage each basin water management. The principal roles of the organization should include those things such as collecting water permit data including surface and ground waters, establishing and implementing water quality and quantity plans, estimating available water within a basin, and mediation of water conflicts.

6.8.2 Permit System and Allocation

As mentioned earlier, Korea does not have the comprehensive system between surface water and groundwater resources in aspects of laws and management system. The notions and principles of stream-aquifer connectivity can be incorporated into a wide range of the existing water policy instruments. Linking of permit systems and allocation arrangements of the surface and groundwater resources is strongly required. Different approaches are possible to better coordinate regulation. There are options as follows:

- *Total Water Accounting.* Taking a watershed-wide approach to the water balance evaluated as the inputs and outputs of groundwater and surface water resources is a prerequisite for a conjunctive use management. Estimates of the sustainable limits to water allocation should be based on budgets for the water resources, or at the very least that there is coordination between surface water and groundwater;
- *Linking of Water Management Plans.* Surface and groundwater management plans for a watershed should handle the same goals and their development should be coordinated. In a hydraulically interconnected system a single water plan would combine the management of two resources, taking advantage of their inherent characteristics;
- *One permitting system.* Existing surface water and groundwater permits are not compatible. The united permitting arrangements across an interconnected water

resource would use consistency of water securities. A key issue in developing a single permit system is the combination of surface water and groundwater securities, including water supply, volumes, etc;

- *Trigger or Thresholds.* Water access may be temporarily restricted on the basis of triggers such as using defined thresholds for minimum stream flows or groundwater levels. This requires assessment of the influences of groundwater use on stream-flow. For example, in the case of stream depletion a robust and transparent assessment of both the magnitude of the change in groundwater discharge and the time lag for response is required.

6.8.3 Risk Management

Risk management methods are generic employed in the management of surface water reservoir. For example, dams are drawn down during drought seasons based on the estimation that there is a high probability that dams levels will recover during the planning timeframe. The variability of monthly rainfall in Korea is high. Similar risk management approaches can be used for connected water resources to take advantage of the different characteristics of surface and aquifer storages.

6.8.4 Management Zones

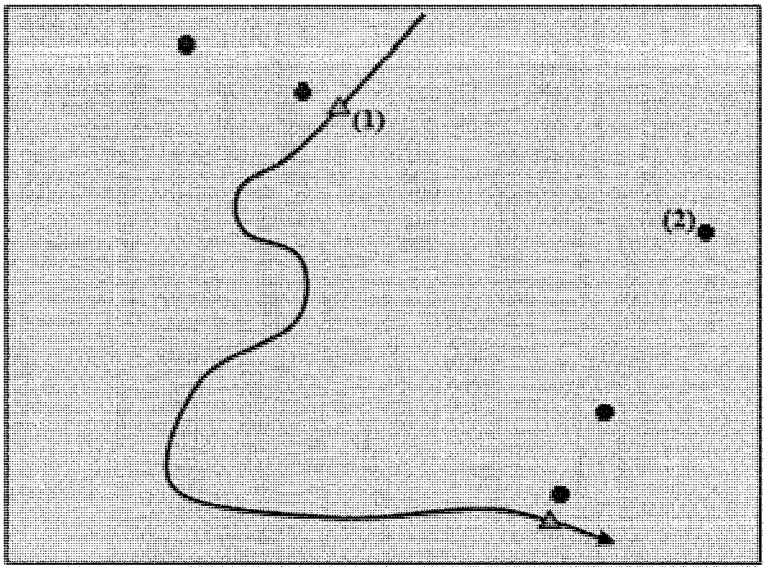
The advantages of conjunctive use are storage buffering and time lag for water use during drought seasons. Defining zones as stream buffers which have specific management is a useful tool in conjunctive management. This approach tends to subdivide the drainage basin on the basis of the likely impact on stream flow or water quality by changes to groundwater discharge. Management zones can be used to address the effect of groundwater extraction. Table 6.12 illustrates buffer zones around these streams that have different management rules as an example.

Table 6.12 An Example of Zonal Approach for Managing Highly Interconnected Alluvial Systems

Distance from High Bank of Stream	**Management Rule**
<300m	Surface water works approval and surface water rules only
300~500m	Groundwater works approval and surface water rules only
>500m	Groundwater works approval and groundwater rules only

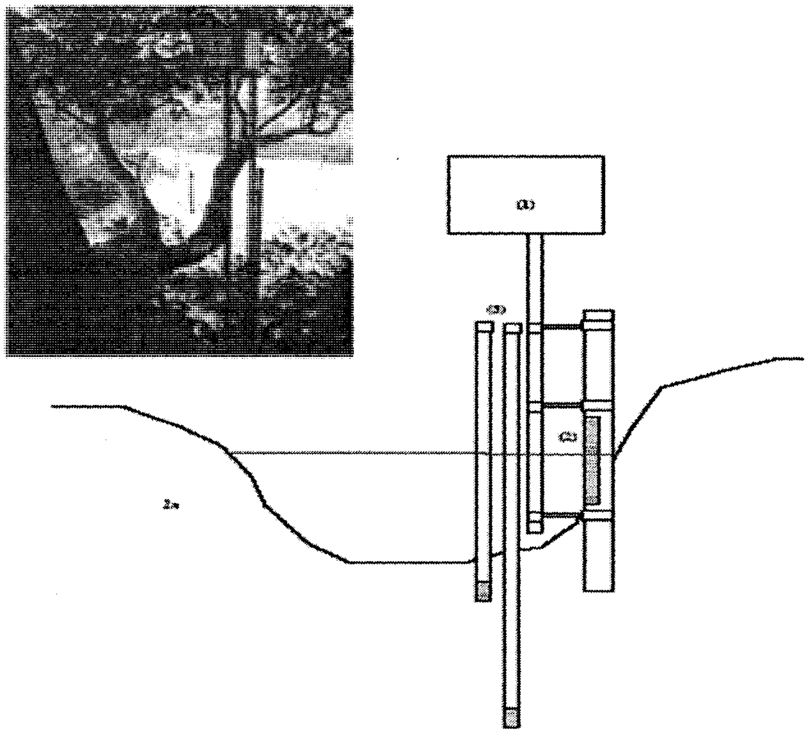
6.8.5 Monitoring Performance

A part of a conjunctive use management approach is a well-designed monitoring program. The current understanding of watershed processes through the processes of data investigation, assessment, conceptualization and predictive modeling can be used to design a cost-effective and robust monitoring program. Monitoring is the practical check for managers. This requires reviews on a regular basis to: identify any emerging management issues in the watershed; identify information gaps; evaluate progress towards the management targets identified for the watershed; check that conjunctive use management options were implemented appropriately; test the appropriateness and effectiveness of these management options, etc. Figure 6.6 and Figure 6.7 illustrate the network program to collect interconnected data about surface and ground water together.



Source: http://www.connectedwater.gov.au/framework/monitor_review.html

Figure 6.6 Schematic diagram of a suggested approach to monitoring of a connected water resource (including integrated in-stream sites (1) and observation wells (2))



Source: http://www.connectedwater.gov.au/framework/monitor_review.html

Figure 6.7 Example of combined monitoring of stream and shallow groundwater systems (a) Design of water level, temperature and water quality monitoring (b) Example in the Lower Richmond catchment (Brodie et al., 2005)

6.9 Summary

If water managers and decision makers understand the connection between groundwater and surface water, management for the limited water resources will be more effectively and efficiently managed. However, the connection between surface water and groundwater has been ignored in water resources management in Korea. Therefore, rivers and aquifers have been separately managed. This is due to a number of factors such as the hidden attribute of groundwater, stream-flow domination, timeframes for groundwater movement and response, and institutional separation of expertise and administration.

This chapter highlighted four elements such as water rights system, organization, instream flow requirements, and data management. In implementing conjunctive management, some gaps exist such as problems related to water allocation organization including conflict coordination system, vagueness of legal status of current water use right in water allocation law and institution, unclear permit criteria instream flow requirements, and shortage and inaccuracy of observed stream-flow and groundwater level data. Alternatives to improve include organization coordination, one permitting system including total water accounting, linking of water management plans, trigger or thresholds, management zones, and monitoring performance.

CHAPTER 7

SUMMARY AND CONCLUDING REMARKS

7.1 Summary and Conclusions

In this dissertation, I have demonstrated the use of technical and institutional analyses of a conjunctive surface and groundwater use system where the aquifers are small. This analysis included connectivity between surface and ground waters, response coefficients of stream depletion, instream flow requirements, and conjunctive use ; water right system, organization, instream flow requirements, and data management to effectively and efficiently manage a limited water source. The results show paths to a potential solution of conflicts. The major issue of the case study area in the central reach of the Geum River is the increase of instream flow requirements by downstream stakeholders and nongovernmental organizations after the dam completion due to trans-basin diversion.

