Assessing the Tradeoffs of Water Allocation: Design and Application of an Integrated Water Resources Model

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By

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Abstract

The Bow River Basin in Southern Alberta is a semi-arid catchment, with surface water provided from the Rocky Mountains. Water resources in this basin, primarily surface water, are allocated to a variety of users- industry, municipalities, agriculture, energy and needs for the environment. The largest consumptive use is by agriculture (80%), and several large dams at the headwaters provide for over 800,000 MWhrs of hydropower. This water is managed by the 1990 Water Act, distributing water via licenses following the "first in time first in right" principle. Currently, the basin is over-allocated, and closed to any new licenses. Conflicts between different water users have consequences for the economy and the environment. By using an integrated water resources model, these conflicts can be further examined and solutions can be investigated and proposed.

In this research an integrated water resources model, referred to as Sustainability-oriented Water Allocation Management and Planning Model applied to the Bow Basin ($SWAMP_B$), is developed to emulate Alberta's Water Resources Management Model (WRMM). While having the same allocation structure as WRMM, $SWAMP_B$ instead provides a simulation environment, linking allocation with dynamic irrigation and economic sub-models. $SWAMP_B$ is part of a much larger framework, SWAMP, to simulate the water resources systems for the entire South Saskatchewan River Basin (SSRB). $SWAMP_B$ integrates economics with a water resources allocation model as well as an irrigation model- all developed using the system dynamics approach. Water is allocated following the allocation structure provided in WRMM, through operation rules of reservoirs and diversions to water users. The irrigation component calculates the water balance of farms, determining the crop water demand and crop yields. An economic valuation is provided for both crops and hydropower generation through the economic component.

The structure of $SWAMP_B$ is verified through several phases. First, the operation of reservoirs with fixed (known) inflows, and modeled releases, are compared against WRMM for a historical simulation period (1928-2001). Further verifications compare the operation of $SWAMP_B$ as a whole without any fixed flows but fixed demands to identify errors in the system water allocation. A final verification then compares both models against historical flows and reservoir levels to assess the validity of each model. $SWAMP_B$, although found to have some minor differences in model structure due to the system dynamics modeling environment, is to be evaluated as an acceptable emulator.

$SWAMP_B$ is applied to assess a variety of management and policy solutions to mitigating environmental flow deficit. Solutions include increasing irrigation efficiency (S1), requiring more summer release from hydropower reservoirs at the headwaters (S2), a combination of the previous two (S3), implementing the *In-Stream Flow Needs* (S4) and implementing *Water Conservation Objectives* (S5). The solutions are not only examined by their ability to restore river flows, but also with respect to the economic consequences and effect on hydropower, irrigation, and municipalities. It is found that the three technical solutions (S1, S2, and S3) provide economic gains and allow more efficient water use, but do little to restore streamflows. Conversely, the two policy solutions (S4 and S5) are more effective at restoring river flow, but have severe consequences on the economy and water availability for irrigation and municipal uses. This analysis does not recommend a particular solution, but provides a quantification of the tradeoffs that can be used by stakeholders to make decisions. Further work on the SWAMP methodology is foreseen, to link $SWAMP_B$ with other models, enabling a comprehensive analysis across the entire SSRB.

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List of Acronyms

α	Albedo
β	Soil Moisture (Irrigation) Trigger
Δ	Slope of Vapour Pressure Deficit Curve
γ	Psychometric Constant
AENV	Alberta Environment and Parks
AERD	Alberta Environment and Rural Development
BN	Bayesian Network
BRB	Bow River Basin
CLD	Causal Loop Diagram
CP	Compromise Programming
CWEEDs	Canadian Weather, Energy, and Engineering Dataset
DBM	Data-based Mechanistic Modeling
DEMo	Dynamic Emulation Modeling
DP	Deep Percolation
DSS	Decision Support System
e	Hydropower Efficiency
E	Irrigation Efficiency
ea	Actual Vapour Pressure
ELECTRE	Elimination and Choice Expressing Reality
ENV	Environmental
es	Saturated Vapour Pressure
ET	Evapotranspiration
ET_0	Reference Evapotranspiration
ET_H	Hargreaves Evapotranspiration

ET_{MH}	Modified Hargreaves Evapotranspiration
FC	Field Capacity
G	Ground Heat Flux
GCM	Global Climate Model
h	Head
ICWE	International Conference on Water and the Environment
IFN	In-stream Flow Needs
IO	In-stream Objective
IRR	Irrigation Water Supplied
IWA	International Water Association
IWMSC	Irrigation Water Management Study Committee
IWRM	Integrated Water Resources Management
kc	Crop Coefficient
K_Y	Crop Yield Factor
MAUT	Multi-attribute Utility Theory
MCDM	Multiple Criteria Decision Making
MCM	Million Cubic Meters
MROC	Marginal Resource Opportunity Cost
NSE	Nash-Sutcliffe Efficiency
NSRB	North Saskatchewan River Basin
OKA	Out of Kilter Algorithm
P	Precipitation
PET	Potential Evapotranspiration
PM	Penman-Monteith
Q	Flow

R	Rainfall
Rel	Reliability
Res	Resilience
RMSE	Root Mean Square Error
Rn	Net Radiation
RO	Runoff
Rs	Solar Radiation
S1	Irrigation Efficiency Scenario
S2	TransAlta Operation Scenario
S3	Combined Irrigation-TransAlta Scenario
S4	In-stream Flow Needs Scenario
S5	Water Conservation Objective Scenario
SAMS	Stochastic Analysis, Modeling, and Simulation
SD	System Dynamics
SFD	Stock Flow Diagram
SI	Sustainability Index
SM	Soil Moisture
SR	Snow Sublimation and Redistribution
SSRB	South Saskatchewan River Basin
SWAMP	Sustainability-Oriented Water Allocation Management and Planning model
$SWAMP_B$	Sustainability-Oriented Water Allocation Management and Planning model (Bow)
$SWAMP_{OM}$	Sustainability-Oriented Water Allocation Management and Planning model (Oldman)
$SWAMP_{RD}$	Sustainability-Oriented Water Allocation Management and Planning model (Reddeer)
$SWAMP_{SK}$	Sustainability-Oriented Water Allocation Management and Planning model (Saskatchewan)

T	Temperature
TAU	TransAlta Utilities
T_{max}	Maximum Daily Temperature
T_{min}	Minimum Daily Temperature
u_2	Wind Speed at 2m Above Surface
Vul	Vulnerability
WCO	Water Conservation Objective
WFD	Water Framework Directive
WGP	Weighted Goal Programming
WP	Wilting Point
WRMM	Water Management Model
WSSD	World Summit on Sustainable Development

Chapter 1 Introduction

1.1 Background

In Canada the majority of water resources are generated from surface sources, which support rural and municipal populations and are an important asset for the development of agriculture, industry, energy, and the protection of the environment. Specifically in the province of Alberta, 97% of all water allocated is from surface water (Government of Alberta, 2010). Of interest in this research project is the South Saskatchewan River Basin (SSRB), which receives the largest portion of its water from runoff from the Rocky Mountains in Western Alberta. Flow in this region is derived mainly from snow and glacier melt from the mountains, with limited contributions from the prairies (Pomeroy et al., 2005). The SSRB in Alberta includes the Oldman River Basin, the Bow River Basin, and the Red Deer River Basin (Figure 1.1). The Oldman River and Bow River basins are both characterized by peak runoff in June- coinciding with snowmelt runoff (AMEC, 2009). Uniquely, the Red Deer River Basin has two annual peak flows, one in April due to snow melt in the lower reaches and another in late July from a combination of glacial melt in the upper reaches and rain in the Rocky Mountain foothills (AMEC, 2009). The SSRB is classified as semi-arid, with evapotranspiration in irrigated areas exceeding precipitation (Martz et al., 2007), and requiring the melt-runoff to balance water resource needs. The Bow River basin will serve as the case study in this research.

Figure 1.1- South Saskatchewan River Basin Overview (SSRWS, 2015)

The largest water consumer in the Bow River Basin (BRB) is agriculture (78.2%), followed by municipal (19.7%) and industrial (2.1%) uses (Martz et al., 2007). Irrigated agriculture in the Bow is privately owned both by independent operators and within the 13 irrigation districts. The majority of irrigated crops not within the districts (independent operators) are forages for livestock, whereas the irrigation districts produce mostly cereal crops and alfalfa (AARD, 2013; Lorraine et al., 2012). Although not a consumptive demand, hydropower in Alberta is quite actively developed. Hydropower reservoirs within the BRB provide over 800,000 MWh of energy annually (Bow River Basin Council, 2010). These reservoirs are owned by TransAlta Utilities, located along the Bow River upstream of Calgary as shown in Figure 1.2. In Alberta over 30% of the GDP is generated from the energy industry, agriculture, and utilities (including hydropower) (Province of Alberta, 2012). All three of these sectors require water, whether it is for irrigating crops and watering livestock, cooling thermal plants, or processing coal and oil. Water is valuable to the growth of Alberta, and Canada as a whole.

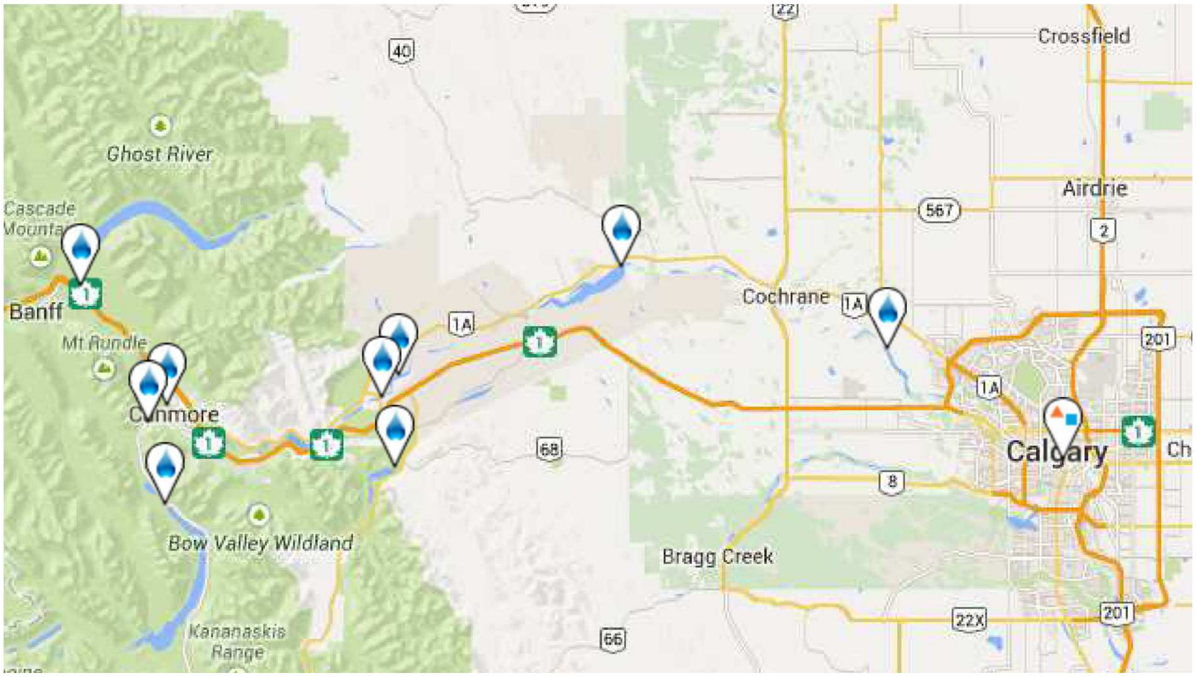


Figure 1.2-TransAlta hydropower reservoirs shown as water drops, extending from Banff to Calgary, Alberta.

Water use in Alberta is managed at the provincial level, following the 1999 Water Act (Province of Alberta, 2014). This act allocates water based on a ‘first in time, first in right’ rule. Water is allocated in a hierarchal manner, supplying water to senior users (licensees), before junior ones. Although the terms are loosely used, a Senior license usually refers to licenses obtained before the 1950’s, and Junior licenses during or after the 1950’s. The date of acquisition of the license is what is referred to for priorities, and the Senior/Junior distinction is just used as a generalization. In reality there are multiple levels of priorities within the Senior and Junior licenses alike.

Water allocations are provided as a percentage of natural flow, distributed as tradable licenses. Although the priorities of licenses are mixed between sectors, large municipalities (e.g. Calgary) and private irrigation generally have priorities over smaller municipalities (since smaller communities often applied later than the two aforementioned) and industry. Licenses are not tradable between basins, but an apportionment agreement exists between provinces as specified in the Master Agreement on Apportionment (1969). The specific junction of interest is the border between Alberta and Saskatchewan, as the SSRB is an inter-provincial basin. This agreement requires that half the natural flow of each water course must pass from Alberta to Saskatchewan on an annual basis. Natural flow, in this context, is the magnitude of flow that would naturally occur if there were no human induced alterations. Specifically, two provisions are made for the SSRB:

1. If natural flow at the Saskatchewan/Alberta border is **greater** than 3000 ft^3/s (85 m^3/s), then a minimum of 1500 ft^3/s (42.5 m^3/s) of flow must pass to Saskatchewan;
2. If natural flow at the Saskatchewan/Alberta border is **less** than 3000 ft^3/s (85 m^3/s), then half the natural flow must pass to Saskatchewan.

Water allocation to irrigation is managed differently than for uses previously mentioned. In Southern Alberta irrigation is managed in two ways: (1) by individual irrigators and (2) by the irrigation districts. Individual irrigator follows the 1999 Water Act, with a mixture of both Junior and Senior license holders. It is up to the individual irrigators here to maintain their own infrastructure to divert water from natural sources.

The irrigation districts, on the other hand, are clusters of farms managed by a district. In Alberta there are 13 irrigation districts, as shown in Figure 1.3. In the BRB there are three districts: the

Eastern, Western, and Bow River Irrigation Districts. Rather than individual farms obtaining licenses, these districts hold the licenses and manage the administration and infrastructure. Water is promised as a percentage of naturalized flow, specified by the Irrigation Districts Act (Province of Alberta, 2014). This water is usually stored in man-made reservoirs (lakes) before being redistributed to farms. Currently, all three districts in the Bow River basin are fully allocated, and as of 2007 no more licenses were available. Current strategies from the *Water for Life* Initiative aim to either increase productivity, or conserve water, by 30% by 2015 from 2009 (Government of Alberta, 2009).

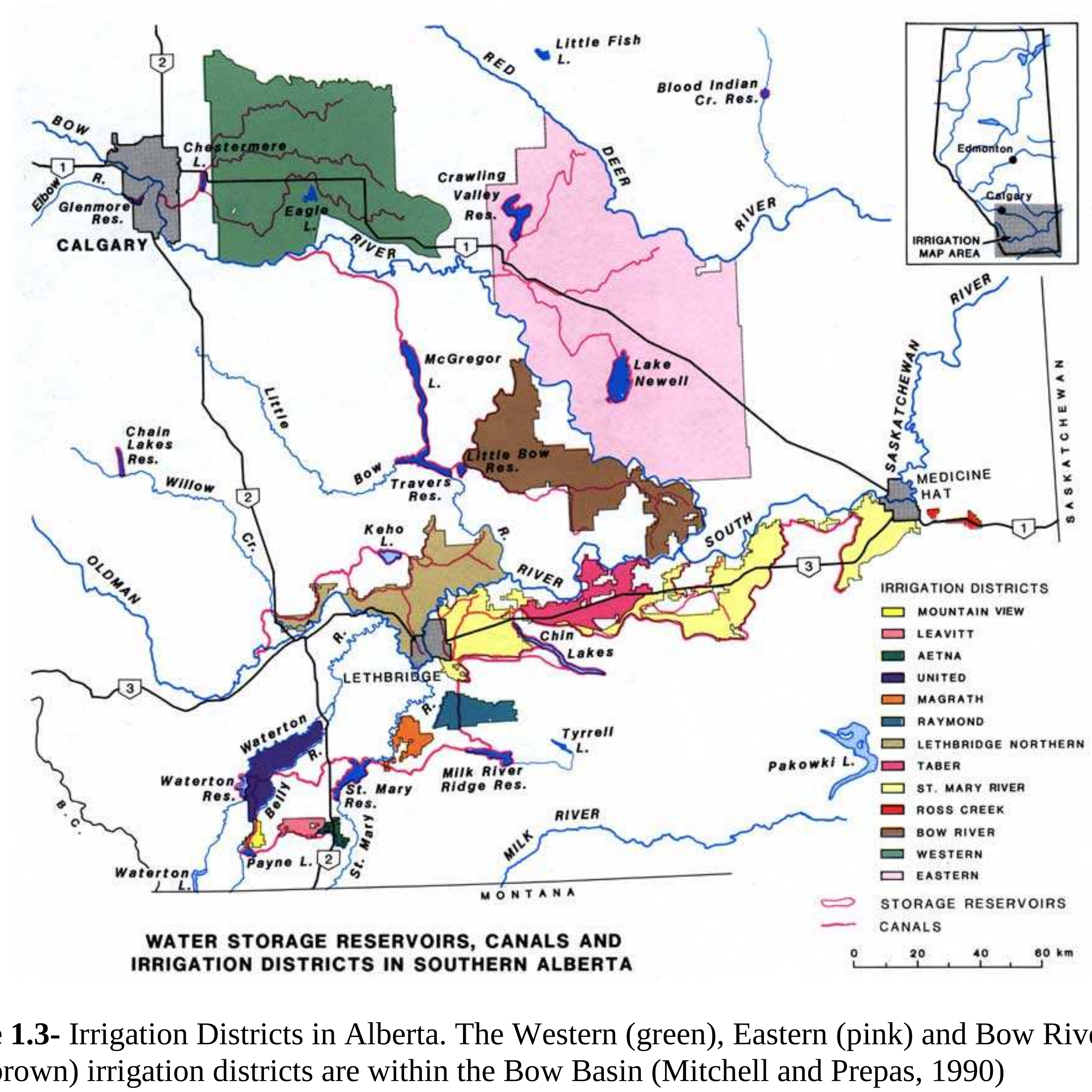


Figure 1.3- Irrigation Districts in Alberta. The Western (green), Eastern (pink) and Bow River (dark brown) irrigation districts are within the Bow Basin (Mitchell and Prepas, 1990)

Although licenses are not provided for environmental water use, an in-stream flow need (IFN) and in-stream objective (IO) are prescribed. The IFN recognizes that a minimum flow is required in river channels to support ecology. This minimum flow determination is based on water quality, fish habitat, channel maintenance and riparian health. Alberta quantifies these flows using the DeskTop Method (Locke & Paul, 2011), with values for two reaches along the Bow River.