Most alluvial aquifers along the main rivers in the case study area are relatively narrow and small, and highly interconnected with a stream. Therefore, the critical time to reverse the hydraulic gradient in the gaining stream is relatively short.

In the recharge analysis, the annual amount of recharge accounts for 220mm/year that mainly comes from precipitation. The ratio of groundwater recharge to average annual precipitation is about 20% in the rainy season from June to September in the study area. The ground-water recharge is strongly correlated with the precipitation. When the precipitation is large, the groundwater recharge is also large.

The response coefficients of stream depletion due to the pumping wells are presented by using analytical and numerical methods. The results obtained illustrate dependence on the thickness of aquifers, hydraulic conductivity, and distance between the well and the stream. With increasing the thickness, hydraulic conductivity, and decreasing distance, the response of the stress intensity occurs in a short time.

In order to estimate the instream flow requirements, it is necessary to simulate the daily stream-flow at an ungaged site so that the DAWAST model (Noh, 1991) is used, which is a rainfall-runoff model that can also simulate the reservoir operation by using the standard operating policy. The simulated daily data set is used for analyzing the hydrologic alterations before and after the dam completion. Under the given conditions, Yongdam reservoir has the potential of high ecological impacts according to the results of the overall hydrologic alteration. The main factor of hydrologic alteration is trans-basin water supply. In order to meet the water supply and downstream instream flow requirements for fish and aquatic habitat, the downstream instream flow requirement obtained by the IHA method (Richter, 1996) is about $3m^3/s$ based on the simulated data to minimize the hydrologic alterations.

In order to evaluate the conjunctive use, a multi-objective linear optimization model is developed as considering trans-basin diversion, instream flow requirements for fish and aquatic habitat, and withdrawal of groundwater and surface waters for irrigation. The response coefficient of stream depletion is estimated using the MODFLOW program (McDonald and Harbaugh, 1988) in transient state and fixed multiple wells. The response coefficient is incorporated into the conjunctive use model. For the reservoir operation, the hedging rule is used to ration the deficit of various water demands during the drought periods. The CPLEX software is used for running the mixed-integer linear model.

In the application of the model, the first step is performed to set the priorities of water supply such as trans-basin diversion, instream flow requirements, and irrigation water use. The next step is specified as the order of instream flow requirements, trans-basin diversion, and irrigation water use. There exists the effect of using both of surface and ground waters, even though the thickness of aquifers developed along a main stream is relatively thin. The better understanding of connection between groundwater and surface water can give water managers a better base to manage the limited water resources.

When setting the order of trans-basin diversion, instream flow and irrigation water use for water supply, the release for instream flow requirement of $5m^3/s$ from the reservoir, usage of only the surface water, and the application of the hedging rule for instream flow and irrigation water use, the total deficit of water for irrigation is 11.6 MCM during the analysis period from 1996 to 2005. When considering the weighting factor for the groundwater, the total deficit of the irrigation water use is reduced to between 0.0 MCM and 3.6 MCM. This analysis shows the effect of connection between surface and ground waters. The effect of conjunctive water use can also represent the reduction of total deficit for irrigation water use.

When specifying the order of instream flow, trans-basin diversion, and irrigation water use, the release for instream flow requirement of $5m^3/s$ from the reservoir, the usage of only surface water, and the application of hedging rule for all demands, the total system deficit is 13.7 MCM during the analysis period of 120 months, and the maximum deficit 6.3 MCM for all demands, while when setting the weighting factors of one for both of surface and groundwater, the total system deficit of 2.1 MCM is reduced.

According to the comparison of two policies for reservoir operation, the policy for the order of instream flow requirements, trans-basin diversion, and irrigation water use indicates the better one of conjunctive water management considering reservoir operation under the given conditions.

In performance measurement, the three measures used were reliability, resilience, and vulnerability. Reliability is a count of the number of deficit periods divided by the total number of periods, a measure of frequency and probability of failure. A resilience measure is used as the maximum number of consecutive periods of shortages that occur prior to recovery. The larger this number, the less resilient the reservoir. Vulnerability is a measure of significance of failure. Measurement of average release may be adequate for long term performance evaluation but it is insufficient to account for the infrequent and extreme events that a reservoir will experience in its economic life.

The more water managers and decision makers understand the connection between groundwater and surface water, the more water management for the limited water resources is effectively and efficiently managed. The connection between surface water and groundwater has been ignored in water resources management in Korea. Therefore, rivers and aquifers have separately been managed in terms of institutions. This is due to a number of factors such as the hidden attribute of groundwater, stream-flow domination, time frames for groundwater movement and response, and institutional separation of expertise and administration.

In the institutional arrangements, four elements are highlighted to include. These are water rights system, organization, instream flow requirements, and data management. In implementing conjunctive management, there exist some gaps such as problems related to water allocation organization including conflict coordination system, vagueness of legal status of current water use right in water allocation law and institution, unclear permit criteria instream flow requirements, and shortage and inaccuracy of observed stream-flow and groundwater level data. Its alternatives or options which are applied in Korea and not new are presented such as organization coordination in cooperating between agencies or creating the river basin organization, one permitting system including total water accounting, linking of water management plans, one permitting system, trigger or thresholds, management zones, and monitoring performance.

In conclusion, even though alluvial aquifers along the main river are narrow, small and thin in Korea, surface and ground waters must be considered and managed as a single source in technical and institutional aspects. Furthermore, groundwater problems in small rivers or streams, not mentioned here, are more severe than in the main rivers. Research is also to be needed based on water availability. Perhaps this dissertation can contribute to the understanding of interaction between surface and ground waters in Korea. In more understanding, water managers and regulators can seek a more reasonable way to manage water. Acts or laws with respect to water management should recognize the interaction between surface and ground waters.

7.2 Direction for Future Work

Research is a continuous process. The dissertation research has only begun the process of examining and providing the potential solution for water use conflicts.

Topics for further consideration in this area include the following:

1) Knowing water availability within a basin can offer water managers better

decisions of water management. The research should be continued to evaluate water availability considering surface and ground waters.

2) To mitigate the impact of dam construction, the reservoir operation rule should be studied to simulate the natural state of hydrologic variations.
3) Instream flow requirements should be studied in small rivers, as well as in the main rivers, considering the water availability with a small basin.

REFERENCES

Acreman, M.C., and King, J., "Defining water requirements: flow: the essentials of environmental flows", Gland Switzerland and Cambridge, UK, 2003.

Acreman, M.C. and Dunbar, M.J., "Defining environmental river flow requirements-a review", Hydrology and Earth System Sciences, Vol. 8, No. 5, 2004, pp 861-876.

Ahlfeld, D.P., and Mulligan, A.E., "Optimal management of flow in groundwater systems", Academic Press, San Diego, California, 2000, 185p.

Ahlfeld, D.P., and Heidari, Manoutchehr, "Application of optimal hydraulic control to ground-water systems", Journal of Water resources Management and Planning, Vol. 120, No. 3, 1994, pp 350-365.

Ahlfeld, David P., Michele R. Minihane, "Numerical issues in management of stream/aquifer interaction", Proceedings of the 24th International Conference on Computational Methods in Water Resources, June 23-28, 2002, The Netherlands, pp 1471-1478.

Alaerts, G.J., "Institutions for rive basin management: The role of external support agencies (International Donors) in developing cooperative arrangements", The World Bank, Washington, DC.

Babbitt, B, and Groat C.G, "Strategic Directions for the U.S. Geological Survey Ground-Water Resources Program", U.S. Department of the Interior and U.S. Geological Survey, A report to Congress, 1998, 14p.

Bandaragoda, D.J., "Institutional adaptation for integrated water resources management: an effective strategy for managing Asian river basins", International Water Management Institute, Working Paper 107, Colombo, Sri Lanka, 2006, 44p.

Barlow, P.M., and Hess, K.M., "Simulated hydrologic response of the Quashnet river stream-aquifer system to ground-water withdrawals, Cape Cod, Massachusetts", U.S. Geological Survey Water-Resources Investigations Report 4064, 1993, 52p.

Barlow, P.M., Ahlfeld, D.P., and Dickerman, D.C., "Conjunctive-management models for sustained yield of stream-aquifer systems", Journal of Water resources Management and Planning, Vol. 129, No. 1, 2003, pp 35-48.

Barlow, P.M., and Dickerman, D.C., "Numerical-simulation and conjunctive-management models the Hunt-Annaquatucket- Pettaquamscutt stream-aquifer system, Rhodo Island", U.S. Geological Survey Professional Paper 1636, 2001, 88p.

Basagaoglu, H., and Marino, M.A., “Chance constraint nodel for jioint management of stream-aquifer system”, UCOWR ’96 Proceedings, San Antonio, Texas, 1996, pp 136-145.

Basagaoglu, H., and Marino, M.A., "Joint management of surface and ground water supplies", Ground Water, Vol. 37, No.2, 1999, pp 214-222.

Batu, V., "Aquifer hydraulics: a comprehensive guide to hydrogeologic data analysis", John Wiley & Sons, Inc., New York, 1998, 727 p.

Belaineh, G., Peralta, R.C. and Hughes, T.C., "Simulation/optimization modeling for water resources management", Journal of Water Resources Management and Planning, Vol. 125, No. 3, 1999, pp 154-161.

Blomquist, W., Dinar, A., and Kemper, K., “Comparison of institutional arrangements for river basin management in eight basins”, World Bank Policy Research Working Paper 3636, USA, 2005, 46p.

Bowman, J.A., “Ground-water-management areas in United States” Journal of Water Resources Planning and Management, Vol. 116, No. 4, 1990, pp 484-502.

Brodie, R., Sundaram, B., Tottenham, R., Hosltetler, S., and Ransley, T., “An adaptive management framework for connected groundwater-surface water resources in Australia”, Bureau of Rural Science, Canberra, Australia, 2007, 177p.

Bredehoeft, J.D. and Young, R.A., "The temporal allocation of ground water - a simulation approach", Water Resources Research, Vol. 6, No. 1, 1970, pp 3-21.

Bredehoeft, J.D. and Young, R.A., “Conjunctive use of ground water and surface water for irrigated agriculture: risk aversion”, Water Resources Research, Vol. 19, No. 5, 1983, pp 1111-1121.

Butler, J.J. Jr., V.A. Zlotnik, and M.S. Tsou, “Drawdown and stream depletion produced by pumping in the vicinity of a partially penetrating stream”, Ground Water, Vol. 39, No. 5, 2001, pp 651-659.

Caldwell, R.R., and Bowers, C.L., "Surface-water/ground-water interaction of the Spokane river and the Spokane valley/ Rathdrum Prairie aquifer, Idaho and Washington", U.S. Geological Survey Water-Resources Investigations Report 4239, 2003, 60 p.

California, “Water rights fact sheet”, 2001, (http://www.blm.gov/nstc/WaterLaws/california.html).

California, “California Water Plan Update 2005”, (http://www.waterplan.water.ca.gov/previous/cwpu2005/index.cfm).

Cha, Kee-Uk, “Conjunctive management methodology considering stream-aquifer system and reservoir operations”, Ph.D., Dissertation-Colorado State University, Fort Collins, Colorado, 2007.

Chen, X. and Yin, Y., “Streamflow depletion: modeling of reduced baseflow and induced stream infiltration from seasonally pumped wells”, Journal of the American Water Resources Association, Vol. 37, No.1 2001, pp 185-195.

Chen, X., “Analysis of pumping stream-aquifer interactions for gaining streams”, Journal of Hydrology, 275, 2003, pp 1-11.

Coe, J.J., “Conjunctive use-advantages, constraints, and examples”, Journal of Irrigation and Drainage Engineering, Vol. 116, No. 3, 1990, pp 427-443.

Colorado, “Water rights fact sheet”, 2001, (http://www.blm.gov/nstc/WaterLaws/colorado.html).

Colorado Division of Water Resources, “Guide to Colorado well permits, water rights, and water administration”, 2006, (http://water.state.co.us/pubs/wellpermitguide.pdf).

Conrad, L.P., and Bejin, M.S., "Evaluation of an induced infiltration model as applied to glacial aquifer systems", Water Resources Bulletin, Vol. 32, No. 6, 1996, pp1209-1220.

Jenkins, C.T., "Computation of rate and volume of stream depletion by wells", U.S. Geological Survey Techniques of Water-Resources Investigations, Ch. D1, Book 4, 1968, 17p.

Danskin, W.R., and Gorelick, S.M., "A policy evaluation tool: management of a multi-aquifer system using controlled stream recharge", Water Resources Research, Vol. 21, No. 11, 1985, pp 1731-1747.

Daubert, J.T. and Young, R.A., "Ground-water development in western river basins: large economic gains with unseen costs", Ground Water, Vol. 20, No.1, 1982, pp 80-85.

Ahlfeld, David P., Michele R. Minihane, "Numerical issues in management of stream/aquifer interaction", Proceedings of the 24th International Conference on Computational Methods in Water Resources, June 23-28, 2002, The Netherlands, pp 1471-1478.

DeMeo, G.A., Laczniak, R.J., Boyd, R.A., Smith, J.L., and Nylund, W.E., "Estimated ground-water discharge by evapotranspiration from Death valley, California, 1997-2001", U.S. Geological Survey Water-Resources Investigations Report 4254, 2003, 27p.

Deninger, R.A., "Systems analysis of water supply systems", Water Resources Bulletin, Vol. 6, No. 4, 1970, pp 573-579.

Draper, A.J. and Lund, J.R., "Optimal Hedging and carryover storage value", Journal of Water Resources Planning and Management, Vol. 130, No. 1, 2004, pp 83-87.

Dunning, C.P., Feinstein, D.T., Hunt, R.J., and Krohelski, J.T., "Simulation of ground-water flow, surface-water flow, and a Deep Sewer Tunnel System in the Menomonee valley, Milwaukee, Wisconsin", U.S. Geological Survey Scientific Investigations Report 5031, 2004, 40p.

Eggleston, J.R., "Evaluation of strategies for balancing water use and streamflow reductions in the Upper Charles River basin, Eastern Massachusetts", U.S. Geological Survey Water-Resources Investigations Report 4330, 2003, 85p.

Fontane, D.G., Labadie, J.W. and Loftis, B., "Optimal control reservoir discharge quality through selective withdrawal", Water Resources Research, Vol.17, N0.6, 1981, pp 1594-1604.

Fontane, D.G., and Donald K. Frevert, "Water management under drought conditions: Overview of practices", Journal of Irrigation and Drainage Engineering, Vol.121, N0. 2, 1995, pp 199-206.

Fox, G.A., DcChateau Paul and Durnford D., "Analytical model for aquifer response incorporating distributed stream leakage", Ground Water Vol. 40, No.4, 2002, pp 378-384.

Fredericks, J.W., Labadie, J.L., and Altenhofen, J.M., "Decision support system for conjunctive stream-aquifer management", Journal of Water resources Management and Planning, Vol. 124,No. 2, 1998, pp 69-78.

Flynn, R.H., and Tasker, G.D., "Generalized estimates from streamflow data of annual and seasonal ground-water-recharge rates for drainage basins in New Hampshire", U.S. Geological Survey Scientific Investigations Report 5019, 2004, 61p.

Foster, S., Chilton, J., Moench, M., Cardy, F., and Schiffler, M., "Groundwater in rural development Facing the challenges of supply and resources sustainability", World Bank Technical Paper No. 463, The World Bank, Washington D.C. 2000, 97p.

Frasier, W.M., Michelsen, A.M., Taylor, R.G., Booker, J.F., and Huffaker, R.G., "Evaluating economic and institutional alternatives for meeting interstate ESA instream floOw requirements in the Platte River Basin", American Journal of Agricultural Economics, Vol. 81, No., 5, 1999, pp 1257-1261.

Fullagar, I., "River & aquifers: towards conjunctive water management", Workshop proceeding: Adelaide, 6-7 May, 2004.

Glover R.E. and Balmer, G.G., "River depletion resulting from pumping a well near a river", American Geophysical Union Transactions, Vol. 35, No. 5, 1954, pp 468-470.

Gorelick, S.M., "A review of distributed parameter groundwater management modeling methods", Water Resources Research, Vol. 19, No. 2, 1983, pp 305-319.

Gorelick, S.M., "Large scale nonlinear deterministic and stochastic optimization: formulations subsurface contamination", Mathematical Programming, Vol. 48, 1990, pp 19-39.

Gorelick, S.M., Freeze, R.A., Donohue, D., and Keely, J.F., "Groundwater contamination: optimal capture and containment", Lewis Publishers, Boca Raton, Florida, 1993, 385 p.

Granato, G.E., Barlow, P.M., and Dickerman, D.C., "Hydrogeology and simulated effects of ground-water withdrawals in the Big river area, Rhode Island", U.S. Geological Survey Water-Resources Investigations Report 4222, 2003, 76p.

Grigg, N.S., "Water resources planning", McGraw-Hill, New York, NY, 1985.

Grigg, N.S., "New paradigm for coordination in water industry", Journal of Water resources Management and Planning, Vol. 119, No. 5, 1993, pp 572-587.

Grigg, N.S., "Institutional analysis of infrastructure Problems: case study of water quality in distribution systems", Journal of Management in Engineering 21 (4), 2005, pp 152-158.

Gustard, A., Cole, G., Marshall, D, and Bayliss, A., "A study of compensation flows in the UK", Institute of Hydrology Report 99, Wallingford, UK. 1987.

Gupta, Ram S., and Goodman, Alvin S., "Ground-water reservoir operation for drought management", Journal of Water resources Management and Planning, Vol. 111, No. 3, 1985, pp 303-320.