Unfortunately, this method does not cover every tributary within Alberta. Where fish data is not available, the DeskTop Method recommends (i) no abstractions when flow is at or below the 20% non-exceedance value; and (ii) for flows above the 20% non-exceedance, up to 15% of flows can be abstracted. The method outlined above is simplistic, and not necessarily the status quo of other fish conservation practices globally. Poff et al. (2010) has developed more sophisticated means to quantify environmental flows, taking into account connectivity, geomorphology, and biology. Although the present study only considers the DeskTop Method, future studies should include more sophisticated means of quantifying environmental flow requirements.

The IO is less stringent than the previously mentioned IFN. Whereas the IFN employs multiple surrogates for required flow needs, the IO only considers fish habitat. Fish rule curves are developed for specific reaches. The IO is specified as an added condition to the existing licenses, specifying what flow is required for a license holder to divert water. For example, when the Bow River reach immediately downstream of Bassano has flow less than 39.6 m^3/s, then only EID licenses can divert water from that reach (AENV, 2003). When flow exceeds 39.6 m^3/s additional licenses are then qualified to divert water. This acts to ensure river flow is at specific values (e.g. 39.6m^3/s) by limiting when specific licenses can divert water (e.g. EID licenses). Though the example above only provided one constraint (39.6m^3/s), the IO specifies a hierarchy of flow values to the hierarchy of licenses. Historically, an 80% fish rule curve was enforced by Alberta Environment- operating infrastructure to keep flows above this value.

Although neither the IFN nor the IO is currently employed in the Bow Basin, a 2007 amendment enforced a Water Conservation Objective (WCO) that is still in use today. The WCO is defined as the greater of 45% of the natural flow, or an additional 10% more than the previously established IO (AMEC, 2009). The IO was found inadequate and the WCO is intended to further secure water for the environment. Although neither the IFN nor WCO is currently in legislation, they are considered sound management practices for any current and future projects. These environmental practices, if enforced, can conflict with other water users.

Several conflicting uses arise from current or proposed future uses of water. The first major issue is ambitious plans for the basin to increase irrigation productivity, even though the Bow is over-allocated. The IWMSC (2002) determined that irrigation land in the Bow basin can be expanded by 20%. This expansion, unless met by improved water productivities, will be in direct conflict with existing water resource uses. More generally, the Bow experiences conflict between economic viability and environmental sustainability. The competition between various sectors- such as expanding irrigation, increasing population, and water for power and industry- and with the needs of the environment requires careful investigation with a focus on sustainability, balancing all the needs of the Bow. A simulation tool that can handle all possibilities of development, and possible changes in the supply and demand under various uncertainties is needed. This tool can evaluate different solutions to these conflicting uses, considering a variety of criteria relevant to the Bow.

1.2 Current Management Model in Alberta

One tool to assess and predict water allocation in Alberta is the Water Resources Management Model (WRMM), currently in use by Alberta. WRMM was developed to allocate water in the SSRB (Alberta Environment 2002), with the most recent version produced in 2010. This is a linear optimization model that utilizes penalty values for water shortages, and distributes water to minimize the system penalty. It incorporates extensive information on the system physical characteristics and constraints, as well as penalties that simulate the hierarchal water license structure. WRMM has been employed for several studies, both by the province of Alberta (AERD, 2006) and independently (Bennett et al. 2013; AMEC, 2009; Sheet et al. 2013). The wide use of this model by water managers in Alberta and Saskatchewan supports the fact that WRMM is a good baseline model for water allocation.

Although WRMM is shown to be an effective model, with strong resource optimization capabilities, there are some deficiencies to be addressed. This includes the lack of integration with the economy, reducing the dimensionality of tradeoffs. Further, the water demand and allocation is not coupled (demands are entered prior to any simulation rather than calculated by the model). In particular, the irrigation demands for crops are dynamic in reality, in that prior allocations and climate affect the demand for future allocations. WRMM does not account for these dynamic interactions between water supply and demand, which are vital in understanding implications of different scenarios. Considerations of integrating water allocation with socio-economic values and linking water supply with water demand draws upon the concept of Integrated Water Resources Management.

1.3 Integrated Water Resources Management

The classical engineering approach to water management in the past has focused on "hard" solutions. "Hard solutions" refer to solutions that are generally supply oriented, and are usually involving one objective. Examples of such solutions include the "hydraulic mission," whose goal is to utilize every single drop of water (Allan, 2005). The idea was to dam up and store as much water as possible, since any water that made it to the ocean was considered a waste. This philosophy includes solutions primarily concerned with increasing water withdrawals with little concern for socio-economic well-being. By altering timing and magnitude of river flows, the environment can be affected (e.g., inadequate flows for fish migration). By only considering a single objective (e.g., more water for food or power), other socio-economic objectives, such as preserving water quality, may not be met. Tradeoffs exist between various water uses. Instead of considering the "hard" solution, one can consider softer demand-based solutions, or solutions considering multiple objectives. Integrated water resources management (IWRM) is one such approach to address this.

IWRM is described by Mitchell (1990) as having three considerations: (1) integration of the ecological systems; (2) connections between land, water, and the environment, and (3) connections between water and socio-economic development. More recently, this definition has been expanded by Biswas (2004) to include the integration of water supply and demand, surface and ground water, water quantity and quality, public and private sectors, national, regional, and international issues. These two definitions of IWRM provide a diverse means to manage water. It is important to recognize that effective water management relies on a multitude of other fields. This scope can be very wide and it was argued by Biswas (2004) that implementation of these ideas can be difficult. One such application of IWRM is integrated water resources modeling, commonly implemented through hydro-economic models. Hydro-economic models reduce the scope of IWRM to include a minimum of water resources and economics (though other aspects of IWRM can be included).

Two key features of integrated models discussed by Silva-Hidalgo et al. (2008) are multi-sector integrality and accessibility. The former feature recognizes the need for a model to allow communication between various sectors, such as policy, engineering, and economics. The latter feature refers to the fact that a model is only useful when it can be understood by the users. From these features the model being developed must be simple enough for water managers and policy makers to make use of. Thus, an important consideration of model building is transparency and coherency of the model.

1.4 Problem Definition

Many issues pertaining to water resources decision making rely on the ability of water managers and stakeholders to make well-informed decisions. In southern Alberta, many conflicts deal with over-allocation of water and resulting in competition for this scarce resource. Currently, the Water Resources Management Model (WRMM) exists as a modelling tool that optimizes water allocation based on a set of constraints and objectives (AEP, 2002). By running the model, decision makers can observe future projections of water allocation based on the allocation structure specified. Although this model approximates the licensing structure and realistically represents components, it is not integrated with the economy, nor does it have a fully transparent structure whereby users can easily manipulate allocations and specifics of model components.

The work of this research is to emulate WRMM- maintaining the same structure and components, but link it with an economic valuation and crop water demand generation. By building an integrated simulation model, drawing upon concepts of IWRM, stakeholders will have a tool that can examine decisions in multiple dimensions. Tradeoffs between economic return, environmental protection and water consumption by different users can be examined by a single tool. As this model aims to be transparent, this tool provides stakeholders a means to adjust the model structure and evaluate different management scenarios. To assess the validity of such a process, the integrated model developed will need to pass a verification process, and be implemented on current management issues in Alberta.

1.5 Objectives

The goal of this research is to provide water managers and policy makers a tool to make well-informed decisions to better manage the water resources within the Bow River basin. This goal is achieved through meeting the following objectives:

- To develop an integrated water resources system model that links water allocation and distribution with socio-economic factors; and
- To simulate management decisions and changes within the basin, and quantify their impacts on water and economics.

1.6 Scope

The development of this decision support tool builds upon the already established Sustainability-oriented Water Allocation, Management, and Planning (SWAMP) modeling framework (Hassanzadeh et al.., 2014). SWAMP is not a model in itself, but an underlying structure of an integrated water resources modeling approach, containing components as outlined in Figure 1.3. This structure is applied to develop individual models (with the possibility of being linked in the future) for individual basins. The Saskatchewan component, $\text{SWAMP}_{\text{SK,}}$ has been developed by Hassanzadeh et al. (2014) as a hydro-economic System Dynamics based decision support model for Saskatchewan, modeling both the water resources and economy of the water resource system. $SWAMP_B$ is the subject of this research, SWAMP applied to the Oldman River basin ($SWAMP_{OM}$) is currently being developed, and SWAMP applied to the Red Deer River basin ($SWAMP_{RD}$) is a prospective project yet to be developed. Although each model is a fully functioning model on its own, the end goal is to unify them as one system to simulate the entire South Saskatchewan River Basin. For example, implications from the headwaters of the Bow and Oldman for water consumption in Saskatchewan can be quantified. Within this thesis, SWAMP is extended to the Bow basin, and future work will include the Oldman and Red Deer basins, as well as the possibility of Manitoba and the North Saskatchewan River. The end product will connect each individual SWAMP model into one fully integrated system.

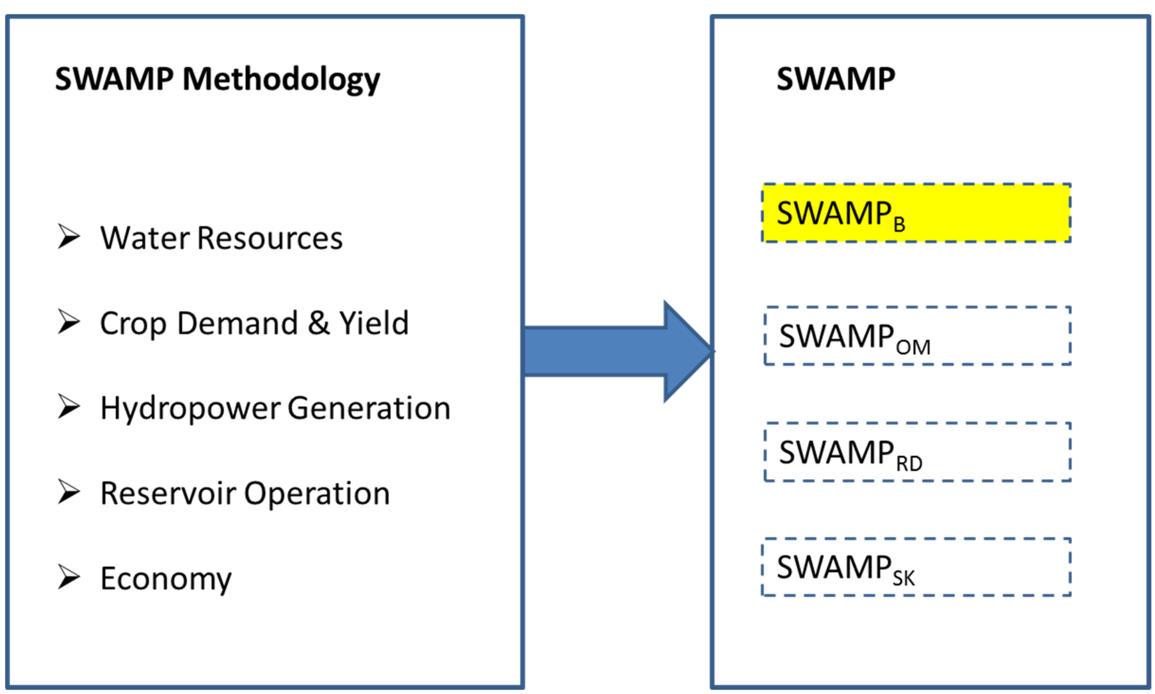


Figure 1.3- Diagrammatic Overview of SWAMP

This modeling framework is an emulation model, and not necessarily a reflection of reality. The term emulation is used in literature most commonly as the processes of developing a low order approximation (the emulator) of another model (Castelletti et al., 2012a,b; Young et al., 1996; Young and Ratto, 2009). Often the aim of such simplification is to reduce computational burden or to identify key structures. Other less common applications of emulation include (but are not limited to) simplifying the model to promote coherency (Holzkamper et al., 2012), identifying underlying mechanics of the system in question (Young and Leedal, 2013), or subdividing a model into components (Li et al., 2006; Rosenberg, 2009). It should be noted that there are several terms within the literature that are often seen to be used interchangeably. Emulation towards low order approximations is often referred to as meta-models or surrogate models (Razavi et al., 2012a, Razavi et al., 2012b). For simplicity, the term emulation is used in the work presented here. In this context, $SWAMP_B$ is an emulator of WRMM, providing a transparent simulation modelling environment. The aims of the modeling work are to approximate WRMM in allocation, when under similar conditions. Because WRMM is considered as a baseline, any deviations from reality seen in WRMM will also be seen in $SWAMP_B$. Although further efforts could address this potential deviation, the current study assumes WRMM as a valid benchmark. By emulating a linear optimization allocation model to a simulation model, the allocations will better reflect the realistic causal relationships within the system governing the allocations rather than optimizing penalty functions.

The subject of this thesis is the application of SWAMP to the Bow basin as $SWAMP_B$. This will include two major topics. First, as the construction of $SWAMP_B$ was quite intensive, a significant portion is devoted to the model building. Lessons learned during the model building phase are highlighted, giving the reader insight into the challenges of developing a complex integrated water resources simulation model. Second, $SWAMP_B$ is applied to investigate allocation scenarios, as mentioned in section 1.1. This includes satisfying irrigation water needs and efforts to include the IFN and WCO in the water allocation strategy. Both the historical period (1928-2001) and a 30 year dry period are utilized to ensure the analysis is valid under normal and wet periods. The 30 year dry period is taken as the driest consecutive 30 years found in paleo records (1600-1928). These records provide streamflows developed from tree-ring proxies.

1.7 Application of the Integrated Water Resources Model

The integrated water resources model, $SWAMP_B$, is utilized to assess water allocation in the Bow Basin, as discussed in Section 1.4 (Problem Definition). Mentioned earlier, the Bow is no longer accepting new licenses and is already over-allocated. As of 2006, the basin stopped accepting new licenses. AMEC (2009) has forecasted demands to increase from 1,981 MCM (million cubic meters) in 2007, to 3,040 MCM by 2030. This 53% increase in water demand is due to growing populations and irrigation land expansion in the three districts. Currently as new license acquisitions are frozen, Alberta must improve the efficiency of the water allocated, or provide strategies to reduce water demand. This conflict between growing demand and a hold on licenses is well suited to be addressed within a water resources modelling context. Solutions should propose water management interventions to utilize the water resources in the Bow Basin more effectively.

Not only is there shortage of water among the junior license holders and irrigation districts, but deficits in environmental flow occur frequently. Both the diversions for agricultural demands, and reduced summer releases from the TransAlta reservoirs decrease water available for the environment. The largest deficit in the Bow occurs below Bassano, where water has already been diverted for consumptive use. The flow in this region is much below natural levels during summer, and above during winter, as seen in Figure 1.4. Summer flows can be restored by either altering releases from the TransAlta reservoirs, or by reducing the overall consumption in the Bow basin. $SWAMP_B$ is applied to investigate various solution to this problem, considering effects on the economy, environment and water consumption.

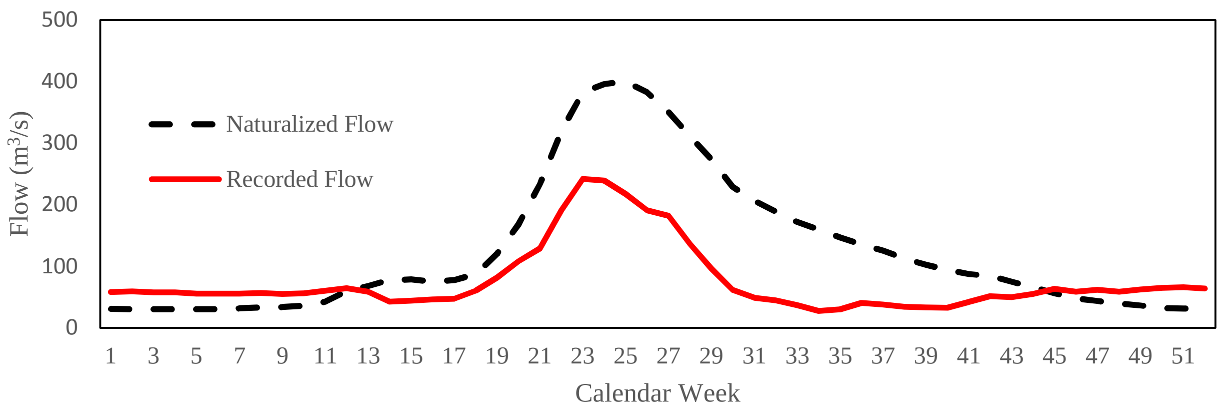


Figure 1.4- Naturalized and recorded average weekly flow of the Bow River below Bassano from 1928-2001.