Hansen, C.V., and Aucott, W.R., "Status of ground-water levels and storage volume in the Equus Beds aquifer near Wichita, Kansas, January 2000 - January 2003",U.S. Geological Survey Water-Resources Investigations Report 4298, 2003, 36 p.

Hantush, M.S., "Wells near streams with semipervious beds", Journal of Geophysical Research, Vol. 70, No. 12, 1965, pp 2829-2838.

Hantush, M.S., "Depletion of flow in right-angle stream bends by steady wells", Water Resources Research, Vol. 3, No. 1, 1967, pp 235-240.

Hantush, M.S.M., and Marino, M.A., "Chance-constrained model for management of stream-aquifer system", Journal of Water resources Management and Planning, Vol. 115, No. 3, 1989, pp 259-277.

Hashimoto, T., Stedinger, J.R., and Loucks, D.P., "Reliability, resiliency, and vulnerability criteria for water resources system performance evaluation", Water Resources Research, Vol. 18, No.1, 1982, pp 14-20.

Haugh, C.J., Carmichael, J.K., and Ladd, D.E., "Hydrogeology and ground-water-flow simulation in the Former Airfield Area of Naval support activity Mid-South, Millington, Tennessee", U.S. Geological Survey Scientific Investigations Report 5040, 2004, 31p.

Heidari, M, "Application of linear system's theory and linear programming to groundwater management in Kansas", Water Resources Bulletin, Vol. 18, No. 6, 1982, pp 1003-1012.

Hill, M.T., and Beschta, R.L., "Ecological and geomorphological concepts for instresam and out-of-channel flow requirements", Rivers 2, 1991, pp 198-210.

Howe, C.W., "Policy issues and institutional impediments in the management of groundwater: lessons from case studies", Environmental and Development Economics 7, 2002, pp 625-641.

Hunt, Bruce, "Unsteady stream depletion for ground water pumping", Groundwater, Vol. 37, No.1, 1999, pp 98-102.

Hunt, Bruce, "Unsteady stream depletion when pumping from semiconfined aquifer", Journal of Hydrologic Engineering, Vol. 8, No. 1, 2002, pp 12-19.

Hunt, Bruce, "Bank-storage problem and the Dupuit approximation", Journal of Hydrologic Engineering, Vol. 10, No. 2, 2005, pp 118-124.

Hunt, Bruce and Scott, David, "Extension of Hantush and Boulton Solutions", Journal of Hydrologic Engineering, Vol. 10, No. 3, 2005, pp 223-236.

Hunt, Bruce, "Groundwater analysis using function.xls", Civil Engineering Department, University of Canterbury, New Zealand, 2006, 59p.

Hutson, S.S., "Guidelines for preparation of state water-use estimates for 2005", U.S. Geological Survey, Techniques and Methods Book 4, Chapter E1, 2007, 28p.

Hashimoto, T., Stedinger, J.R., and Loucks, D.P., "Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation", Water Resources Research, Vol. 18, No. 1, 1982, pp 14-20.

Illangasekare, Tissa and Morel-Seytoux, H.J., "Stream-aquifer influence coefficients as tools for simulation and management", Water Resources Research, Vol. 18, No. 1, 1982, pp 168-176.

Jaspers, Frank G.W., "Institutional arrangements for integrated river basin management", Water Policy, Vol. 5, 2003, pp 77-90.

Jenkins, C.T., "Computation of rate and volume of stream depletion by wells", U.S. Geological Survey Techniques of Water-Resources Investigations, Ch. D1, Book 4, 1968, 17p.

Jenkins, C.T., "Techniques for computing rate and volume of stream depletion by wells", Ground Water, Vol. 6, No. 2, 1968b, pp 37-46.

Jenkins, M.W., Draper, J.D., Lund, J.R., Howitt, R.E., et al., "Improving California water management: optimizing value and flexibility", Center of Environmental and Water Resources Engineering, Report No.01-1, Univ. Calif. At Davis, CA, 2001.

John B. Czarnecki, Brian R. Clark, and Thomas B. Reed, "Conjunctive-use optimization model of the Mississippi river valley alluvial aquifer of Northeastern Arkansas", U.S. Geological Survey Water-Resources Investigations Report 4230, 2003, 29p.

John B. Czarnecki, Brian R. Clark, and Gregory P. Stanton, "Conjunctive-use optimization model of the Mississippi river valley alluvial aquifer of Southeastern Arkansas", U.S. Geological Survey Water-Resources Investigations Report 4230, 2003, 26p.

Junk, W.J., Bayley, P.B., and Sparks, R.E., "The flood pulse concept in river-floodplain systems", Canadian Journal of Fisheries Aquatic Science, 106, 1989, pp 110-127.

Karamaouz, M., Tabari, M.R., and Kerachian, R., "Conjunctive use of surface and groundwater resources: application of genetic algorithm and neural network", ASCE Environmental and Water Resources Institute Conference Proceedings, pp 1-10, 2004.

Kim, J.W., Kim, C.H., Han, J.H., and Kang W.H., "21c Frontier R&D program – Sustainable water resources research center- Policy development for sustainable water resources", Korea Land Development Institute, 2004.

Klug, Heinz, "Straining the law: conflicting legal premises and governance of aquatic resources", Society and Natural Resources, 15, 2002, pp 693-707.

Ko, Ick Hwan, "Integrated river basin operational planning considering water quantity and water quality", Ph.D., Dissertation-Colorado State University, Fort Collins, Colorado, 1997.

Ko, S-K., "Optimizing reservoir systems operation with multi-objective decision analysis", Ph.D., Dissertation-Colorado State University, Fort Collins, Colorado, 1989.

Kwanyuen, Bancha, "Improved multiobjective groundwater planning model", Ph.D, Dissertation-Colorado State University, Fort Collins, Colorado, 1996.

Lall, U. and Y.W.H. Lin, "A groundwater management model for Salt Lake County, Utah with some water rights and water quality considerations", Journal of Hydrology, Vol. 123, 1991, pp 367-393.

Lall, Upmanu, "Yield model for screening surface- and ground-water development", Journal of Water Resources Planning and Management, Vol. 121, No. 1, 1995, pp 9-22.

Lee, J.Y., Yi, M.J., Yoo, Y.K., Ahn, K.H., Kim, G.B., and Won, J.H., "A review of the national Groundwater Monitoring Network in Korea", Wiley InterScience, 2006.

Lee, S. I.and J. S. Aronofsky, "A linear programming model for scheduling crude oil production," Journal of Petroleum Technology, Vol. 213, 1958, pp 51-54.

Lefkoff,L.J., and Gorelick, S.M., "Simulating physical processes and economic behavior in saline, irrigated agriculture: model development", Water Resources Research, Vol. 26, No. 7, 1990, pp 1359-1369.

Lefkoff,L.J., and Gorelick, S.M., "Benefits of an irrigation water rental market in a saline stream-aquifer system", Water Resources Research, Vol. 26, No. 7, 1990, pp 1371-1381.

Lefkoff, L.J., and Gorelick, S.M., "AQMAN: linear and quadratic programming matrix generator using two-dimensional ground-water flow simulation for aquifer management modeling", U.S. Geological Survey Water-Resources Investigations Report 4061, 1987, 164p.

Lettenmaier, D.P., and Burges, D.R., "Cyclic storage: a preliminary assessment", Ground Water, Vol. 20, No.3, 1982, pp 278-288.

Maddock, T., III., "Algebraic technological function from a simulation model", Water Resources Research, Vol. 8, No. 1, 1972, pp 129-134.

Maddock, T., III., "The operation of a stream-aquifer system under stochastic demands", Water Resources Research, Vol. 10, No. 1, 1974, pp 1-10.

Maknoon, Reza and Burges, S.J. "Conjunctive use of ground and surface water", Journal of American Water Works Association, 1978, pp 419-478.

Male, J.W., and Mueller, F.A., "Model for prescribing ground-water use permits", Journal of Water resources Management and Planning, Vol. 118, No. 5, 1992, pp 543-561.

Maass, A., Hufschmidt, M.M., Dorfman, R., Thomas, Jr., H.A., Marglin, S.A., and Fair, G.M., "Design of water-resources systems", Harvard University Press, Cambridge, MA, 1962.

Matsukawa, Joy, Finney, B.A, and Willis, Robert, "Conjunctive-use Planning in MAD River Basin, California", Journal of Water Resources Planning and Management, ASCE, Vol. 118, No. 2, 1992, pp 115-132.

Matteo, L.D., and Dragon, W., "Empirical relationships for estimating stream depletion by well pumping near a gaining stream", Ground Water, Vol. 43, No. 2, 2005, pp242-249.

McKee, P.W., Clark, B.R., and Czarnecki, J.B., "Conjunctive-use optimization model and sustainable-yield estimation for the Sparata aquifer of Southeastern Arkansas and North Central Louisiana", U.S. Geological Survey Water-Resources Investigations Report 4231, USA, 2003, 30p.