1.8 Layout of Thesis

In Chapter 2 relevant literature is reviewed. This includes developments in the integrated water resources field in general, as well as simulation, optimization, and emulation modelling applications. In Chapter 3 the model building methodology and process are discussed in detail. System Dynamics, as the simulation environment, is presented and the development of the $SWAMP_B$ components is reviewed. Results are split into two chapters for coherency, as both are significant components. Chapter 4 contains the results of the verification of the $SWAMP_B$ model, in regards to its accuracy of emulating WRMM and simulating reality. The results pertaining to the simulation of the case study is presented in Chapter 5. Finally, conclusions, containing a summary, discussion of contribution to the literature, future work and limitations are discussed in Chapter 6.

Chapter 2 Literature Review

This research focuses on integrated water resources modeling. Both the development of such a model and its application to water resources management is discussed. Before the methodology is presented, some key concepts related to water management and modeling are discussed. This literature review begins by introducing the integrated modeling concept. This concept is then developed to include various forms of hydro-economic modeling. The examples of simulation, optimization, and model emulation will be discussed in turn. Since the model in question is a simulation model, it is important to give background on the purpose of this approach, and contrast it to other methods of modelling.

2.1 Integrated Modeling Concept

Integrated water resources management (IWRM) is a multidisciplinary approach to managing water. There is a long history to the many foundations of this ideology. This concept was first introduced in 1977 at the United Nations Global Water Conference in Mar de Plata (Biswas, 2004). Although IWRM was not fully realized at that time, it addressed issues of sustainable water management. In 1992 these issues were revisited, both at the International Conference on Water the Environment (ICWE, 1992) in Dublin, Ireland, and the World Summit on Sustainable Development in Rio de Jeneiro (WSSD). From the ICWE came the *Four Dublin Principles*, defining water both as a human right and as an economic good. These principles can be stated succinctly as: (1) fresh water is finite, needed for life, development, and environment; (2) developing and managing resources involves participation of all users; (3) women have a central role; and (4) water must be valued economically. The *Agenda 21* (UN, 1992) that came from the WSSD complimented the *Dublin Principles* by investigating the social and economic dimensions of water. The *Agenda 21* outlined an action plan for sustainable development, developed by multiple organizations at the Rio de Janeiro conference. Some of the discussed topics that relate to IWRM are: (1) decision making through integrating development and the economy (Agenda 21, Section 1), and (2) the application of integrated approaches to protect and manage fresh water supplies (Agenda 21,Section 2). Both the *Dublin Principles* and the *Agenda 21* built the foundations of IWRM, through considering management in a way that integrates multiple groups. From these fragments came many different interpretations of IWRM.

This paradigm shift towards IWRM has seen increasing trends to incorporate socio-economic and ecological dimensions in water management (Pahl-Wostl, 2011). In particular these socio-economic considerations were addressed by key IWA UNEP (2002) principles: recognition of water as an economic good, integrating water and environmental management, and recommendation of a systems approach. Further, this shift recognized the need to incorporate uncertainty, multiple sectors and the science of integration of parts (Lansey et al., 1989; Cai et al., 2003; Letcher et al., 2004). The common adage “the whole is greater than the sum of its parts” is well applied to complex water resource systems, and solutions should consider the integration and not just the parts.

There are several requirements identified for an IWRM model to be successful at providing useful information to the modeler: (1) The need to link spatial and temporal scales suitably (Maneta et al., 2009)); (2) modeling of conjunctive water sources, such as ground and surface water (Fernandez and Selma, 2004; Schoups et al., 2006; Pulido-Velazquez et al., 2008); (3) linking supply with demand forecasting (Hanson et al., 2012); (4) accounting for feedbacks within a system (Fernandez and Selma, 2004; Chen et al., 2005) and (5) providing a social and/or economic valuation (Heinz et al., 2007; Ward, 2009). Concerns for these five requirements pointed to the need to integrate water, economy, and environment utilizing a systems approach. A hydro-economic model is a relatively simple form of IWRM modeling, as it considers just the hydrological and economic aspects, but can be extended to include environmental aspects. *"Combining engineering, economics and hydrological science, a hydroeconomic approach is well positioned to help foster integrated water resources management."*(Harou et al., 2005)

Two broad approaches to hydro-economic modelling developed were the simulation and optimization approaches. Both of these approaches were seen to have advantages and disadvantages as described by Harou et al. (2005). Simulation has the advantage of being conceptually simpler than optimization, and allows one to examine changes to a pre-defined scenario. The main disadvantage of simulation models is that they do not provide a means to determine a best solution. Conversely, optimization models allow one to identify a best solution based on one or more pre-defined objective functions, e.g. minimizing cost or maximizing marginal utility. Optimization models are often more complex than simulation models and do not normally provide any means to understand the system. Further, Keeney and Wood (1977) argued against optimization models on the grounds that the objectives when optimized may not be meaningful to stakeholders.

Brouwer and Hofkes (2008) segregated hydro-economic models into three basic groups: modular, integrated/holistic, and metamodel. A modular approach consists of components and sub-models that interact with each other as exogenous forcing. This allows for multiple modeling platforms to be combined, and coordinated. The integrated/holistic approach treats all components as one model, allowing equations to be solved endogenously, as seen in a systems approach. Less common are the meta-models, which relate one model to another through cause and effect. Although there is a multitude of ways to classify integrated water resources models, the distinctions by Brouwer and Hofkes (2008) are succinct. In short it is convenient to consider two modeling approaches; optimization-based and simulation-based modeling, each with three model structures.

The application of integrated water resource systems models is the theme of the following sections. It was shown as a means to translate IWRM principles to practice. An integrated model should consider scale, conjunctive water use, supply and demand, and feedbacks and the economy-although not all considerations are always present (e.g. a surface water dominant system may have little feedback with groundwater sources). This can be achieved through coupled and holistic models, both optimization- and simulation-based. From the previous paragraphs one could appreciate the breadth of applications and multitude of factors involved. Depending on the case study, one has a variety of options to choose from. The remainder of this review will discuss the application of both optimization- and simulation-based IWRM models, as well their use as emulators.

2.2 Optimization-based Integrated Water Resource Systems Models

Optimization models define an objective function that is either minimized or maximized in the modelling process. The optimization model seeks to find a solution (such as how to allocate water) achieving the objective function. A common approach is to satisfy a single objective function (e.g. maximize economic return) under a set of constraints; e.g., apportionment laws, using both linear and non-linear functions. There were many studies examining, for example, irrigation efficiency in terms of maximum economic returns. Ahrends et al. (2008) examined the effects of different irrigation strategies in the Naouri Basin, Ghana, by linking a physical hydrological model with farm irrigation models. Alternatively, irrigation efficiency was seen to be optimized through varying incentives (tradable water rights vs fixed water rights) and technology (Cai et al., 2003). Rosegrant et al. (2000) used a hydro-economic model to understand the impacts of water trading in the Maipo River basin, Chile. Optimization models are also useful in determining the balance of different water uses. Cai and Rosegrant (2004) developed a model for the Yellow River Basin, China, to examine the balance between ecological and agricultural uses. Water allocation in California was optimized by minimizing water scarcity under different operations (Jenkins et al., 2004). Infrastructure is another important asset in integrated water management. Heinz et al. (2007) combined policy and infrastructure changes in the Jucar River basin by examining effects on the marginal resource opportunity cost (MROC). By optimizing productivity, the MROC was computed as a time series to observe effects of these policies and structure improvements.

Often there are multiple objectives defined in complex problems, such as optimizing both economic returns and minimizing environmental damage. This kind of problem usually has conflicting objectives, for example increasing economic returns may decrease water available for environmental use. One common resolution considers multiple-criteria decision making (MCDM), which contains different approaches. Weighted Goal Programming (WGP) is an extension to linear-programming that allows multiple objectives to be weighted by degree of importance, and rates solutions by weighted distance from some goal. This technique was utilized by Xevi and Khan (2005) to optimize economic and ground water pumping requirements in a catchment where the economy and environment were in conflict. Zarghaami (2006) utilized Compromise Programming (CP) to weight economic, social, and environmental objectives to determine optimal crop pattern, water allocation, and infrastructure design. The ideal solution lies within optimum values of each objective for CP, rather than some target that is either achieved or not achieved as in WGP. Latinopoulos (2008) developed utility functions for crop water demand, allowing for optimal water allocation under different scenarios. This more accurately reflects farmer's decisions, as it considers labor and risk, in addition to maximizing profit. These utility functions provided a relative preference between different objectives. CP was further advanced by Geng and Wardlaw (2013) by using a genetic algorithm to optimize objectives at every time step of the model. This adaption allowed for considering 11 criteria over a large set of constraints to reduce ground and surface water depletion. The MCDM application to conflicting resource management problems is quite comprehensive, and a full review is beyond the scope of this thesis. A more comprehensive review of MCDM techniques applied to resource management in general can be found in Mendoza and Martins (2006).

In addition to objective programming solutions, optimization was achieved through stochastic models used to identify optimal management over different policies. Jenkins and Lund (2000) determined least cost management measures to prevent water shortages to a municipality. Based on physical constraints, operational rules and cost parameters, probability distributions of shortages were produced and optimized. Tilmant et al. (2008) were able to identify optimal reservoir operation in a multi-reservoir system in the Euphrates using dynamic stochastic programming. These operations were aimed at timing releases to maximize hydropower production while minimizing damages due to floods and droughts. Anghileri et al. (2013) examined the impacts of individual optimal management, versus a coordinated optimal management. Minimization of irrigation water deficit in conjunction with maximization of hydropower productivity was considered for each water user. These three studies showed that feasible management relies on a multitude of drivers.

Some studies linked hydro-economic models with climate models to examine optimal water allocation under uncertainty. Hurd et al. (2004) developed a model of several river basins across the United States under ten different climate scenarios. Their study aimed to maximize welfare and equalize marginal return of water under perfect competition of users. Effects of climate change on water use in Spain were examined through coupling a physical hydrological model with a linear programming economic model for the Guadiana Basin (Varela-Ortega et al., 2011) and the Ebro Basin (Graveline et al., 2013). Both studies in Spain were able to determine optimal policies under varying climate projections. In the River Orb Basin (France), a least cost optimization model assessed agricultural and urban water reduction measures, considering uncertainty in future evapotranspiration and precipitation (Girard et al., 2015).

What can be clearly observed is that optimization-based IWRM models can effectively supply model users with a best alternative. Whether this best alternative is supplied through single or multiple objectives, or through stochastic means, it is a rigid choice. Water resources problems pose a unique challenge that cannot be solved through considering optimality (Reed and Kasprzyk, 2009). Although MCDM goes beyond a single optimum solution, it is still a process where specific objectives and model structure are assumed. Instead, one can utilize a simulation approach that allows for the modification of model structure. In reality systems are always changing, and the model user needs a means of investigating these changes. Also, the objectives assumed by the modeler may not necessarily be the objectives used by all stakeholders. What is needed is a modeling approach the clearly illustrates feedbacks, and gives the end user a flexible and adaptive means to assess any possible situation modeled. The next section will discuss such an approach to foster flexibility and clearly define feedbacks.

2.3 Simulation-based Water Integrated Water Resource Systems Models

Simulation models provide a different approach from that of optimization models. In many cases it may not be of interest to find an optimal solution, but rather to understand the implications of different scenarios. A simulation approach allows users to understand the behavior of a system. From the behavior, users can test different options or scenarios - whether that is policy alteration, climate change, or structural upgrades. Several case studies were presented by Jakeman and Letcher (2003) to understand effects of deforestation in Thailand, and investments in water supply systems in Australia on farm productivity. Hydro-economic models were seen to have a strength, especially in the case of simulation models, to allow the user to understand how specific mechanisms of water allocation interact. Some extensions included the interaction between ground water storage and urban water use (Srinivasan et al., 2010), irrigation district growth and farm profits (Bennette et al., 2013), and how management of channel vegetation impacted flood damages (Kourgialas and Karatzas, 2013). Simulation models also simulated non-market values, such as recreation, greenhouse gases and habitat biodiversity (Grossman and Dietrich, 2012). These models proved to be useful at examining the feasibility of the European Water Framework Directive (WFD) over current practices. Bateman et al., (2006) observed pre-WFD and post-WFD effects on agricultural productivity and non-market values of stream quality and habitat. Through water resource systems simulation models, effects of policies on reducing the dependence on groundwater, water licenses, irrigation limits and environmental flow requirements were understood in both short and long term time frames (Letcher et al., 2004).

Some studies have recognized the need to examine market mechanisms, and their effect on water allocation. The global trade in blue and green water, considering the relationship of trade-networks on water resources, was simulated by Konar et al. (2012). This simulation was achieved through utilizing a compartmental model linking hydrology, river routing, crop growth, reservoir operation and human consumption (Hanasaki et al.., 2010). Mahan et al. (2012) quantified welfare gains under different trading scenarios by linking a farm sub-model to a non-linear economic welfare model. Game Theory was shown to depict the motivations of various parties, as ulterior motives of different parties can lead to a sub-optimal allocation (Madani, 2010). An extensive list of case studies applying game theory to water management can be found in Madani (2010). Water transfers for controls on water quality and agricultural production were examined in Southern Iran using a simulation model (Mahjouri and Ardestani, 2010). A coalition analysis was applied to the South Saskatchewan River Basin, illustrating the effects of water transfers to promote higher value crops (Hipel et al., 2013). Both game theory case studies showed that reality can be better simulated by considering realistic strategies of different water users. A further development to the literature presented so far is the advancement towards decision support systems.

Loucks et al. (2005) discussed a decision support system (DSS) as a means to aid the decision making process. This was achieved through various levels of support (e.g. whether to allow the user or model to rank alternatives). This was useful in IWRM as it gives stakeholders a shared vision, allowing them to interact as they build the model (Loucks et al., 2005). One of the oldest DSSs to be used in IWRM is the AQUATOOL, currently being used by the River Basin Agency of Spain (Andreu et al., 1996). AQUATOOL addressed early initiatives of integrating hydrological characteristics with risk assessments in a user interface. The WaterWare was also developed at the same time, providing a GIS interface and a river-basin planning module (Fedrac, 1996a; Fedrac and Jamieson, 1996). Early studies found WaterWare competent in managing surface water-ground water interactions dealing with contaminant transport (Fedrac, 1996b). With the advent of the WFD, MULINO was developed to include socio-economic considerations of policy changes (Mysiak et al., 2005; Giupponi et al., 2004). This platform utilized a cause and effect relationship for stakeholders to assess consequences of different management strategies. The WFD also required volumetric water pricing to promote sustainability. Multi-attribute Utility Theory (MAUT) was applied to develop water demand functions to irrigation districts in northern Greece (Latinopoulos, 2008). These utility functions allowed stakeholders to analyze water management decisions while considering the farmer's values. In Australia, the Water Accounting System (Turner et al., 2009) managed water through accounting. This allowed stakeholders to perform a design-based approach, minimizing 'tensions' in the system. Weng et al. (2010) developed the MEMO model, an integrated scenario-based multi criteria DSS. MEMO utilized fuzzy theory and multi-criteria decision analysis to present decision makers with preferred solutions. The strength of MEMO was that multi-criteria capabilities allow it to analyze many performance indicators. The SimBat DSS is a flow network model that considers municipal, irrigation, and environment users (Preziosi, 2013). Preziosi et al. (2013) applied this model to assess impacts of hydrological droughts, considering different alterations in streamflow. The DSS was found effective as it quantified impacts of various management decisions by using vulnerability indices.

Further advancements in hydro-economic modelling allowed for a systems thinking approach. System Dynamics (SD) is a novel approach to systems thinking, pioneered by Jay Forrester- initially used as a tool to understand industrial systems (Forrester, 1961). When compared to other modelling approaches for integrated assessment, SD was found to best characterize feedback loops (Ford, 1999). These strong feedbacks are useful in allowing the user to easily identify leverage points in the system (Hjorth and Bagheri, 2006). This modeling approach is highly applicable to water resources modeling as it provides a user-friendly simulation environment with capabilities to analyze complex system interactions (Mirchi et al., 2012). SD also provides a strong environment for stakeholder participation (Stave, 2002; Winz et al., 2009; Mirchi et al. 2012) and system validation (Barlas, 1996; Peterson and Eberlein, 1994).

SD was widely used in water resources modeling and management (Elshorbagy and Ormsbee, 2006; Hassanzadeh et al., 2014; Elshorbagy et al. 2007; Simonovic et al., 1997). SD was shown in many case studies to provide management alternatives to complex, multi-objective problems. The CanadaWater model integrated the economy, freshwater, groundwater, agriculture, and population to holistically examine different management policies (Simonovic and Rajasekaram, 2004). Wei et al. (2012) were able to determine the optimal environmental flow in a river basin in China by examining the feedback between environmental flow demand and socio-economic development. Benefits of agricultural productivity under different water transfer schemes between Mexico and US were examined by Gastelum et al. (2009). By using an SD model, Qin et al. (2011) determined that economic growth in Shenzhen, China, is strongly linked to population and pollution. Often, water resources systems have complex feedbacks between resource consumption and socio-economic development, and SD is a valuable approach in examining carrying capacities of such systems under different policies by understanding these feedbacks (Song et al. 2011, Yang et al. 2014, Yang et al. 2015). Similar complexities linking ground water extraction to net present value in an irrigation district was analyzed by Karamouz et al. (2013). These studies serve to illustrate the use of SD to understand the cause and effect mechanisms within a resource system.

A further advancement was the integration of SD into a DSS framework. As discussed previously, DSS's strength is in *aiding* model-users in the decision process. This, combined with SD, can provide a system that fosters integration and feedback between multiple components of the model. Many studies have applied SD in compartmental models to handle complexity within a DSS framework. The NHREYS DSS (Kazeli and Keravnou, 2003) linked together four compartments (Data, Manager, Display, and Decision Maker) for an intelligent water management DSS. A stochastic model (Data) accounted for uncertainty in the inputs to the SD-based water allocation model and results from the SD model are saved in the Decision Maker compartment. This constituted an intelligent system as it was able to determine recommended resource allocations at each time step of the model based on previously stored information. Studies by Chen et al. (2005) and Nikolic et al. (2012) linked SD with a GIS tool to account for spatial variability in the decision process. The first study employed the Driving-force State Response (DSR) framework, and the second used intelligent agents, to incorporate policy in decision making. A compartmental DSS, known as TAI WAP (Liu et al., 2009), integrated a weather generator and the physical hydrological model, GWLF, to produce inputs to the SD model. To stream-line the decision making process regarding infrastructure upgrades, Xi and Poh (2014) evaluated the outputs of their SD model using Analytic Hierarchy Process. This process allowed three subjective attributes (adequacy, self-sufficiency, and cost) to be weighted for each scenario and provide users with the optimal solution. These five modeling studies show the potential of using SD within a DSS framework.

The advantages discussed above make SD a suitable method for the study considered and reported in this thesis. SD was shown to illustrate feedbacks, as well as promoting flexibility and adaptability inherent of all simulation models. Further, SD was shown many times to serve as a DSS. The SD-based model developed in this study, $SWAMP_B$, aims at producing a self-contained DSS model, not requiring any external modules. This means that the entire modeling process can be modified within one platform.

2.4 Emulation

A point of interest for this research was the development of an SD-based DSS through emulation, also known as meta-modeling. An emulation model is a model developed to simulate another model, often with improvements (Razavi et al., 2012). Most commonly, these improvements are in the form of reducing the complexity of the emulated model, but also can extend to adding additional capabilities. The model developed in this study utilized emulation by simulating an existing optimization-based model, and considering dynamic feedback and additional modules, as discussed in the previous chapter. This section is provided to give a general background to emulation, and illustrate its usage.

The earliest work in this area began with Blanning (1975), who developed meta-modeling as a means to emulate a non-dynamic system. This means that the model was emulated over a nominal state (single parameter set). Many authors have recognized that environmental systems are dynamic, requiring the emulation to not just consider nominal states, but all states across the system. Work by Castelletti et al. (2012a, b) developed the Dynamic Emulation Modeling (DEMo) framework for addressing this complexity in environmental systems. Castelletti et al. (2012a) identified two categories of dynamic emulation: (1) structural emulation and (2) data based emulation. Structural emulation recognizes the need to simplify the model by manipulating the mathematical structure. Data based emulation is performed through simulations of the original model to produce a lower order mechanistic model. This data based methodology was applied to the Tono dam in Japan to emulate the rules governing water release (Castelletti et al., 2012b). The model was reduced from 1000 variables to 53, and the authors were able to determine that most of the variability originated from just eight of the variables.

Mechanistic emulation has been extensively applied to a top-down modeling approach, known as the Data Based Mechanistic Modelling (DBM) framework (Young and Leedal, 2013; Young and Ratto, 2009; Young et al., 1996; Young, 2003). This is an inductive modeling approach, as the emulator model structure is determined through statistical analysis of data rather than *a-priori* assumptions. A reduced order model (referring to the order of a time differential) is first produced through signal analysis of the simulation model, and then emulated through mapping a transfer function linking the reduced order model with the simulation model. The above-mentioned authors have noted benefits in DBM being able to identify dominant behaviors of systems and reducing complexity where unnecessary. Young et al. (1996) and Young and Ratto (2009) were able to reduce the order of the Enting-Lassay Global Climate Model (GCM) through developing a series of parallel equations. In addition to simplicity, this model was physically plausible as the feedbacks of varying time delays approximated the behavior of energy storage of oceanic and climate systems. Similarly, Young (2003) was able to reduce the number of variables needed in a rainfall-runoff model. With fewer variables, the dominant behavior of advective time delay and the parallel between quick flow and slow flow became apparent. The HEC-RAS model was emulated by Young and Leedal (2013) by converting a complex finite-difference model into 6 first-order transfer functions. These studies showed that emulation can be used as a tool not only to reduce dynamic complexity, but to more easily identify the underlying mechanics of the system.

A decision support model needs to be simple enough for stakeholders to use (Loucks et al., 2005). Different users are interested in different scales, meaning simpler models can be of better use to some users. Of the three dynamic simulation models discussed by Kelly et al. (2013) - Bayesian Networks (BNs), System Dynamics, and Agent-based-modeling, only BNs have been used as emulation models for simplification purposes. Holzkamper et al. (2012) used BNs to smooth the connection between sub-models by lumping together various ecological indicators into one coherent value. These results allowed the user interface to be simplified and more easily employed by stakeholders. Other studies illustrate BNs' use in translating qualitative data into quantitative data (Ticehurst et al., 2007; Borsuk et al., 2004; Carmona et al., 2011) and providing model stability (Fienen et al., 2013) to produce a coherent DSS.

Within a systems context, hierarchical models have been used to examine multi-scale interactions. In ecological modeling, patch dynamics recognizes that within a system, there are heterogeneous subsystems (Pickett, 1985). These patches (subsystems) can be modeled in a hierarchal way to examine scale-dependent behavior. Some studies have modeled the nested, scale-dependent landscapes (Wu and Levin, 1994), groundwater systems (Li et al., 2006) and urban water use scales (Rosenberg, 2009). Although Rosenberg (2009) did not consider a nested model, the household, city, and regional scale models had distinct solutions to water savings that could be applied holistically.

This section showed a brief overview of the meta-modelling applications. The above studies have illustrated its use in the following: (1) Reducing the model order, effectively reducing the number of variables involved; (2) identifying the underlying mechanics of a system; (3) promoting simplicity, coherency, and stability of the meta-model to be more user-friendly; and (4) sub-dividing large systems into a series of small/simpler ones. The aim of the emulation conducted in this study through the developed model ($SWAMP_B$) was to provide all four attributes, but primarily (2) and (3). The run time of $SWAMP_B$ was much less than the original emulated WRMM model, and the SD framework allows processes to be understood through feedbacks. The end product will promote usability as it will have built in capabilities to alter the model through an object-oriented approach.

Chapter 3 Materials and Methods

In this chapter several topics are discussed, pertaining to the development and application of $SWAMP_B$. First, the emulated model, WRMM, is discussed. This model is the current allocation model in Alberta, and section 3.1 provides a thorough discussion of its allocation algorithm and general characteristics. Central to $SWAMP_B$ is System Dynamics, the modeling approach utilized, which is discussed in section 3.2. The model building was performed for multiple model components, discussed as sub sections within section 3.3. Finally, the application of $SWAMP_B$ is outlined through its verification in section 3.4, meteorological and hydrological data acquired and constructed in section 3.5, and the design and evaluation of scenarios in sections 3.6 and 3.7, respectively.

3.1 Water Resources Management Model

The Water Resources Management Model (WRMM) was developed and made available to model water allocation in Alberta (AEP, 2002). This is a flow network model coded in FORTRAN, which utilizes the Out of Kilter algorithm (OKA) (AEP, 2002). The OKA was advancement from the earlier Simplex Method to solve minimal-cost network flow problems (Fulkerson, 1961). This algorithm optimizes a system by bringing Out of Kilter variables (those that are not optimal or feasible) In Kilter (optimal and feasible) by changing a pricing vector. Because OKA progresses monotonically, it is much more stable than the earlier Simplex Method (Fulkerson, 1961). In using the OKA algorithm WRMM aims to optimize a water allocation network through the objective function in equation 3.1

$$Objective = Min \sum Penalty * Water\ Volume \qquad (3.1)$$

WRMM approximates reality by representing licensed water allocations as nodes and flows with demand values. The priority/seniority of every demand is approximated by a penalty value, with larger penalty values reflecting higher priority demands. Rather than a single value for each demand there is a range of values, this range represents the boundaries of a penalty value. Such ranges of demands that are assigned a penalty number are referred to as zones. Some nodes or flows may have several zones, representing distinct severities. For every component in the system, there is one discrete value (the magnitude may differ for different time steps, but for each time step there is only one number), known as the *Ideal*, that represents the optimal value of any component where the penalty value is zero, and any value larger or smaller is subject to a penalty zone. An example of this would be a diversion license, where the ideal allocation would satisfy the full demand without giving excess water. A penalty zone directly above the full demand would represent consequences for over allocation (e.g. not following license agreement), and one or more zones below the ideal would represent consequences of under allocation (e.g. inadequate streamflow or reservoir storage to satisfy all licensed demands). Large magnitude penalty values represent severe consequences and low magnitude penalty values represent minor consequences. A reservoir, for example, may have low penalty values specifying the bounds of the active storage zone. Then a more severe penalty would represent the physical maximum and minimum storage. Likewise, irrigation demands have escalating penalties as they become more water stressed. Also, penalties are used to mirror the seniority system- more senior demands have a higher penalty value. Since more senior users have higher penalty values, the system will allocate water to them first to reduce overall system penalty.

WRMM is represented as a node-link model shown in Figure 3.1, with the BRB outlined in red. Arrows represent natural river reaches, diversion channels, and return flows, hexagons represent minor and major demands, squares represent irrigation, triangles represent reservoirs, and circles represent junctions. The BRB is represented by 12 reservoirs, 37 irrigation demand nodes, 36 Major demand nodes (municipal and industrial demands), and eight Minor demand nodes (municipal). The distinction between the Major and Minor demands are that the Major demands follow the optimization-penalty system, whereas Minor demands are always met regardless of the outcome of the objective function (WRMM reports an error if Minor demands are not met). Physically, the Minor demands represent vital water demands, such as municipal water for the city of Calgary, which must be met under any scenario. Although the name suggests a demand that is either small or insignificant, they can have demand magnitudes larger than Major demands. The nomenclature used- Minor and Major- is that specified by WRMM, and is referred to in the same manner here for consistency. Within WRMM, each of these components has physical characteristics, demands, and penalties that can be specified by the user. Currently, the model uses historical climatic inputs (precipitation, evaporation, inflows, and outflows) and fixed demands based on water policy of 2010 for Major and Minor demands, and the 1991 Irrigation Expansion limits (IWMSC, 2002). These demands are not calculated by WRMM, but required as inputs from a text file. Operational rule curves and various water demands vary by week, but do not have any growth rate or adaptive measures included. Irrigation demands were calculated externally by the Irrigation Requirements Model developed by the Alberta Environment and Parks (AEP, 2002).

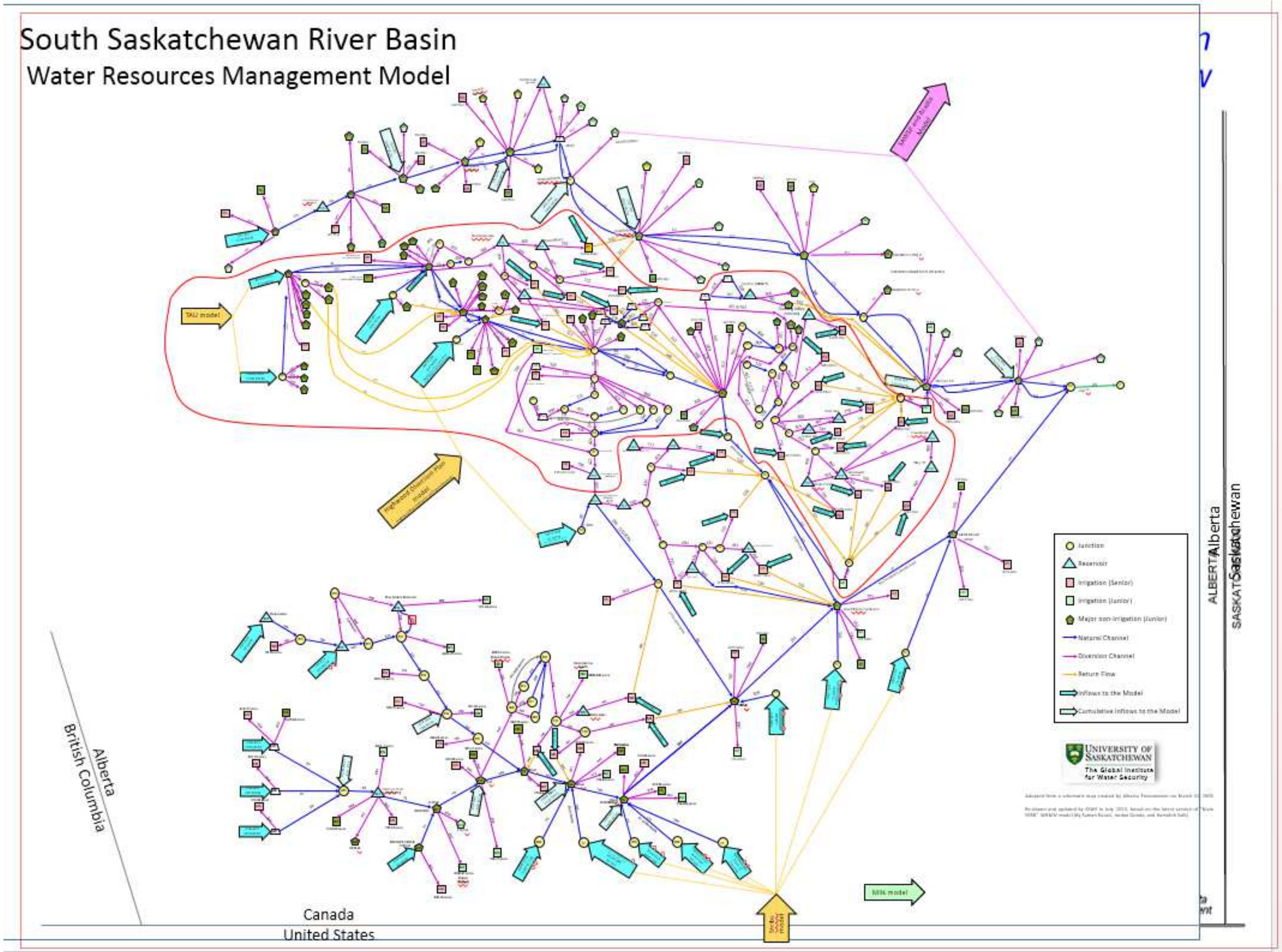


Figure 3.1- WRMM's schematic of the water resources system in Alberta. Developed by Jordan Gonda and Saman Razavi, adapted from WRMM User Manual (AEP, 2002)

3.2 System Dynamics

System Dynamics was the tool of choice for developing the $SWAMP_B$ model as it has been proven an effective tool for modeling water resources problems (Elshorbagy and Ormsbee, 2006; Mirchi et al 2012). System Dynamics is designed to represent a *system* that is *dynamic* in nature. A *system* is any network of interacting or coupled components that comprise a whole. In a systems based model, the system itself gives rise to behavior, rather than the other way around (Sternman, 2001). A *dynamic* system is one in which change, often temporal change, is attributed. A water resources system is a *dynamic system* as there are many interacting components that are constantly changing over time and space. For example, a reservoir may allocate water based on some demand, and this demand is a function of what is allocated- all of which changes over time. System Dynamics provides the means to connect the various demands, supplies and storages, and relate them in a dynamic way.

There is a need in dynamic systems to deal with what Sternman (2001) describes as *Dynamic Complexity*. This is a complexity that is not necessarily due to a combinatorial complexity, or due to a large number of components, but through complexity due to the interactions of components. These complexities can arise due to non-linearities, highly coupled components, delays and adaptivity- just to name a few (Sternman, 2001). The water resources system considered in the Bow possesses these qualities: the crop water demands are coupled with hydrology and allocation, return flows from agriculture are delayed, and many non-linearities arise between the reservoir evaporation and precipitation. By using System Dynamics, a means is available to address these complexities.

Essentially any dynamic system gives rise to information feedbacks, where new results lead to new decisions and so on. Information feedback is a key process that must be understood in order to understand a dynamic system (Forrester, 1961). One way to illustrate and understand such feedbacks is through Causal Loop Diagrams (CLD). A CLD illustrates how one variable (e.g. parent) affects another variable (e.g. child) through the use of arrows and signs. Figure 3.2 illustrates a very simple CLD for a reservoir operation. Positive relationships are represented by an arrow ending with "+" and a negative relationship by a "-". A positive relationship means that an increase of the parent variable leads to an increase in the child variable; a negative relationship implies the opposite. In Figure 3.2, the precipitation is positively linked to reservoir storage, as more rainfall increases storage volume; the inverse is true with evaporation.