McDonald, M.G., Harbaugh A.W., "A modular three-dimensional finite-difference ground-water flow model", U.S. Geological Techniques of Water-Resources Investigations, USA, Book 6, A1, 1988, 586p.

Ministry of Construction and Transportation (MOCT), "Groundwater Management Master Plan", South Korea, 2002.

Ministry of Construction and Transportation (MOCT) and Korea Water Resources Corporation (KOWACO), "Report of the Geum River Basin investigation in Korea", South Korea, 2004.

Ministry of Construction and Transportation (MOCT) and Korea Water Resources Corporation (KOWACO), “The Geum River groundwater basic survey report”, South Korea, 2004.

Ministry of Construction and Transportation (MOCT) and Korea Water Resources Corporation (KOWACO), “Longterm comprehensive water resources plan (2006-2020), South Korea, 2006.

Mohammadi, K. and Eslami, H.R., "Conjunctive stream-aquifer management using an object oriented model : Case study", Proceedings of the 24th International Conference on Computational Methods in Water Resources, The Netherlands, pp 1519-1526, June 23-28, 2002.

Moigne, G.L., Subramanian A., Xie, M., and Giltner, S., “A guide to the formulation of water resources strategy”, World Bank Technical Paper No. 263, 1994, 102p.

Molle, F., “Defining water rights: by prescription or negotiation?”, Water Policy, Vol. 6, 2004, pp 207-227.

Morel-Seytoux, H.J., "A combined model of water table and river stage evolution", Water Resources Research, Vol. 11, No. 6, 1975, pp 968-972.

Morel-Seytoux, H.J., and Daly, C.J., "A discrete kernel generator for stream-aquifer studies", Water Resources Research, Vol. 11, No. 2, 1975, pp 253-260.

Moy, W.S., Cohon, J.L., and ReVelle, C.S., “A programming model of analysis of the reliability, resilience, and vulnerability of a water supply reservoir”, Water Resources Research, Vol. 22, No. 4, 1986, pp 489-498.

Mueller, F.A., and Male, J.W., "A management model for specification of groundwater withdrawal permits", Water Resources Research, Vol. 29, No. 5, 1993, pp 1259-1368.

National Streamflow Information Program Committee, “Design of a national streamflow information program report with recommendations of a Committee”, U.S. Geological Survey Open-File Report 2004-1263, 2004, 42p.

Naval Facilities Engineering Service Center, “Guide to optimal Groundwater Monitoring”, Port Hueneme, California, 2000, 59p.

Newson, J.M., and Wilson, J.L., "Flow of groundwater to a well near a stream-effect of ambient groundwater flow direction", Ground Water, Vol. 26, No 6, 1988, pp 703-711.

Nisai Wanakule and Larry W. Mays, and Leon S. Lasdon, "Optimal Management of Large-Scale Aquifers: Methodology and Applications", Water Resources Research, Vol. 22, No. 4, 1986, pp 447-465.

Noh, Jae-Kyoung, "A conceptual watershed model for daily streamflow based on soil water storage", Ph.D. Dissertation, Seoul National University, Seoul, South Korea, 1991.

Noh, Jae-Kyoung, "Development of system for simulating daily runoff by DAWAST model", Proceeding 1999 of Korea Water Resources Association, Seoul, South Korea, 1999, pp 69-74.

Noh, Jae-Kyoung, "Effect of increasing water supply capacity of reservoir from limiting water supply", Proceeding 2000 of Korean Society of Civil Engineers, YongPyoung, South Korea, 2000, pp 432-435.

Noh, Jae-Kyoung, "Applicability of the DAWAST model considered return flows", Journal of the Korean Water Resources Association, Vol. 36, No. 6, 2003, pp 1095-1105.

Park, Myung-Ky, "Optimal reservoir system operation policy using risk evaluation criteria", Ph.D. Dissertation-Chungnam National University, Daejoen, South Korea, 2001.

Park, Sun-Je, "Water Policy South Korea: Towards a New Paradigm", Ph.D., Dissertation-Colorado State University, Fort Collins, Colorado, 2004.

Paul M. Barlow, Brian J. Wagner, and Kenneth Belitz, "Pumping Strategies for Management of a Shallow Water Table: The Value of the Simulation-Optimization Approach", Ground water, Vol. 34, No. 2, 1996, pp 305-317.

Philbrick, C.R. and Kitanidis, P.K., "Optimal conjunctive-use operations and plans", Water Resources Research, Vol. 34, No. 5, 1998, pp 1307-1316.

Pinder, G.F., and Sauer, S.P., "Numerical simulation of flood wave modification due to bank storage effects", Water Resources Research, Vol. 7, No. 1, 1971, pp 63-70.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.I., Richter, B.D., Sparks, R.E., and Stromberg, J.C., "The natural flow regime", Bioscience 47, 1997, pp 769-784.

Prince, K.R., Reilly, T.E., and Franke, Lehn, "Analysis of the shallow groundwater flow system near Connetquot brook, Long island, New York", Journal of Hydrology, Vol. 107, 1989, pp 223-250.

Prudic, D.E., “Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model”, U.S. Geological Survey, Open-File 88-729, 1989, 113p.

Prudic, D.E., “A new streamflow-routing (SFR1) package to simulate stream-aquifer interaction with MODFLOW-200”, U.S. Geological Survey, Open-File 2004-1042, 2004, 95p.

Rastogi, A.K., "Optimal pumping policy and groundwater balance for the Blue Aquifer, California, involving nonlinear groundwater hydraulics", Journal of Hydrology, Vol. 111, 1989, pp 177-194.

Reilly, T. E., O. L. Frank, and G. D. Bennett, “The principles of superposition and its application in groundwater hydraulics,” Techniques of water resources investigation of the United States Geological Survey, Chapter B6, US Government Printing Office, Washington, DC, 1987.

Remson, I., Hornberger, G.M., and Molz, F.J., "Numerical methods in subsurface hydrology with an introduction to the finite element method", John Wiley & Sons, Inc., New York, 1971, 389p.

Richter, B.D., Baumgartner, J.V., Powell, J., and Braun, D.P., “A method for assessing hydrologic alteration within ecosystems”, Conservation Biology, Vol. 10, No. 4, 1996, pp 1163-1174.

Richter, B.D., Baumgartner, J.V., Wigington, R, and Braun, D.P., “How much water does a rive need?”, Freshwater Biology, Vol. 37, 1997, pp 231-249.

Robert H. Prucha and Tissa Illangasekare, "An integrated conceptual and modeling framework for studying groundwater recharge in arid and semi-arid regions", Proceedings of the 24th International Conference on Computational Methods in Water Resources, The Netherlands, June 23-28, 2002, pp 1503-1510.

Rosenwald, G.W., “A method for determining the optimum location of wells in a reservoir using mixed-integer programming”, SPE-AIME 47th Annual Fall Meeting, San Antonio, Texas, SPE 3981, Vol. 255, 1974, pp 44-54.

Rutledge, A.T., “Basic concepts for the linear model of ground water level recession” Groundwater, Vol. 44, No. 3, 2006, pp 483-487.

Rutledge, A.T., “Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow data – update”, U.S. Geological Survey Water-Resources, Investigations Report 98-4148, 1998, 43 p.

Sargent, R.G., “Simulation model verification and validation”, Proceeding of the 1991 Winter Simulation Conference, 1991, pp 33-39.

Sawyer, C.S., and Ahlfed D.P., “Groundwater remediation design using a three-dimensional simulation model and mixed-integer programming”, Water Resources Research, Vol. 31, No. 5. 1995, pp 1373-1385.

Schlager, Edella, “Challenges of governing groundwater in U.S. western states”, Hydrogeology Journal, 2006, pp 350-360.

Schwartz, F.W., and Zhang, H., "Fundamentals of ground water", John Wiley & Sons, Inc., New York, 2003, 583p.

Shiau, J.T., and Lee, H.C., “Derivation of optimal hedging rules for a water-supply reservoir through compromise programming”, Water Resources Management, 2005, 19, pp 111-132.

Shih, J.D., and ReVelle, C., “Water supply operations during drought: continuous hedging rule”, Journal of Water Resources Planning and Management, Vol.120, No.5, 1994, pp 613-629.

Shih, J.D., and ReVelle, C., “Water supply operations during drought: A discrete hedging rule”, European Journal of Operational Research 82, 1995, pp 163-175.

Simonovic, S.P., and Burn, D.H., “An improved methodology for short-term operation of a single multipurpose reservoir”, Water Resources Research, Vol. 25, No. 1, 1989, pp 1-8.

Singh, S.K., “Rate and volume of stream depletion due to pumping”, Journal of Irrigation and Drainage Engineering, vol. 129, No. 6, 2000, pp 336-338.

Singh, S.K., “Flow depletion of semipervious streams due to pumping”, Journal of Irrigation and Drainage Engineering, vol. 129, No. 6, 2002, pp 449-453.

Smith, B.J., "Ground-water flow and ground- and surface- water interaction at McBaine Bottoms, Columbia, Missouri - 2000-02",U.S. Geological Survey Water-Resources Investigations Report 4234, 2003, 83 p.

Sophocleous, Marios, Koussis, Antonis, Martin, J.L., and Perkins, S.P., "Evaluation of simplified stream-aquifer depletion models for water rights administration", Ground Water, Vol. 33, No.4, 1995, pp 579-588.

Sophocleous, M.A., Towsend, L.D., Vogler, T.J., McClain, E.T., “Experimental studies in stream-aquifer interaction along the Arkansas river in Central Kansas – field testing and analysis”, Journal of Hydrology, 1988, pp 249-273.

Sophocleous, M., "Interactions between groundwater and surface water: the state if the science", Hydrogeology Journal, 2002, pp 52-67.

Spalding, C.P., and Khaleel, Raziuddin, "An evaluation of analytical to estimate drawdowns and stream depletions by wells", Water Resources Research, Vol. 27, No. 4, 1991, pp 597-609.

Srinivasan, K., Neelakantan, T.R., Narayan, P.S., and Nagajukumar, C., "Mixed-integer programming model for reservoir performance optimization", Journal of Water Resources Planning and Management, Vol. 125 No. 5, 1999, pp 298-301.

Swamee, P., Mishra, G.C., and Chahar, B.R., "Solution for a stream depletion problem", Journal of Irrigation and Drainage Engineering, Vol.126, No. 2, 2000, pp 125-126.

Talbot, Cary A., Downer , Charles W., Lin , Hsin-Chi, Howington , Stacy E., and Richards, David, "Computational methods for simulating interaction between surface and subsurface hydrologic system", Proceedings of the 24th International Conference on Computational Methods in Water Resources, June 23-28, 2002, The Netherlands, pp 1511-1518.

Taylor C.J. and Alley, W.M., "Ground-water-level monitoring and the importance of long-term water-level data", U.S. Geological Survey Circular 1217, Denver, Colorado, 2001, 66p.

Tharme, M.C. and King, J.M., "Development of the building block methodology for instream flow assessments and supporting research on the effects of different magnitude flows on riverine ecosystems", Report to Water Research Commission, 176/1/98, South Africa, 1998.

Theis, C.V., and Conover, C.S., "Chart for determination of the percentage of pumped water being diverted from a stream or drain: in Bentall, Ray, compiler, Shortcuts and special problems in aquifer tests", U.S. Geological Survey Water Supply Paper 1545-C, pp C106-C109.

Theis, C.V., "The effect of a well on the flow of a nearby stream", American Geophysical Union Transactions, Vol. 22, part 3, 1941, pp 734-738.

Tu, M.Y., Hsu, N.S., and Yeh, W.W.-G, "Optimization of reservoir management and operation with hedging rules", Journal of Water Resources Planning and Management, Vol. 129, No. 2, 2003, pp 86-97.

United Nations (UN), "Groundwater management: the search for practical approaches", Water Reports 25, 43p.

United Nations (UN), "Freshwater 2004-Republic of Korea", 2004, (http://www.un.org/esa/agenda21/natlinfo/countr/repkorea).

Unite States General Accounting Office (GAO), "Watershed management: Better coordination of data collection efforts needed to support key decisions", 2004, 145p.

Vadas, R.L. and Weigmann D.L., "The concept of instream flow and its relevance to drought management in the James River Basin", Virginia Water Resources Research Center, Bulletin 182, 1993, 79p.

Wahl, K.L. and Crippen, J.R., "A pragmatic approach to evaluating a multipurpose stream-gauging network", U.S. Geological Survey, Water Resources Investigations Report 84-4228, 1984, 13p.

Wallace, R.B., Darama, Yakup, and Annable, M.D., "Stream depletion by cyclic pumping of wells", Water Resources Research, Vol. 26, No. 6, 1990, pp 1263-1270.

Weaver, J.C., and Fine, J.M., "Low-flow characteristics and profiles for the Rocky river in the Yadkin-Pee Dee river basin, North Carolina, through 2002",U.S. Geological Survey Water-Resources Investigations Report 4147, 2003, 50p.

Wesche, T.A. and Rechard, P.A., "A summary of instream flow methodologies for fisheries and related resource needs", Eisenhower Consortium Bulletin, USDA Forest Service, 1985.

Willis, R., and Yeh, W. W-G, "Groundwater systems planning and management", Prentice-Hall, Eaglewood Cliffs, New Jersey, 1987, 416p.

Wilson, J.L., "Induced infiltration in aquifers with ambient flow", Water Resources Research, Vol. 29, No.10, 1993, pp 3503-3512.

Winter, T.C., "Recent advances in understanding the interaction of groundwater and surface water", Reviews of Geophysics, Supplement, U.S. National Report to International Union of Geodesy and Geophysics, 1995, pp 985-994.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., "Groundwater and surface water a single resource", U.S. Geological Survey Circular 1139, Denver, Colorado, 1998, 79p.

Wolfe, D., "Surface water and ground water administration in Colorado", 2005, (http://water.state.co.us/pubs/presentations/wateradmin101.pdf).

World Bank, "GE-MATE Briefing Note Series", Washington D.C., (http://www.worldbank.org/gwmate).

Yeh, W.W-G., "Systems analysis in ground-water planning and management", Journal of Water resources Management and Planning, Vol. 118, No. 3, 1992, pp 224-237.

Yeh, W.W-G., "Reservoir management and operations models: a state-of-the-art review", Water Resources Research, Vol. 21, No. 12, 1985, pp 1797-1818.

Young, R.A. and Bredehoeft, J.D., "Digital computer simulation for solving management problems of conjunctive groundwater and surface water systems", Water Resources Research, Vol. 8, No. 3, 1972, pp 533-556.

Young, R.A., Daubert, J.T., and Morel-Seytoux, H.J., "Evaluating institutional alternatives for managing an interrelated stream-aquifer system", American Journal of Agricultural Economics, Vol. 68, No. 4, 1986, pp 787-797.

Zekster, I.S. and Everett, L.G., "Groundwater resources of the world and the use", the United Nations, Educational, Scientific and Cultural Organization, Paris, 2004, 346p.

APPENDIX A

Theory and Method of Recharge

In order to analyze the recharge effect to the aquifers, a series of programs is used that Rorabaugh developed as a computational program to analyze the recharge between groundwater and surface water using stream-flow records. The method and process of a procedure are briefly described. The process involves three programs:

1) The RECESS program determines the master recession curve (MRC) of stream-flow recession during times when all flow can be considered to be ground water discharge;
2) The RORA program uses the recession-curve-displacement method, called the Rorabaugh Method (Rorabaugh, 1964) to estimate the recharge for each peak in the stream-flow record;
3) The PART program uses stream-flow portioning to estimate a daily record of base flow under the stream-flow record. The two programs, RECSS and RORA, are mainly used in analyzing recharge.

The recession-curve-displacement method is based on the upward shift in the recession curve on the stream-flow hydrograph for ground-water discharge that occurs as a result of recharge. Only the parts of upward shift on the stream-flow hydrograph can contribute to ground-water discharge. The program assigns days that fit a requirement of antecedent recession. The following expression was given by Linsley et al. (1982) as an empirical relation to determine days of antecedent recession:

$$N = A^{0.2} \tag{A.1}$$

where, N is the time base for days, and A the drainage area (A) upstream from a stream-flow gauging station.

To estimate the amount of time after a recharge event, Rorabaugh (1964) expressed the critical time for ground-water discharge to a stream as a linear function of time instead of an infinite series function. The critical time is given by the following equation:

$$T_c = \frac{0.2 \cdot a^2 \cdot S}{Tr} \tag{A.2}$$

where, T_c is critical time, a is the average distance from the stream to the hydrologic divide, S is the storage coefficient, and Tr is transmissivity.

A formulation that gives critical time as a function of the recession index can be obtained by combining equation (3.11) with the following equation from Rorabaugh and Simons (1966):

$$K = \frac{0.933 \cdot a^2 \cdot S}{Tr} \tag{A.3}$$

where, K is the recession index (T), which is the time required for ground-water to decline through one log cycle after the critical time. By solving for $a^2 S / Tr$ and substituting into equation (3.11), T_c can be expressed as:

$$T_c = 0.2144 \cdot K \tag{A.4}$$

The total potential ground-water discharge, V, is the total volume of water that will discharge from the system (Meyboom, 1961). The following equation used to determine the total potential groundwater discharge is based on a linear relation between the logarithm of ground-water discharge and time:

$$V = \frac{Q \cdot K}{2.3026} \tag{A.5}$$

where, V is the total potential ground-water discharge, Q is the ground-water discharge at initial time, and K is the recession index, the time required for ground-water discharge and to decline through one log cycle.