A second concept with feedbacks is that *loops* can be represented. Similar to the positive and negative relationships between individual components, a closed loop can be positive or negative. By counting the number of "+" and "-" linkages one can find positive loops to contain only positive or only negative relationships, whereas negative loops contain at least one of each. Positive loops, also known as reinforcing loops, are those that amplify an increasing or decreasing relation. An example of this is the precipitation loop (bolded "+"); precipitation increases the reservoir volume, which in turn increases reservoir area, and the increase in area allows further precipitation to increase the volume even more. Conversely, the negative loops, known as counteracting loops, aim to counteract components. As seen in evaporation, the increasing reservoir volume and area reinforce the increase in evaporation, but this increased evaporation then counteracts the loop by decreasing volume of the reservoir. Counteracting feedbacks are important in SD models as they give the ability to negate exogenous factors, and prevent a system from reaching extreme growth (Ford, 1999). An obvious example of this is that without the presence of evaporation or outflow, the reservoir would fill indefinitely. The presence of both positive and negative loops develop complex systems.

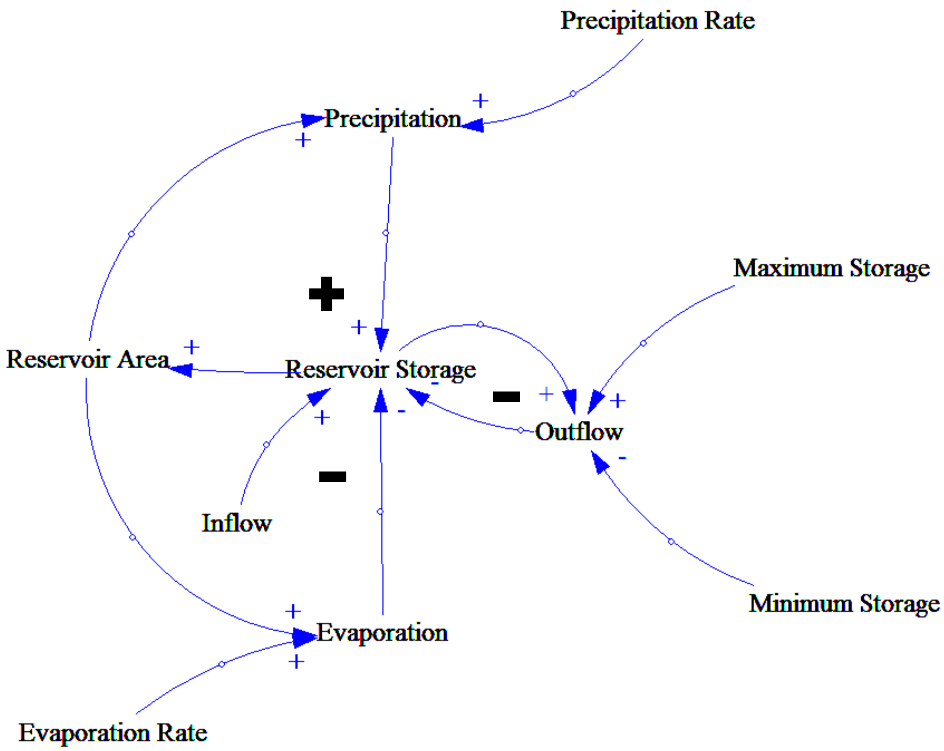


Figure 3.2- Causal Loop Diagram of Reservoir

A final note on feedbacks concerns delays. Sternman (1989) suggests that one of the common misconceptions with dynamic systems is that users fail to account for correcting actions that have not yet taken effect. In other words, the delay of action/influence on some result is often neglected. An example of this is the return flow from an irrigation district. Excess irrigation water may not return to water bodies for re-use instantaneously, but will have a travel time as a function of channel properties. Thus, the return flow may return at a later date, perhaps not accounted for by the modeler. SD allows the user to specify delays to provide for a more realistic representation of the system.

System Dynamics has several tools that are used to model a dynamic system, such as the one seen above. The "bread and butter" of an SD model are the stocks and flows. Stocks, often represented by boxes (but can be specified as any shape in VENSIM (Ventana Systems, 2014)), accumulate values, with suitable units of depth, area or volume (L, L^2, L^3). Bank account balances, soil moisture storage, reservoir storage and soil moisture can all be suitable stocks as they increase or decrease over time. Flows specify a rate (e.g. LT^{-1}, L^3T^{-1}, etc.) either inflowing to or outflowing from a stock. Examples of flow include runoff, reservoir release, and cash flow.

Although stocks and flows are the bulk of the model, defining states and flows, there is still some need for modifications. Such modifications are needed to present calculation units, such as converting reservoir storage to area, or by setting conditions for the stocks and flows. Conditions could influence requirements for flows to operate (e.g. conditions necessary for a reservoir to release water). These modifications are known usually as *converters*, or in VENSIM are known as *auxiliary variables*. Converters are linked to stocks and flows through connectors, displayed as arrows, and show how variables are connected.

Once the modeler has identified key processes and their feedbacks, in the form of a CLD, one can then progress to modeling the system. By using the stocks, flows, converters/auxiliary variables, and connectors a Stock Flow Diagram (SFD) is built. Figure 3.3 displays the SFD of a simplified reservoir. The reservoir, represented as a box, stores volume of water. This reservoir either gains or loses storage through the flows of Inflow, Release, Precipitation Vol and Evaporation Vol. By using an auxiliary to convert the reservoir storage (L^3) to surface area (L^2), the precipitation (mm) can be converted to precipitation (m^3) to be consistent with the stock. This is done through the "Reservoir Area" converter, which utilizes "Reservoir" (current volume of stock) and "Volume-Area Relationship" (contains the bathymetry of the reservoir) to calculate the surface area of the reservoir at every time step. The auxiliaries "maximum storage" and "minimum storage" impose limits on the reservoir release.

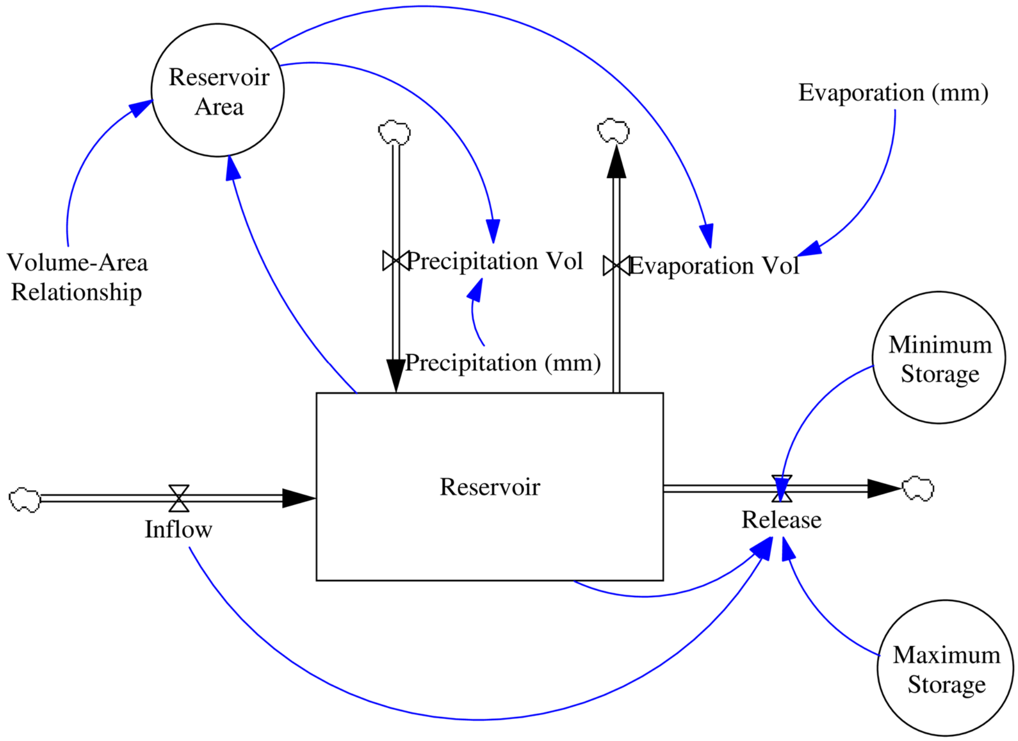


Figure 3.3- Stock Flow Diagram of a single reservoir

System Dynamics simulates the model- assembled by the combination of stocks, flows, and auxiliaries- over a specified time step. The time step, Δt, is of importance to the accuracy of the model. By using this specified Δt, the SD model solves the components using first order differential equations. These equations can either be solved analytically, or for more complex models it is solved numerically. Ford (1999) notes that analytical solutions become infeasible once the differential equations become sufficiently complicated. As a rule of thumb, Ford (1999) suggests that any SD models with non-linear terms must be solved numerically. An example of the equation for the stock in Figure 3.3 is illustrated below in Equation 3.2:

$$\frac{dReservoir\ Storage_t}{\Delta t} = Reservoir\ Storage_{t-1} + Inflow_t + Precipitation_t \qquad (3.2)$$

$$-Outflow_t - Evaporation_t$$

Since the solution time step relies on Δt in this explicit calculation scheme, it is important for the modeler to use an appropriate value. As Δt becomes more refined numerical performance is enhanced, but this introduces complexity through requiring more iterations. At the maximum, Δt should be the same length of time as units of time in the model. For example, if the given reservoir model allocated water on a weekly time step, then Δt needs to be one week or less. If the modeler chose two weeks or more for Δt, then the system equations cannot be solved. Even if Δt is the same length as the system delay it still may not be adequate. Stocks with high volume flows may require a shorter Δt so that negative values do not occur within the stock. A general rule of thumb to choosing Δt is to choose the largest value that does not alter the results (Ford, 1999). For example, if a time step of 0.25 does not improve model accuracy significantly over a time step of 0.5, but a time step of 0.5 is an improvement over a time step of 1, then 0.5 should be used.

Though the chosen software to implement SD was VENSIM DSS, there are a variety of other potential platforms. There is no best overall platform, as each one contains their own strengths and weaknesses which must be considered for the task at hand. Commonly used SD platforms are Stella (isee systems, 2015), VENSIM, PowerSim (Powersim Software, 2015), and AnyLogic (AnyLogic, 2015). Stella is the most visually appealing of the aforementioned platforms, and is easy to learn- making this best suited for educational purposes. Another benefit of Stella is that it has a built in sensitivity analysis and many tools to build a model interface (e.g. slider bars, buttons, on/off switches, graphs, etc.). Although Stella is visually powerful, it lacks the additional tools available in the other platforms. Both VENSIM and Powersim contain additional analysis tools, providing for more robust modeling. These two softwares allow the user to optimize, perform sensitivity analyses, and provides a variety of additional functions not available in Stella. In addition, VENSIM DSS allows for Monte-Carlo Analyses and can model variables with subscripts (allows a model structure to be repeated as subscripts instead of rebuilding the structure to replicate). Powersim is especially powerful for business applications as it has a built in risk analysis tool. With these additional capabilities of VENSIM and Powersim comes an additional complexity on the part of the user, often making it difficult to learn this software. Another disadvantage with VENSIM, though minor, is the outdated looking interface and non-intuitive naming convention of variables. Finally, AnyLogic is a powerful SD platform with added capabilities to perform Agent-based modeling. The Agent-based modeling can be combined with SD in AnyLogic for hybrid modeling. The author has direct modeling experience with both Stella and VENSIM, but has relied upon product information and user reviews for information pertaining to Powersim and AnyLogic.

With considerations of the four SD platforms above, VENSIM was felt by the author to be the best choice for this project. The additional tools available in VENSIM over both PowerSim and Stella were felt to be supportive. As the $SWAMP_B$ is a complex model that will be further worked upon after the completion of this project, a robust tool was needed. Since the Agent-based option was not considered in the model building, VENSIM was found sufficiently powerful for modeling needs.

3.3 Model Construction

The BRB was emulated using the SD method discussed previously to produce $SWAMP_B$. By modeling the entire system in SD, with all components linked, the Water Allocation Component was coupled to both the TransAlta Component and the Irrigation Component. As $SWAMP_B$ is built in one modeling platform there is no need to link together multiple components. Each of these three components are not separate entities (e.g. individual models) but are groupings of model elements solely for coherency in describing the model. When executing the model all components are interacting at every time step. $SWAMP_B$ was able to dynamically calculate the water demands and allocations, as well as the resulting crop yields, hydropower generation and economic return. Considering this, the model was built as three major components: (1) Water Allocation, (2) Irrigation, and (3) TransAlta Utilities. Each component is not a model on its own, but a *process* representation within the overall $SWAMP_B$. Figure 3.4 illustrates how these three components interact. Black ovals represent user specified inputs and/or equations, red circles represent outputs from each component and the boxes and bolded arrows are the stocks and flows respectively. Dashed arrows illustrate how inputs and outputs are affected by and affect other components of the model.

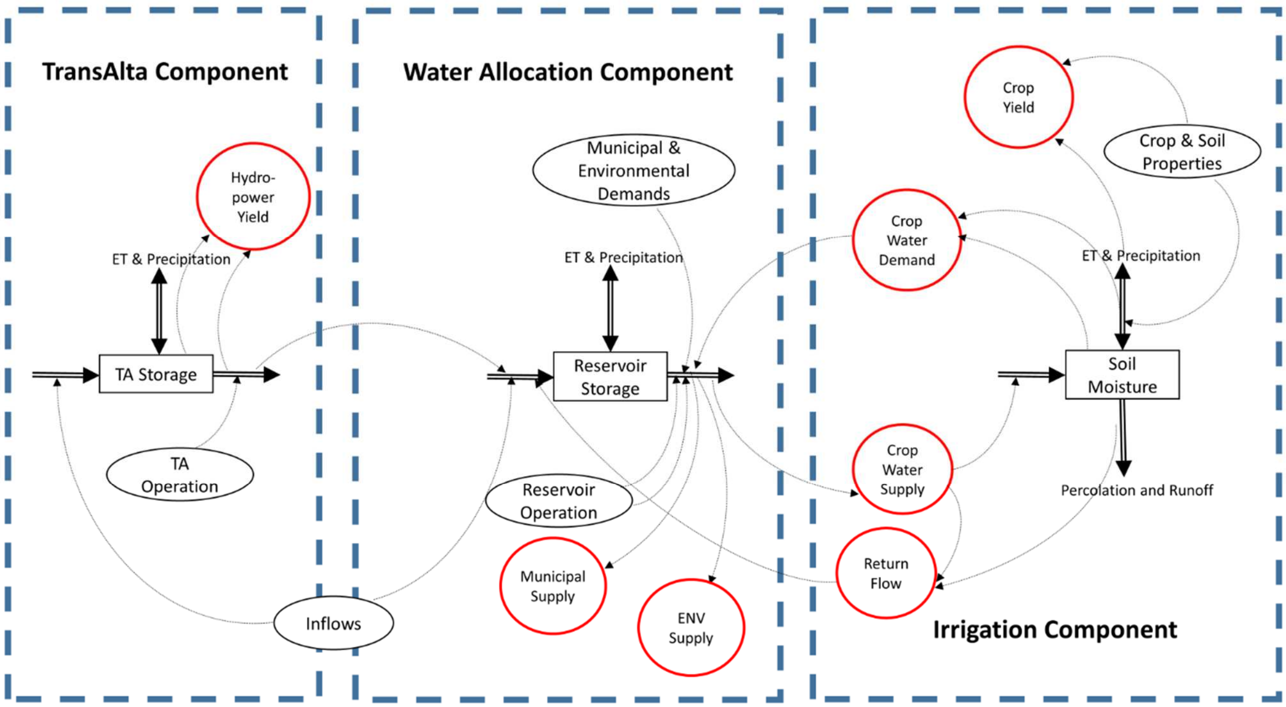


Figure 3.4- General Overview of $SWAMP_B$

The TransAlta and Irrigation components were not provided in the WRMM. Thus, these two components were needed to be developed as they affect the water allocation. Since the majority of the inflows to the BRB come from the headwaters, passing through the TransAlta reservoirs, it was important to model such a process. Inflows are stored and then released from TransAlta reservoirs, resulting in hydropower generation and inflows to reservoirs of the Water Allocation component. As seen, a small portion of inflows do not pass through TransAlta, but directly to the main model. Operation of reservoirs, illustrated in the Water Allocation component, requires operation rules and demands to determine timing and magnitude of releases. Releases from the Water Allocation component are linked to the Irrigation component by supplying water to crops, thus increasing soil moisture. Again, the Irrigation component is linked to the Water Allocation component by providing crop water demands based on soil moisture and Crop & Soil Properties. A strong synergy exists between the Irrigation and Water Allocation components, as the output from one is the input to another. This is a good example of the kind of feedbacks that an SD approach is well suited to model.

The components shown in the previous figure can be represented as a causal loop diagram. Figure 3.5 illustrates the relationships of the model components, representing positive and negative feedbacks. The available water in the system both affects, and is affected by various demands and allocations. One example of the strong feedbacks are the positive effects of available water on irrigation supply, which in turn increases soil moisture and decreases crop water demand, and a decrease in crop water demand decreases irrigation supply. This clearly illustrates that the economic return and water consumption have many feedbacks. The subsequent sections will describe the relations among the components in the previous figure, and explain specific equations relating to the causal loop diagram.

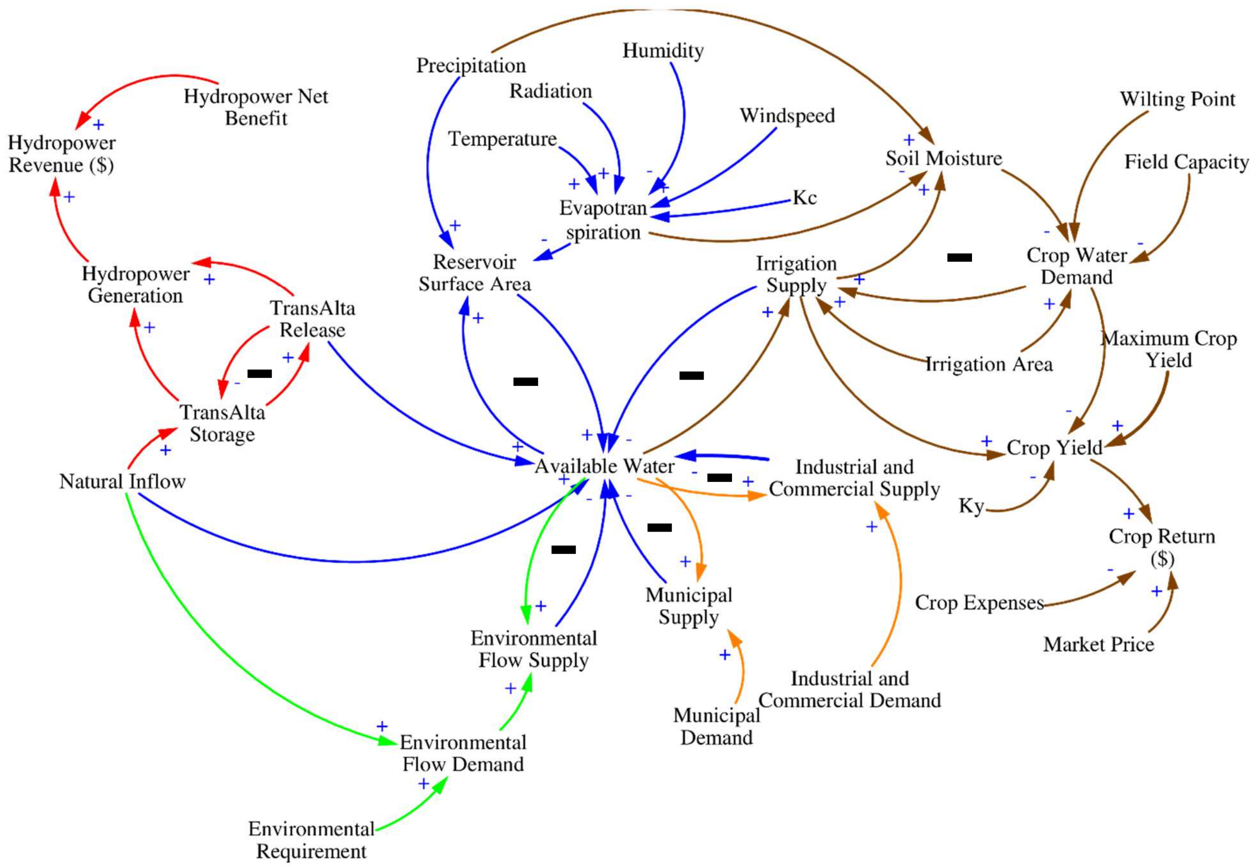


Figure 3.5- Causal Loop Diagram of $SWAMP_B$

3.3.1 TransAlta Component

WRMM provided operational rules only for components downstream of Ghost Reservoir. As seen in Figure 3.1, the upper left corner of the model has a yellow input arrow representing the TAU (TransAlta Utilities) model. In order to accurately account for the perturbation of natural flow into the BRB, and the production of hydropower, this section needed to be modeled. Since operation rules were not known, efforts were put forth to approximate this. Thus, a black box model was developed to provide outflows from the TransAlta system from known inflows. To coincide with the *main* $SWAMP_B$ model (components currently included in WRMM, not including the TransAlta model), the TAU model operates on the same temporal resolution of one week, and utilizes historical data from the same time period (1928-2001).

As seen in Chapter 1, Figure 1.2, there are 8 reservoirs between the headwaters and the input into the model. The operation of individual reservoirs as a system can be complex. This complexity was reduced by lumping the reservoirs into one surrogate reservoir, developing a system of one inflow, one outflow and storage. The TAU model could be thought of as a black box; flows enter the box and then leave the box as shown in Figure 3.6. Historical gauged data provided known inflows to the box and outflows were known (extracted from WRMM) for the same period (1928-2001). A linear regression model was developed to approximate the outflow from the system.

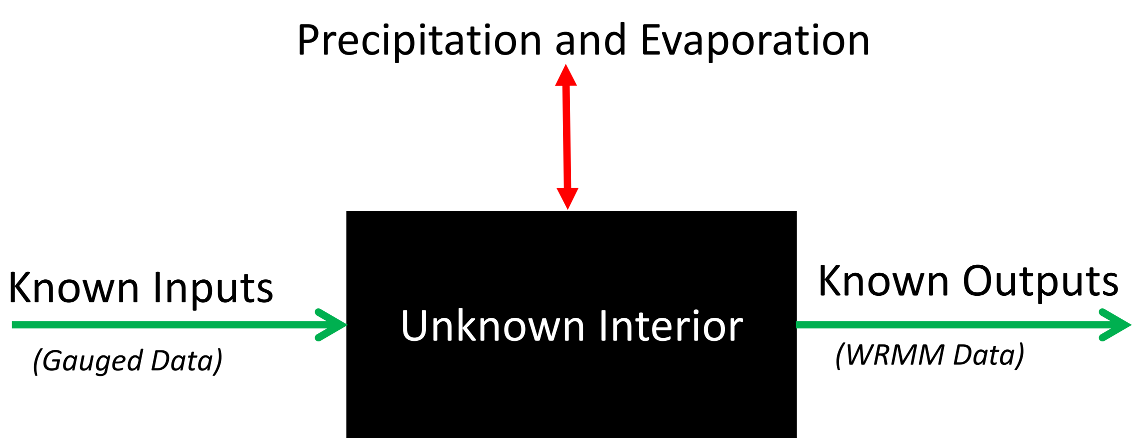


Figure 3.6- TransAlta Black Box Depiction of the TransAlta system.

At any given time (t), storage, inflow evaporation and precipitation were known, and release and $Storage_{t+1}$ needed to be determined. Release was calculated through linear regression based on the form of equation 3.3. Here the inflow was taken from weekly naturalized streamflow of the Bow River below Ghost dam (gauge# 05BE006), and the weekly precipitation and evaporation were monitored at Banff. Pan evaporation was used as a proxy for lake evaporation. From the black box system described above there were two variables that were needed to be determined: (1) *Release* from the TransAlta System, and (2) *Area* of the TransAlta system (rainfall and evaporation depth were known, but combined area of TA was not). Both of these unknowns were determined through two separate analyses. The following will describe how each was determined.

$$Storage_{t+1} = Storage_t + Inflow_t + Area * (Precipitation_t - Evaporation_t) - Release_t \quad (3.3)$$

From the given records both the precipitation and evaporation depths were known, as they were available from climate data. For precipitation and evaporation to be useful, an area needed to be known, such that the evaporation and precipitation depths can be converted to volume. A challenge with this was that in order to have a representative area of the TransAlta system the elevation or volume of each reservoir must be determined. Since the TransAlta system is quite complex and little was known about the operation rules, the storage of each individual reservoir was not considered. Thus, the real challenge here was approximating the TransAlta surface area without having to model the operation of each individual reservoir.

Approximation of the lumped reservoir area could not be made through constructing a volume-area curve. Since not all of the reservoirs fill evenly (e.g. all reservoirs at 50% capacity when the lumped system is at 50% capacity) one cannot develop a curve for the full system. To do this, assumptions would have needed to be made as to how the reservoirs fill. Since it was beyond the scope of this project to model each individual reservoir this approach could not be used. Instead, a feasible solution was to apply a ratio that can relate the lumped TransAlta storage to surface area. As shown in equation 3.4, an *area factor* could be multiplied by *storage volume* to approximate *area*. Although this solution was incorrect in assuming a fixed relationship between area and storage, it would have been be equally incorrect in assuming how the reservoirs are filled.

The *area factor* was determined through fixing the inflows (historical) and outflows (WRMM), and regressing to accurately model the lumped reservoir storage. Using data from 1928-2001 (simulation period of WRMM), the *area factor* was calibrated such that the modeled maximum lumped reservoir volume never exceeds the historical maximum volume in this period. This was done because the lumped reservoir outflow was obtained from WRMM, to attempt to emulate releases as represented by WRMM. Thus, it is inaccurate to match historical reservoir volume since the historical record is limited, and does not follow the same as from WRMM.

$$Area = Area\ Factor * Storage\ Volume \tag{3.4}$$

With the determination of lumped area in the preceding paragraphs, the determination of the lumped reservoir release is discussed. The release from the TransAlta system was modeled by linear regression, considering inflow, storage, precipitation, evaporation, and release. Equation 3.5 below shows the regression coefficients used in this calculation:

$$Release = A * Storage + B * Inflow + C \tag{3.5}$$

A, B, and C represent the regression coefficients. These coefficients were calibrated over a period from 1928-1970, and then validated from 1971-2001 (shown in results section). Since in reality the TransAlta system would follow operation rules it is imperative that equation 3.5 would reflect this. To do so, multiple Release equations were developed for different weeks of the year (e.g. one equation used for every week 1-3 of every year, another for week 4-6, etc.). With these multiple equations, A, B and C could be calibrated for specific seasonal conditions. In other words, the release was customized to approximate a set period of the year. The major drawback of calibrating by fixed weekly periods was that this method assumed that the same seasonal operations occur during the same weeks of every year. This is not true since climate change could cause freeze up and melt to occur at different times, as well as different policies may change the reservoir operation (e.g. stricter standards for environmental flow). Although these drawbacks exist, this method was still shown to produce adequate results in the historical period.

Using the seasonal equations developed, the hydropower generation was modeled as a function of storage and inflow. This release is generally calculated from the classic equation 3.6:

$$HP = e * Q * H \tag{3.6}$$

Where HP is power generation (MW), e is efficiency, Q (m^3/s) is reservoir release, and H (m) is head. Since neither the efficiency nor the head was provided, the equation was simplified to equation 3.7:

$$HP = f * Q * elevation \tag{3.7}$$

Instead of head (H), the reservoir storage elevation (m) is used as a proxy. f is a unitless factor that accounts for both the efficiency, and the difference between the actual head and reservoir elevation. The assumption was made that the head is linearly related to reservoir elevation.

The *f* factor was determined through calibrating the energy generation (MWhrs) in $SWAMP_B$ to match the historical average energy generation. TransAlta has historical average energy generation for their plants available, having a total of 767.2GWhrs per year in the Bow basin (TransAlta, 2013). Using this information, the *f* factor in $SWAMP_B$ was optimized using the VENSIM optimization tool, over 500 simulations.

The operational costs and power pricing from TransAlta Utilities were not known. Instead, prices were estimated based on Alberta's historical power pool prices. Weekly power prices used in $SWAMP_B$ for the simulations were the average weekly power pool prices from 2010-2015 (AESO, 2015).

3.3.2 Irrigation Component

The irrigation component runs for the entire year, over the simulation period. A simple hydrological calculation is included in this component, used solely for soil water balance calculation. Similar to water allocation, the hydrology of this component was represented at a weekly time step. Processes considered during all seasons were precipitation, evapotranspiration (ET), percolation, runoff, snow accumulation and snow redistribution and sublimation. These processes alter the soil moisture balance, as in equation 3.8:

$$SM_t = SM_{t-1} + P_t - RO_t - DP_t - AET_t - SR_t + IRR_t \quad (3.8)$$

where SM is soil moisture (mm), P is precipitation (mm), RO is runoff (mm), DP is deep percolation (mm), AET is actual evapotranspiration (mm), SR is snow sublimation and redistribution (mm) and IRR is water supplied by irrigation (mm). Neither runoff nor deep percolation contribute to streamflows in $SWAMP_B$, but simply is water lost. Runoff as calculated in this section does not apply to runoff in the headwaters that serve as flows for the entire model.

As noted above, the hydrological processes described in this section are only used for soil moisture balance estimation, not for the entire model. There are many assumptions in the present section, which are discussed in more detail below. It should be kept in mind that the irrigation component, though complex, is only one small portion of the entire $SWAMP_B$ model. At this point the purpose of the model is to aid in decision making, so the hydrology is simplified to promote computational efficiency and for consistency with readily available data. The aim of these equations is not to provide detailed hydrological simulations, but only sufficient detail to estimate crop demand and yield. Even with more detailed hydrology there would still be uncertainties pertaining to the irrigation infrastructure, specific cropping patterns used and other cropping factors not included (e.g. soil salinization and soil nutrients). Each of these variables will be further discussed in the proceeding sections.

During the irrigation season (varies by crop type) crop water demand, yield and return flow are calculated. Outside of the growing season the farms accumulate water from rainfall and snow accumulation, and lose soil moisture through percolation, runoff, evaporation and sublimation. To manage the hydrology, individual farms were aggregated into districts. Already, the EID, WID and BRID are existing districts, and are aggregated as such in the model. Non-district farms were aggregated spatially into two districts, one near Calgary and the other near Bassano. Although these two districts are not represented as such in reality, they were lumped solely for hydrological analysis. The precipitation and climate variables for each farm within a district are the same, as is the soil moisture

Crop water demand was calculated based on evapotranspiration (ET), soil moisture, and crop attributes. $SWAMP_B$ utilized methods proposed by Allen et al (1998) for determining actual crop ET (AET) from a reference ET (ET_0). ET_0 was defined by Allen et al (1998) as the ET that occurs over a uniform surface of grass of 0.12 m height, a surface resistance of 70 s/m and an albedo of 0.23 (Allen et al, 1998). This ET_0 was calculated in $SWAMP_B$ using the Penman-Monteith equation, as shown in equation 3.9. This method is physically-based, but is data intensive. Since Environment Canada collects radiation and wind speed data at suitable locations across Alberta, this equation was used in this study.

$$ET_0 = \frac{\left(0.408\Delta(R_n - G)\right) + \left(\gamma * \frac{1600}{T+273}\right) * u_2 * (e_s - e_a)}{\left(\Delta + \left(\gamma * (1 + 0.38u_2)\right)\right)} \quad (3.9)$$

In the above, R_n is net radiation (MJ/m^2/day), Δ is the slope of the vapor pressure-temperature curve (kPa/°C), G is ground heat flux (assumed zero since day heating and night cooling cancels out over periods of one week or greater as noted by Linacre (1993)), γ is the psychometric constant (kPa/°C), T is mean daily temperature (°C), u_2 is the mean daily wind speed at 2m elevation (m/s) and e_s and e_a are the saturated and actual vapor pressure (kPa). ET_0 was converted to the potential ET of the crop (ET_c) through equation 3.10, and converted to actual ET (AET) through equation 3.10.

$$ET_c = ET_0 \; x \; k_c \quad (3.10)$$

This crop coefficient (k_c) corrects ET to more accurately model the crop in question rather than the reference grass surface. Crop coefficients were provided for the initial, mid, and late crop growth stages to account for the effects of crop maturity on crop cover. Crop coefficients for crops available in $SWAMP_B$ are summarized in Table 3.1, provided by Brouwer and Heibloem (1986).

AET was determined utilizing the ratio of available soil moisture (soil moisture minus wilting point) and available water holding capacity (field capacity minus wilting point) as in Equation 3.11. Constraints were placed to ensure that the actual ET never exceeds to the potential

ET. In reality soil moisture exceeding the field capacity would percolate below the root depth or run off.

$$IF\ SM_t > FC$$

$$THEN,\ AET_t = ET_{ct}$$

$$Else, AET_t = ET_{ct}\ x\ \frac{SM_{t-1} - WP}{FC - WP} \tag{3.11}$$

Table 3.1 Crop Coefficient (*Kc*) of various growth stages for crops in the Bow

Crop		Initial	Mid	Late
Spring Wheat & Barley	Duration (weeks)	6	10	3
	value	0.3	1.15	0.25
Corn	Duration (weeks)	5	12	7
	value	0.3	1.2	0.6
Potato	Duration (weeks)	7	14	3
	value	0.5	1.15	0.75
Dry Bean	Duration (weeks)	4	7	4
	value	0.4	1.15	0.35
Flax & Canola	Duration (weeks)	4	10	6
	value	0.4	0.95	0.9
Alfalfa	Duration (weeks)	2	7	2
	value	0.95	1.05	1
Tame Pasture	Duration (weeks)	2	3	winter
	value	0.4	1	0.85
Sugar Beet	Duration (weeks)	7	12	5
	value	0.35	1.2	1

Both wilting point and field capacity were calculated as depth (mm) for each individual crop by multiplying the root depth of each crop by the field capacity (%) and wilting point (%) of the soil in the region. According to the Agroclimatic Information Services soil texture map, the irrigation districts have a medium (loam) soil texture (Alberta Agriculture and Forestry, 2015).

There are many factors that relate AET to crop yield, such as water stress and salinity. Since $SWAMP_B$ did not calculate soil salinity, it only considered the effect of water stress. Steduto et al (2012) recommended Equation 3.12 to relate water stress to crop yield:

$$Yield_t = MaxYield * \left[1 - Ky * \left(1 - \sum \frac{AET}{ET_c}\right)\right] \quad (3.12)$$

Equation 3.12 follows the logic that yield is proportional to the ratio of actual evaporation to potential evaporation, utilizing *Ky* as a coefficient to account for non-linearity. This allows crops sensitive to drought (such as corn) and crops resilient to drought (such as wheat) to be modeled as such using the *Ky* factor. *Ky* factor and Maximum Yield for various crops are presented in Table 3.2. This calculation averages the evapotranspiration ratio over the period of the growing season, thus only producing an annual yield. $SWAMP_B$ sums up the weekly values of each year to produce the annual value.