The total recharge, combined with the principle of superposition, is calculated by use of the following equation (Glover, 1964 and Rorabaugh, 1964):

$$R = \frac{2 \cdot (Q_2 - Q_1) \cdot K}{2.3026} \tag{A.6}$$

where, R is total volume of recharge, Q_1 is ground-water discharge at critical time as extrapolated from the stream-flow recession preceding the peak, and Q_2 is ground-water discharge at critical time as extrapolated from the stream-flow recession following the peak.

APPENDIX B

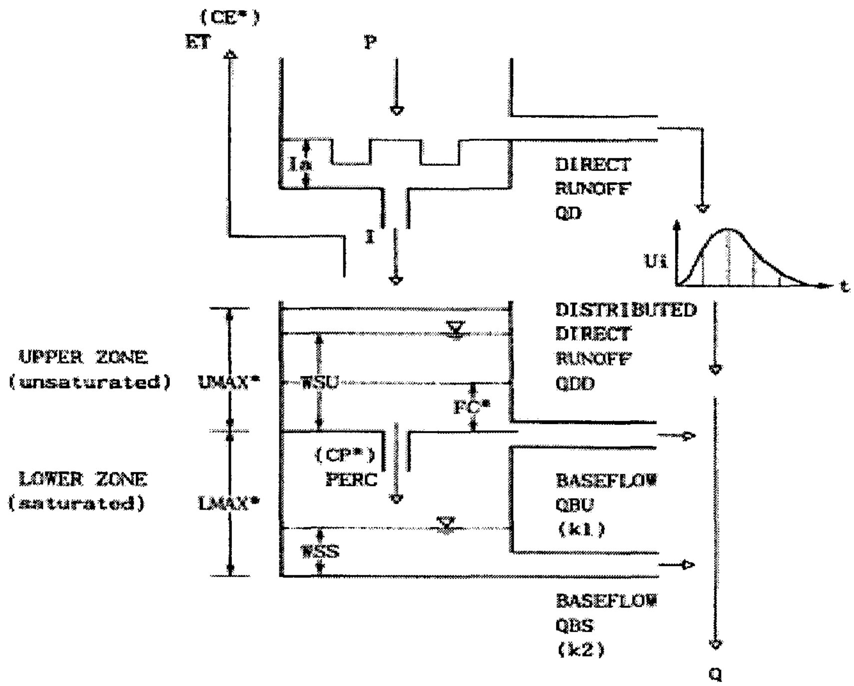
Description of the DAWAST Model

1) Rainfall-Runoff Module

The DAWAST Model can simulate daily continuous stream-flow depending on when rainfall events occur. This model estimates stream-flow considering the direct runoff and base flow if rainfall events occur and only base flow if rainfall does not occur. Input data includes daily precipitation and gage evaporation at a given site. Appendix B.1 illustrates the parameters of the DAWAST model which consist of five water budget parameters and three of soil properties. Appendix B.2 shows the model structure which is composed of two parts; an unsaturated zone in the ground in which direct runoff is calculated based on the water budget considering precipitation, evapotransporation, and infiltration; and a saturated ground zone in which base flow is calculated by using the regression curve coefficients depending on soil moisture conditions.

Appendix B.1 Parameters of DAWAST Model

Div.	Parameter Name	Function	Unit
Water Budget	*UMAX*	Maximum soil moisture capacity in an unsaturated zone	mm
	LMAX	Maximum soil moisture capacity in a saturated zone	mm
	FC	Field moisture capacity	mm
	CP	Percolation rate in a saturated zone	-
	CE	Basin evapotranspiration coefficient	-
Tracking	U_i	Distributed direct runoff ratio	-
	k1	Regression curve coefficient in an unsaturated zone	-
	k2	Regression curve coefficient in a saturated zone	-



Source: Noh (2003)

Appendix B.2 Schematic Diagram of the DAWAST Model

2) Direct Runoff

Direct runoff can be calculated by using the SCS method, so called the runoff curve number method, which is a procedure for hydrologic abstraction developed by the USDA Soil Conservation Service. In the DAWAST model, the field moisture capacity (or potential retention), *S*, is calculated subtracting the value of soil moisture from maximum soil moisture capacity in an unsaturated zone instead of using the runoff curve number. The calculation of field moisture capacity is the core of this model. Direct runoff is estimated through the following equations;

$$QD = (P - 0.2\,S)^2 / (P - 0.8\,S) \tag{B.1}$$

$$S = UMAX - WSU, \quad UMAX > WSU \tag{B.2}$$

where, Q is direct runoff (mm), P is precipitation(mm), S is field moisture capacity (mm), CN is runoff curve number, $UMAX$ is maximum soil moisture capacity in an unsaturated zone(mm), and WSU is soil moisture in an unsaturated zone (mm).

The calculated direct runoff is distributed by the following equation;

$$QDD_i = \sum_{j=i-n+1}^{i} U_{i-j+1} \times QD_j \tag{B.3}$$

$$\sum U_i = 1.0 \tag{B.4}$$

where, QDD_i is distributed direct runoff at ith day, U_i is daily distributed direct runoff ratio, n is base time(days), QD_j is calculated direct runoff based on the field moisture capacity.

3) Base Flow

The following equations are given in order to estimate the base flows in saturated zone and unsaturated zones.

$$QBU_i = (1 - k1) \times (WSS_i - LMAX), \quad if\ WSS_i > LMAX \tag{B.5}$$

$$QBU_i = 0, \qquad if\ WSS_i \leq LMAX \tag{B.6}$$

$$QBS_i = (1 - k2) \times WSS_i \tag{B.7}$$

where, QBU_i is base flow in an unsaturated zone at ith day (mm), QBS_i is base flow in a saturated zone, WSS_i is soil moisture in a saturated zone (mm), $LMAX$ is maximum soil moisture capacity in a saturated zone (mm), $k1$ is regression curve coefficient in an unsaturated zone which ranges 0 from 1 ($0 < k1 < 1$), and *k2* is regression curve coefficient in a saturated zone which ranges 0 from 1 ($0 < k2 < 1$).

4) Water Budget in an Unsaturated Zone

Increases in precipitation cause the soil moisture in an unsaturated increase while increasing in the evapotransporation and percolation rate result in soil moisture decreases. The following equation of water budget is given by;

$$WSU_{i+1} = WSU_i + I_i - ET_i - PERC_i \tag{B.8}$$

where, I_i is precipitation at *i*th day (mm), ET_i is evapotranspiration at *i*th day (mm), and $PERC_i$ is percolation (mm).

If the amount of rainfall is less than that of initial rainfall loss, the percolation set equal to rainfall, while if it is greater, is subtracted from the percolation as shown in the following equations.

$$I_i = P_i, \qquad if \;\; P_i \le I_a \tag{B.9}$$

$$I_i = P_i - QD_i, \qquad if \;\; P_i > I_a \tag{B.10}$$

where, P_i is precipitation (mm), and I_a is initial rainfall loss (mm).

The value of evapotranspiration is estimated using the observed pan evaporation and pan coefficient.

$$ET_i = Eo_i \ (1 - e^{-CE \bullet WS_i}) \tag{B.11}$$

$$Eo_i = C \times EP_i \tag{B.12}$$

where, Eo_i is latent evaporation at *i*th day(mm), Ep_i is pan evaporation at *i*th day (mm), C is evaporation pan coefficient ($C = 0.70$), and CE is basin evapotranspiration coefficient.

Percolation in a saturated zone takes place due to gravitation when soil moisture is greater than field moisture capacity.

$$PERC_i = CP \times (WSU_{i-1} - FC) \times WSU_i \ / UMAX, \quad if \ P_i > 0 \ and \ WSU_{i-1} > FC \tag{B.13}$$

$$PERC_i = 0, \qquad if \ P_i = 0 \ or \ WSU_{i-1} \leq FC \tag{B.14}$$

where, FC is field moisture capacity (mm), CP is percolation rate in a saturated zone.