Table 3.2- Maximum Yield and Yield Response to Water for crops in the Bow Basin

Crop	Maximum Yield	Yield Response to Water (K_y)
Alfalfa	18 Mg/ha Bennet and Harms (2011)	1.1 Bennet and Harms (2011)
Barley	7.3 Mg/ha Bennet and Harms (2011)	1.1 Najarchi et al (2011)
Canola	3.9 Mg/ha Bennet and Harms (2011)	0.37 Bilibio et al (2014)
Corn Silage	44.8 Mg/ha Bennet and Harms (2011)	1.25 Steduto et al (2012)
Dry Bean	3.6 Mg/ha Bennet and Harms (2011)	1.15 Bennet and Harms (2011)
Spring Wheat	7.8 Mg/ha Bennet and Harms (2011)	1.15 Bennet and Harms (2011)
Tame Pasture	1.37 Mg/ha Alberta Agriculture and Rural Development (1998)	1.05 Prendergast (1993)
Flax	2.2 Mg/ha Malhi et al (2007)	1 Assumed, no value for Alberta available
Potato	67.2 Mg/ha Bennet and Harms (2011)	1.1 Bennet and Harms (2011)
Sugar Beet	81.5 Mg/ha Bennet and Harms (2011)	1.1 Bennet and Harms (2011)

Once crop yield is determined, the model then calculates the economic return as in Equation 3.13, simply as price minus costs. Both the market price and costs were unchanging in the model, utilizing the most recent values in Alberta (Agriculture and Rural Development, 2015). The following costs were considered: seeds, fertilizer, chemicals, insurance, trucking and machinery, building maintenance, irrigation, utilities, labor, operating interest, any custom work, and storage (potato and beets only). Depending on the crop, the yield was either reported as bushels or mass (Mg). Since yield is calculated on an annual basis in $SWAMP_B$ the net return was also represented as an annual value.

$$Crop\ Return\ (\$) = Market\ Price\ (\$/unit) * Crop\ Yield\ (units) - \sum Crop\ Costs\ (\$/ha) * area(ha) \qquad (3.13)$$

Crop water demand was calculated for each individual crop, of each individual irrigation district. Figure 3.7 illustrates a typical *Stock* for each cop to be modeled. Although each crop has the same variables, flows, and stock, the values for each differ. Crop water demand was based solely on the soil moisture depletion, which is a function of the hydrological processes governing soil moisture. The hydrological processes governing the water balance in prairie watersheds are quite complex. A central theme to the prairies is the "fill-and-spill" mechanism that controls runoff and infiltration. The connectivity of such regions is often dynamic, developing differently under wet and dry conditions (Shaw et al., 2012). Because of this pothole landscape and unsaturated soils, very little runoff occurs from precipitation; the majority of runoff occurs from snowmelt (Van der Kamp et al., 2003). With deposits of glacial till, there is very little movement of groundwater in this region (Van der Kamp and Hayashi, 1998). In light of this unique hydrology, simplifications were made to reduce the data requirement of $SWAMP_B$. By taking advantage of limited groundwater influence and minor rainfall runoff, a simplified means to quantify infiltration was implemented.

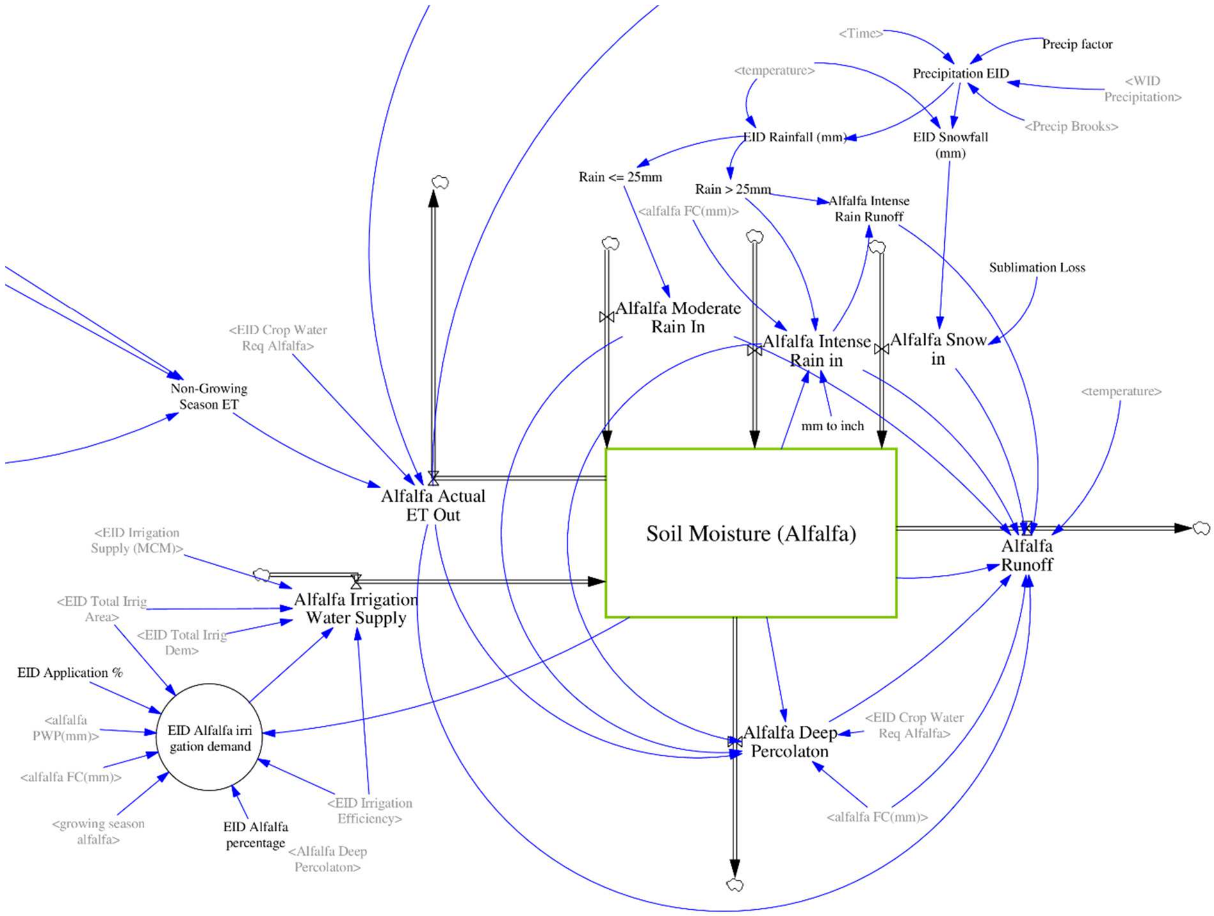


Figure 3.7- Stock-Flow Diagram of Typical Alfalfa crop in Alberta

There are several computational methods for determining infiltration into soil considered. Both the Horton (1939) method and the Green and Ampt (1911) are suitable for iteratively approximating infiltration with basic soil parameters. The issue with these formulations is that the accuracy is dependent on the time resolution of the iteration. Since the irrigation model operates on a weekly resolution, iterating with either the Green and Ampt or Horton method would be unrealistic. The distribution of rainfall over the one-week time step is only represented as one aggregate value, so the evolution of the wetting front over one week is not known. Instead, the Baier and Robertson (1966) approach was used to calculate infiltration and runoff, as it relies on a simple empirical formulation and does not require a fine temporal resolution. The empiricism accounts for the inverse nature of soil moisture saturation to infiltration rate. Although this method over-simplifies the runoff complexities in the prairies (e.g. frozen soils), it provides a simple estimate that can be used for soil water balance calculation. This formulation can be improved in subsequent work, but for the work presented it is a simple estimate.

Precipitation was modeled to undergo several processes before accumulating in the soil moisture stock, as shown in Figure 3.8. First, the total precipitation was separated into either rainfall or snowfall depending on the temperature. It was assumed that the threshold between rain and snow is zero degrees Celsius. Since not all rainfall would infiltrate into the soil (sufficiently intense rainfall would produce runoff) a classification needed to be made between rainfall intensities. Baier and Robertson (1966) prescribed a simple empirical formulation for runoff, as shown in equations 3.14 and 3.15, which only require rainfall, soil moisture and field capacity. Variables in equation 3.15 are shown in mm here, but the original formulation uses inches. Their methodology classified all rainfall less than 25mm/day as *moderate rainfall*, which fully infiltrates. Intensities greater than 25mm/day is classified as *intense rainfall* and is subject to equations 3.14 and 3.15.

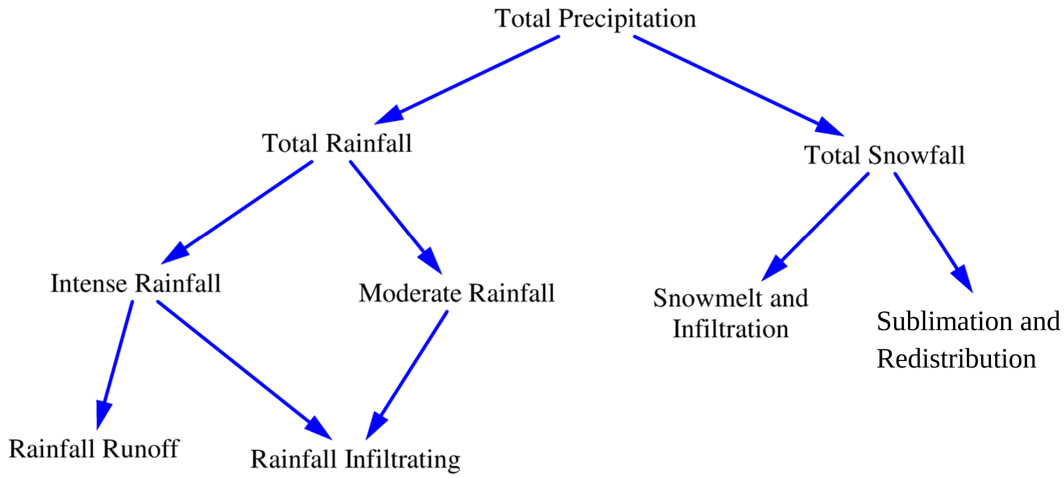


Figure 3.8- Tree diagram depicting the eventual fates of precipitation

$$RO_t = R_t - IN_t \tag{3.14}$$

$$IN_t = 0.9177 + 1.811 * \ln(0.03937 * R_t) - 0.0097 * \ln\left(\frac{SM_{t-1}}{FC}\right) * 100 \tag{3.15}$$

where R is total rainfall (mm), RO is runoff (mm), IN is infiltration (mm), SM is soil moisture (mm) and FC is field capacity (mm). When temperature is below 0°C precipitation is in the form of snowfall. Infiltrability of frozen soils is variable, with dry structured soils able to infiltrate almost all snowmelt water and saturated soils having very little infiltration potential (Gray, 1985). For simplicity it was assumed that the snow not redistributed and sublimated would contribute directly to soil moisture. In reality snow melt would contribute to runoff, but $SWAMP_B$ does not consider freezing and thawing of soil, nor does it consider complex energy processes governing melt rate. Without accurate determination of melt rate and soil temperature an accurate runoff cannot be determined. Furthermore, in prairie regions where wind speed is high, as much as 58% snow can be lost due to transportation (Pomeroy and Li, 2000). Sublimation in these regions vary, but Pomeroy and Gray (1995) estimate on average 20% of annual snow volume is sublimated. Since calculations of sublimation and snow melt required many meteorological variables that may not be available, a constant loss of snow due to the combined sublimation, redistribution, and melt runoff value of 75% of the total snowfall was assumed in the model. Thus, if 100 mm of snow falls, 75 mm would be lost due to sublimation, redistribution and melt runoff.

Both percolation and runoff utilized simple equations, as $SWAMP_B$ only considered one soil layer and did not consider percolation and runoff during winter (e.g. T < 0°C). Runoff caused by *intense rainfall* was accounted for by equation 3.14. Runoff due to snow melt is not considered separately as the previously defined 75% snow loss accounts for this. Percolation was activated only if the soil moisture was at field capacity, and only served to bring water levels back to field capacity. Since each simulation step is one week, it was assumed there is sufficient time to percolate any volume of water over that time period. Pseudo-code for percolation is shown in equations 3.16-3.18:

$$IF, SM_{t-1} + P_t + IRR_t - AET_t - RO_t \geq FC \quad (3.16)$$

$$Then,\ DP_t = (SM_{t-1} + P_t + Irrigation_t - AET_t - RO_t) - FC \quad (3.17)$$

$$Else,\ DP_t = 0 \quad (3.18)$$

The value of demand was calculated to bring the soil moisture to acceptable levels. In the irrigation districts of Alberta the aim of irrigation is not to bring the soil moisture to field capacity, even though this would be optimal. Instead irrigators generally try to achieve a soil moisture between 50% and 90% of field capacity (IWMSC, 2002). To reflect this variability in soil moisture demand, a trigger was specified in SWAMP. The *Soil Moisture Trigger* (referred to as β) specifies what percentage of field capacity to irrigate crops. A Soil Moisture Trigger of 0.8 would mean that once soil moisture drops below 80% of field capacity, $SWAMP_B$ will trigger a demand to raise the moisture back up to 80% of field capacity. Default values of β were set to closely match $SWAMP_B$'s crop water demand with that specified by WRMM. The determination and results of the β value is further discussed in Chapter 4.

The demand for each crop was calculated individually, and then multiplied by a ratio, to determine an average demand. For example, if a given district has 90% wheat and 10% potato by area, then the district demand would be [0.9*wheat demand + 0.1*potato demand]. Similarly, when water was allocated to an irrigation district, each crop received water as a percentage of its demand against the overall irrigation demand. Crop demand and supply are summarized in equations 3.19-3.22:

$$IF\ SM_{t-1} < \beta * FC, \tag{3.19}$$

$$Then, Crop\ Demand_t = \frac{GS_t * Crop\ \% * District\ Area * (\beta * FC - SM_{t-1})}{E} \tag{3.20}$$

$$Else,\ Crop\ Demand_t\ = 0 \tag{3.21}$$

$$Crop\ Supply_t = E * \left(\frac{District\ Supply_t}{District\ Area}\right) * \left(\frac{Crop\ Demand_t}{Distict\ Demand_t}\right) \tag{3.22}$$

β (%) is the soil moisture trigger, representing the threshold at which soil moisture must fall below before irrigation is applied. District Supply (MCM), District Demand (MCM) and District Area (m^2) are the water allocated to, demanded by, and the area of one of the irrigation districts (EID, WID, BRID or private irrigation), respectively. This supply and demand are not necessarily the same because insufficient streamflow and reservoir storage will not always meet district demands. The demand of, and water supplied to, each individual irrigation demand node was lumped as a district demand or supply. Crop Water Demand represents the demand of an individual crop (e.g. Canola) within a district. The ratios seen in Equation 3.22 apportion the total water supplied (District Supply) among each crop weighted by their respective Crop Demand. Finally, Crop Water Supply was multiplied by E, Irrigation Efficiency (%), representing the amount of irrigated water that contributes directly to soil moisture. Irrigation efficiency was determined from the 2013 values provided by Alberta Agriculture and Rural Development (2013), with EID, WID, BRID, and private irrigation having efficiencies of 0.78, 0.77, 0.8, and 0.82, respectively. These values reflect each district's progression towards low pressure irrigation systems (E = 82%).

Return flow was specified as five percent of the total water supplied. In Alberta, return flow is variable, but IWMSC (2002) suggests 5% is a suitable value for projected irrigation practices. $SWAMP_B$ does not contain any components modeling the water lost due to conveyance (e.g. seepage) so a constant value is assumed. Without a "modeled" value for return flow, an estimate based on current practice is used. To simulate the lagged return flow, a fixed-delay was used in VENSIM to delay return flows by one week. This lag ensures that there is no circular use in water.

3.3.3 Water Allocation Component

The $SWAMP_B$ model only allocates water for the Bow basin, unlike WRMM that allocates for the entire SSRB in Alberta. Normally to specify the outflows from the Bow to another basin (e.g. release from McGregor Reservoir to Oldman) requires information of the downstream basin. Hence, a model is required to calculate demands and constraints in the downstream basin.

Currently, as the Oldman and Red Deer models are not available within the SWAMP framework, boundary conditions were used. The user specifies outflows from Red Deer to the apportionment, flows from the Oldman basin to the South Saskatchewan River, and the release from the McGregor Reservoir (See Figure 3.9). These flows and releases were obtained from WRMM. In the future, once the Red Deer and Oldman river basins have been linked with $SWAMP_B$, these boundary conditions can be calculated by the model.