5) Water Budget in a Saturated Zone

The soil moisture in a saturated zone will increase with an increase in percolation rate during rainfall periods while it will decrease through the movement of base flow without rainfall.

$$WSS_{i+1} = WSS_i + PERC_i - QBS_i \ , \qquad if \ P_i > 0 \tag{B.15}$$

$$WSS_i = WSS_i - QBS_i \ , \qquad if \ P_i = 0 \tag{B.16}$$

APPENDIX C

Appendix C.1 Various Acts Related to Water Management

Law or Act Name	Issued Year	Established Purpose
River Act	1961	- To prevent damage due to stream-flow and improve benefits - Focus on flood control of a river basin
Water Supply and Waterworks Installation Act	1961	- To improve the appropriateness and rationalization of facilities installation and management of water supply
Public Waters Management Act	1961	- To prescribe relevant particulars regarding management, conservation and utilization of public waters
Public Waters Reclamation Act	1962	- To improve public benefits and contribute the development of national economics with effectively utilizing public waters which is reclaimed
Specific Multi-Purpose Dams Act	1966	- To improve the national economic by developing and utilizing water resources - Act on the Construction of Dams and Assistances, etc. to their the Environs re-enacted in 1999
Korea Water Resources Corporation Act	1966	- To enforce projects of comprehensive development, utilization and conservation of water resources through establishing the Korea Water Resources Corporation
Hot Spring Act	1981	- To Properly Conserve hot springs and improve development and utilization of hot springs
Framework Act on Environmental Policy	1990	- Prevent damages of health and sanitation due to the pollution of air, water quality and soil, noise pollution, vibration, or stench, and conserve natural environment
Water Quality Conservation Act	1990	- To prevent harms of People health and environment due to the water quality pollution - To suitably conserve the environment
Groundwater Act	1993	- To efficiently develop and utilize groundwater - To pertinently manage and conserve groundwater
Small River Maintenance Act	1994	- To maintain, utilize, manage, and conserve small river
Management of Drinking Water Act	1995	- To be the purposes of reasonable water quality and sanitary management on the drinking water
Act on the Construction of Dams and Assistances, etc. to their the Environs	1999	- To prescribe the articles of dam construction & management, environmental measures caused by the dam construction, and assistances of regional inhabitants

Act on the Improvement of Water Quality and Support for Residents of the Riverhead of the Han River System	1999	- To manage water sources, improve water quality in the upstream of water sources, and efficiently enforce the projects to assist and improve residents' life quality in the Han River System
Act on the Management of Water and Support for Residents of the Nakdong River System	2002	- To manage water sources, improve water quality in the upstream of water sources, and efficiently enforce the projects to assist and improve residents' life quality in the Nakdong River System
Act on the Management of Water and Support for Residents of the Geum River System	2002	- To manage water sources, improve water quality in the upstream of water sources, and efficiently enforce the projects to assist and improve residents' life quality in the Geum River System
Act on the Management of Water and Support for Residents of the Youngsan and Seomjin River System	2002	- To manage water sources, improve water quality in the upstream of water sources, and efficiently enforce the projects to assist and improve residents' life quality in the Youngsan and Seomjin River System

Appendix C.2 Major Federal Agencies in USA

Agency Name	Roles and Interests
Environmental Protection Agency[3]	- To administer the Clean Water Act and the Safe Drinking Water Act - To oversee water quality standards for interstate waters and issues discharge permits for federal installations
National Park service[1]	- To manage, promote and regulate use of unique lands designated as parklands, with emphasis on conservation - To have implied federal reserved water rights for these lands
Bureau of Reclamation[1]	- To develop multipurpose projects for the delivery of water for irrigation, municipal and industrial use, and generation of power
U.S. Fish & Wildlife Service[1]	- To administer the Endangered Species Act, and manage federal fisheries - To be concerned with land acquisition and management
Geological Survey[1]	- To collect, analyze, and publish information on quality and quantity of surface and groundwater - To sponsor water supply investigations in many area
Agricultural Research Service[2]	- Conduct basic and applied research in water management, watershed engineering, and soil management
Natural Resources Conservation Service[2]	- Provide leadership and technical assistance to farmers and other landowners in conserving their soil, water, and other natural resources
Forest Service[2]	- To manage land and water resources on forests; functions involve watershed management, research on forest management, and fire protection - Numerous water-related facilities are located on Forest Service land and subject to its permitting requirements
U.S. Army Corps of Engineers[3]	- To administer Section 404 of the Clean Water Act, granting dredge and fill permits for channel structures; also active in flood control, conservation, and hydroelectric power
Federal Energy[4] Regulatory Commission	- To license proposed non-federal hydroelectric projects, and make recommendations to other agencies such as river basin commission, on their water development projects and long range planning

Note:
1. Agricultural Research Service, Natural Resources Conservation Service (formerly the Soil Conservation Service), and Forest Service are within the U.S. Department of Agriculture.
2. National Park Service, Bureau of Reclamation, U.S. Fish and Wildlife Service, and U.S. Geological Survey are within the U.S. Department of Interior.
3. U.S. Environmental Protection Agency and U.S. Army Crops of Engineers are federal agencies.
4. Federal Energy Regulatory Commission is an independent regulatory agency within the U.S. Department of Energy.

Appendix C.3 Colorado's Agencies Related to Water Management

Agency Name	Roles and Interests
Colorado Water Conservation Board	- To plan, develop, and protect Colorado's water. - Five major programs under the purview of its responsibility. ▪ Water Supply Protection – compact and treaty issues, growth and development analysis, State implementation of Federal policy and partnership with Federal water agencies on development projects ▪ Water Supply Planning and Finance – water project construction loan fund ▪ Stream and Lake Protection – instream flow rights and natural level storage rights, to protect the environment ▪ Flood Protection – flood hazard identification, support for local planning and regulation, technical and financial support for flood protection project implementation, preparedness and response ▪ Conservation and Drought Planning – water efficiency and water conservation planning - State executive branch agency
Division of Water Resources (DWR) or State's Engineer's Office	- To administer regulation and administration of water supply, in accordance with statute, decrees, and interstate. - To issue well permits, regulate dam safety, and enforce rules and policies adopted by the Colorado Ground Water Commission and the State Board of Examiners of Water Well Construction and Pump Installation Contractors. - 7 divisions with each basin in the State.
Colorado Ground Water Commission	- To manage and control the State's eight designated groundwater basins and thirteen groundwater management districts. These are areas in which the aquifers are isolated from the surface system. - To adopt rules and policies governing the basins.
Colorado Water Quality Control Commission	- To develop state water quality policies that implement the broader policies of the Colorado Water Quality Act. - To develop regulations as needed to maintain quality for all beneficial uses. - To enforce the Water Quality Control Commission' rules as well as those of the State Board of Health, which is responsible for drinking water standards. - To issue permits for discharge of pollutants into state waters and administer a non-point source pollution control program.
Colorado Water Resources and Power Development Authority	- To provide funding for water and wastewater utilities in Colorado. - To have the power to initiate, acquire, construct, and operate water projects. - Special agency created by the General Assembly.
Colorado Conservation Districts	- To protect and develop the waters within their boundaries. - To levy taxes, issue bonds, and collect user fees. - 3 conservation districts in the State(Colorado River Water Conservation District, Rio Grande Water Conservation District, and the Southwestern Conservation District) - Local districts
Water Conservancy Districts	- To levy property taxes and issue bonds, and lease or sell water, among other authorities, duties, and responsibilities. - Approximately 50 conservancy districts in the State, including fifteen in the Colorado main stream and Gunnison basins. - Local districts

Appendix C.4 Term Definition of Maintenance Stream-flow

Div.	Year	Definition
Water Resources Development and Utilization Plans	1967	- low flow in a stream, excluding water use such as irrigation, and municipal and industrial water use
Stream Facility Code	1980	- Stream flow to maintain stream in dry season through a comprehensive review such as navigation, fishery, aesthetics, saltwater intrusion, protection of facility on a stream, keeping groundwater level, preservation of fauna and flora, and water quality, and also needed to appropriate water downstream from the designated point
Stream Facility Code (Dam Volume)	1982	- Minimum stream-flow to maintain normal function of stream considering the following items: protection of vested water rights, conservation of fishes, navigation, scenic views, pollution dilution, control of saltwater and rivermouth closure, keeping groundwater level, and facility protection
Stream Facility Code	1993	- Stream-flow needed to maintain a normal function and status at designated major points in terms of river management - Selecting a large one between the average low stream-flow[1] and environmental conservation flow[2]
Guideline of Maintenance Stream-flow	2000	- Minimum stream-flow to maintain normal function of stream considering the following items on the basis of sharing water with human being and nature in natural dry season: protection of vested water rights, conservation of fishes, navigation, scenic views, pollution dilution, control of saltwater and rivermouth closure, keeping groundwater level and water sources, and facility protection - To present a detailed methodology to estimate maintenance stream-flow
Stream Facility Code (Dam Volume)	2001	- Stream-flow considering the average low stream-flow and flow to maintain water quality
Stream Facility Code	2002	- Minimum stream-flow to maintain normal function of stream considering the following items on the basis of sharing water with human being and nature in natural dry season: protection of vested water rights, conservation of fishes, navigation, scenic views, pollution dilution, control of saltwater and rivermouth closure, keeping groundwater level and water sources, and facility protection

Note: 1. Low stream-flow is averaged which keeps flow over 355 days of each year through analysis of the observed data

2. It means maximum stream-flow among the estimated flows considering protection of vested water rights, conservation of fishes, navigation and scenic view, pollution dilution, control of saltwater and rivermouth closure, keeping groundwater level, and facility protection.