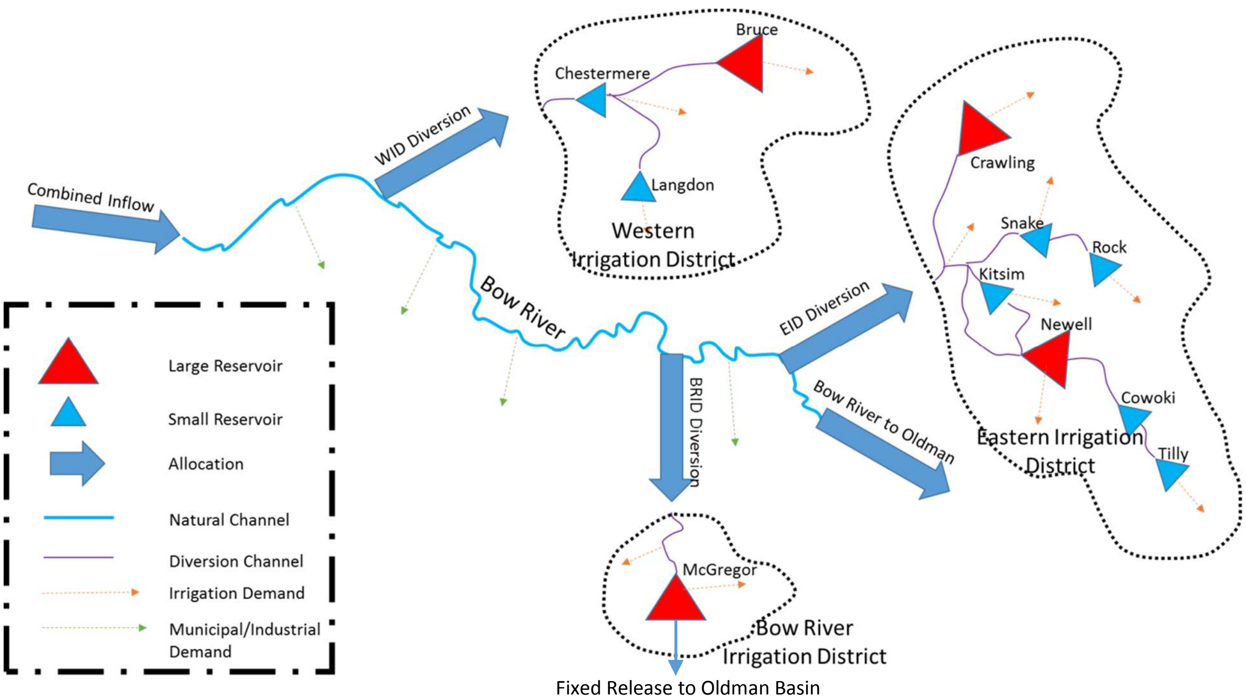


Figure 3.9- Simplified illustration of the Bow River Basin as implemented in $SWAMP_B$ and WRMM. Large red triangles represent the largest reservoirs in the basin.

SWAMP$_B$ allocates water to the same demand nodes as present in WRMM, utilizing the same priorities. The only difference is that the irrigation demand nodes have been lumped by district, as mentioned previously. Priorities in WRMM are defined by penalty values, but SWAMP$_B$ has no such penalty-based system. Instead, allocation priorities were modeled through the use of "If-Then-Else" statements. When demands of a higher priority allocation are met, the model progressively allocates water to lower priority demands. These prioritized demands are present in consumptive demands (municipal and irrigation), flow demands (environmental, hydropower, and diversion channels), and level demands (reservoir rule curves to ensure reservoirs are filled and to prevent spills).

A simple example of the allocation scheme in SWAMP$_B$ is illustrated in Figure 3.10. Here there are two nodes, Node 2 and Node 235, each connected to different flows (blue and purple arrows) and demands (hexagons). At Node 2 SWAMP$_B$ would allocate the flow from *Inflow* to the cluster of major demands, the 'Diversion to WID' and downstream flow consisting of the environmental flow demands and major and irrigation demands. For simplicity this diagram does not show all linkages, but in SWAMP$_B$ all demands downstream node 2 would be connected to Node 2. Node 2 would allocate demands by priority, then Node 235 would allocate by priority, based on all water not allocated to "Node 2 Major Demands" or "Diversion to WID", and so on.

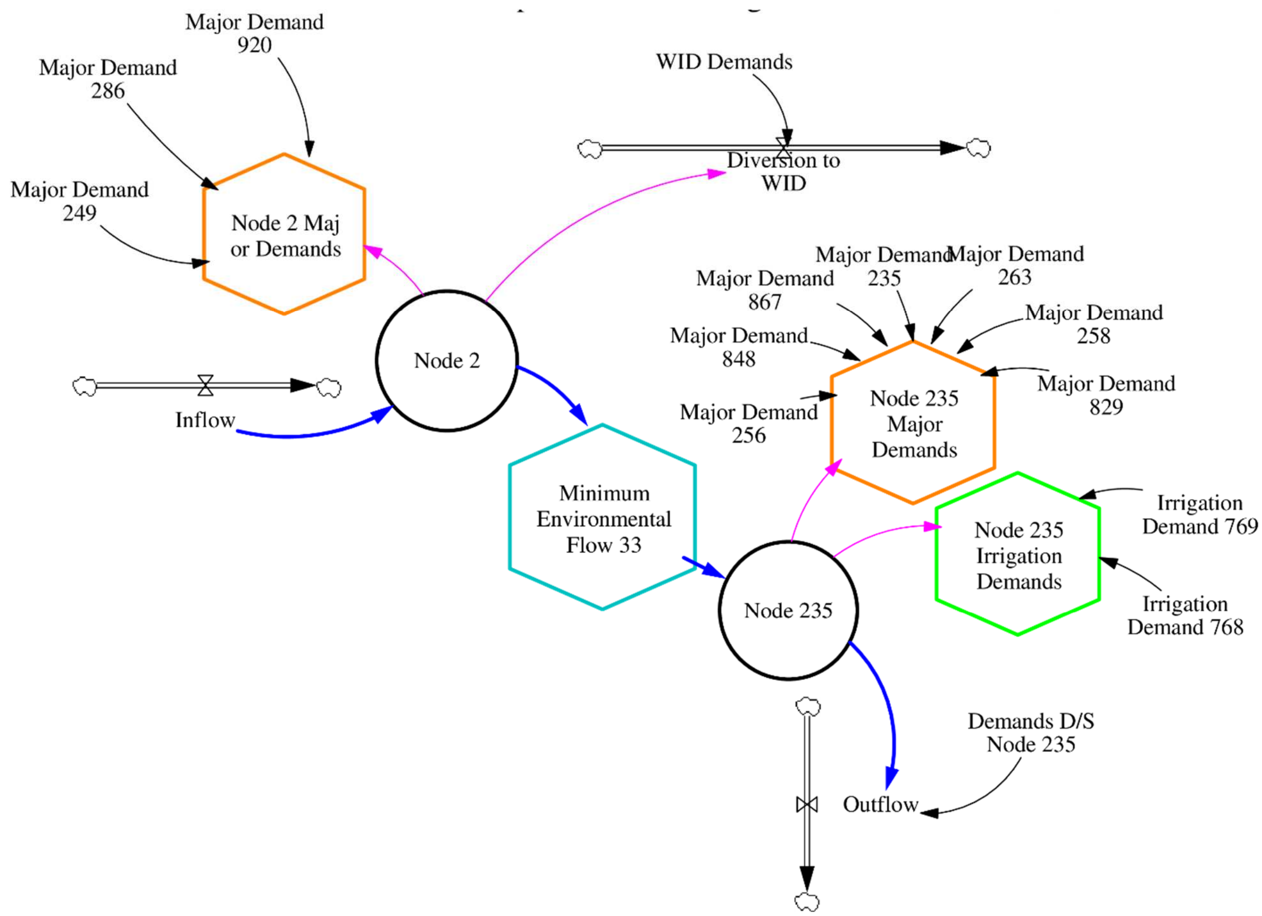


Figure 3.10- Simplified Diagram of Model Allocation at Node 2 and Node 3. Blue arrows represent natural flow channels and purple arrows represent diversion channels

Consider a simple example to illustrate this allocation. Suppose that a hierarchy of demands is set up in this way, from highest to lowest priority: (1) WID Demands, (2) Minimum Environmental Flow 33, (3) Node 2 Major Demands, (4) Node 235 Major and Irrigation Demands, (5) Demands D/S Node 235. A series of equations to allocate from Node 2 would follow:

$$WID\ Supply = MIN(WID\ Demands, Flow\ U/S\ Node\ 2, Max\ Diversion) \tag{3.23}$$

$$Environmental\ Flow\ Supply \tag{3.24}$$
$$= MIN(Inflow - WID\ Supply, ENV\ Flow\ Demand)$$

$$Node\ 2\ Major\ Supply = MIN(Inflow - WID\ Supply - ENV\ Supply, Node\ 2\ Major\ Demands) \tag{3.25}$$

$$Node\ 235\ Irrigation\ and\ Major\ Supply = MIN(Inflow - WID\ Supply - ENV\ Supply - Node\ 2\ Major\ Supply, Node\ 235\ Demands - ENV\ Flow\ Supply) \tag{3.26}$$

$$Outflow = (Inflow - WID\ Supply - ENV\ Supply - Node\ 2\ Major\ Supply - Node\ 235\ Irrigation\ and\ Major\ Supply) \tag{3.27}$$

Equations 3.23 to 3.27 above represent a kind of allocation scheme present in $SWAMP_B$, though the example above has very few components. It is shown in these equations that each allocation not only considers demand, but the water available. As the hierarchy of demands is progressively met, water available is depleted, and updated as seen in equation 3.23 (e.g. Inflow – WID Supply). As evident, $SWAMP_B$ considers constraints on the allocation. In equation 3.23, not only does the allocation consider supply and demand, but also the diversion constraints of that channel. With flow requirements $SWAMP_B$ must allocate to serial demands, demands in which one allocation feeds to another. This is shown in equation 3.25 where the Node 235 Major and Irrigation Supply has a condition of the demands minus the ENV Flow Supply. Since flow was already allocated downstream of Node 2, this flow can then be reallocated to other uses. Not only do nodes function in this manner, but reservoirs also operate following a hierarchal system. Reservoirs are more complex as they must also consider evaporation, precipitation and the elevation rule curve.

A typical reservoir, as modeled in $SWAMP_B$, considered inflow, outflow, precipitation and evaporation. Inflows either come from naturalized flow data, or as releases from upstream reservoirs. The outflows were constrained by both reservoir requirements (storage rule curves) as well as downstream demands. Both precipitation and evaporation were estimated using data from Environment Canada. Weekly evaporation depth from reservoirs was calculated using the Penman equation, utilizing the Shuttleworth (1993) modification to allow for SI units, as shown in Equation 3.28:

$$E = \frac{\Delta * R_n + 6.43\gamma * (1 + 0.556 * U_2) * (e_s - e_a)}{\lambda * (\Delta + \gamma)} \tag{3.28}$$

where E is evaporation (mm/day), Δ is the slope of the saturation vapor pressure temperature curve (kg/°C), R_n is net radiation (MJ/m^2), γ is the psychometric constant (MJ/kg), λ is the latent heat of vaporization (MJ/kg), U_2 is the wind speed at 2m elevation (m/s), e_a is the vapor pressure (kPa) and e_s is the saturated vapor pressure (kPa). R_n was calculated as in equation 3.29:

$$R_n = 0.0864 * \left(\alpha R_s * 24 * {}^{100}/_{8.64} - 40\right) \tag{3.29}$$

where Rn is in MJ/m^2 and Rs is the incoming solar radiation (MJ/m^2) and the albedo (α) is assumed 0.8 for open water (Allen et al, 1998). The other coefficients in Equation 3.29 are for converting W to MJ and MJ to W over a period of 24 hours. The weekly evaporation depth (as determined in Equation 3.22) and precipitation depth were converted to volume through available elevation-volume relationships.

Major demands (municipal and industrial users) were not calculated in $SWAMP_B$, but provided from a table using a lookup function in VENSIM. These values were extracted from WRMM, which are Alberta's projections of water demand in 2015 calculated from 2010. By accessing the tables, users can specify different values. All major demands are fixed values that have no interaction with climate. Minor demands were modeled the same way as Major demands, but given the highest priority in the model. However, the flexible simulation environment of $SWAMP_B$ allows for building sub-models to dynamically calculate and update such demands if needed.

As seen in Figure 3.9, there are three arrows representing demands for each of the irrigation district licenses. These can be thought of as a guaranteed diversion, as a function of naturalized flow at the headwaters. The current version of $SWAMP_B$ looks up naturalized flow values from a table specified by the user, and then performs a calculation as in Table 3.3. The Weekly Flow Requirements are the thresholds at which determine the allotted license demand. Flow in this case is the flow of the Bow River directly downstream of the TransAlta reservoirs. These flow requirements allow the district demands to adapt to changing flows. During low flow periods the allotted license decreases to keep more water in stream, and less conservative during high flows.

Table 3.3- Maximum Allocation for Irrigation Districts

District	Season (period in weeks)	Weekly Flow Requirements (MCM)	Weekly License (MCM)
Eastern (EID)	18-39	Flow<110.68	17.13
	18-39	Flow≥110.68	51.38
	All other	N/A	0
Western (WID)	17	N/A	5.87
	18-39	Flow<93.74	6.85
	18-39	93.74≤Flow<181.44	10.28
	18-39	Flow≥181.44	12.85
	All other	N/A	0
Bow River (BRID)	19-40	N/A	BRID upstream McGregor + 5.87

An important distinction is that these irrigation license demands are not the same as the crop water demands. License demands are water allotments that are purely a function of the upstream flow, as described in Table 3.3. In reality these are promised diversions to the irrigation districts that follow the licensing structure of Alberta, regardless of crop water needs. The true demands of the crop are for crop water use, calculated as a function of soil moisture (discussed previously). In most cases the license demands exceed crop water demands, diverting water based on upstream flows. Both during low flow periods, and periods with sufficiently large crop water demands, the crop water demands could exceed the license demands. Both WRMM and $SWAMP_B$ allocate water to the irrigation districts on a priority basis- first allotting to the license demands (once all higher ranking demands are satisfied), then satisfying any crop water demands not met by the license (again, once all higher ranking demands are satisfied). This allocation is simplified in Equations 3.30-3.32:

$$If\ License\ demand \geq Crop\ Water\ Demand - District\ Water\ Available \tag{3.30}$$

$$Then, District\ Supply = Licence\ Demand \tag{3.31}$$

$$Else, District\ Supply = (Crop\ Water\ Demand - District\ Water\ Available) - License\ Demand \tag{3.32}$$

In Equations 3.30-3.32 the *District Water Available* is the combined reservoir storage in each district, above minimum storage (or if multiple zones, volume of water in zones with less penalty than crop water demands). For example, if the combined storage of Bruce Reservoir, Chestermere Reservoir and Langdon Reservoir was 100 MCM, and the combined minimum storage was 60 MCM, then the District Water Available would be 40 MCM. These equations do not show the numerous constraints imposed by penalties elsewhere in the model, and operation of reservoirs and diversion channels. An example of this would be if providing the full license demand would cause reservoirs to fill beyond their flood zone, even after satisfying crop water demands, then the *District Supply* would be less than the *License Demand*. Another example could be if diverting the license demand exceeds high priority environmental constraints or does not leave enough water for higher priority demands downstream, then the *District Supply* would be further reduced to accommodate this. The apportionment requirement to Saskatchewan was modelled similar to WRMM, using two priority zones. A high priority (above most major demands, but lower than district irrigation licenses) was placed to always meeting 40% of the apportionment target. Next, a lower priority was placed on meeting the full apportionment target (as outlined in section 1.0). Like the district license demands, apportionment values were calculated based on naturalized inflows that the user can specify. Since the apportionment target was calculated for the entire SSRB (not just the Bow), $SWAMP_B$ only calculated the apportionment demand for the Bow's contribution. The user specifies the contribution of the Oldman and Red Deer basins to the apportionment as fixed time series, and the requirement for the Bow is the apportionment target minus the Oldman and Red Deer contributions. Approximately, 40% of the total SSRB apportionment to Saskatchewan comes from the Bow during the historical period used in this study (1928-2001).

3.4 Model Verification

The validity of $SWAMP_B$ as an emulation of WRMM was assessed through a verification process. The purpose of this was to ensure that structure and assumptions inherent of $SWAMP_B$ are credible, and able to approximate WRMM to a satisfactory degree. In the literature there are two terms often used to measure and prove the credibility of a model- validation and verification. Mihram (1972) classified verification as the process of ensuring the underlying structure of the model is correct, whereas validation was ensuring that the model output simulates reality. In a system dynamics context Qudrat-Ullah (2011) and Barlas (1989) just use the term *validity* to measure the acceptability of a model- but separate *model validity* into *structure verification* and *parameter verification*. Structure verification ensures the structure of the model is consistent with knowledge available, and parameter verification ensures parameters in the model are consistent with knowledge available. For simplicity, this work just considered the terms *verification* and *validation*. Similar to Mihram's (1972) classification, verification only tests adequacy of model structure and validation tests adequacy of specific parameters (such as the calibration and validation process). Since $SWAMP_B$ has few parameters to be tuned, the majority of the work was in verifying the structure. The TransAlta component is the only component to be validated, as a structure is assumed, and only specific coefficients are calibrated through a formal regression process (e.g. the reservoir release equation is always assumed linear, and only the regressed coefficients are tuned).

The verification of $SWAMP_B$ was performed in two stages. First, a *structural* verification ensured that $SWAMP_B$ is allocating water in the same way that WRMM does, when under the same conditions. Since WRMM is already in use by Alberta, it was a good baseline to compare to. Once the structure was seen as adequate, then the second stage of verification occurred. This second stage validated that the TransAlta system and Irrigation Components provided realistic values.

The model structure of $SWAMP_B$ was verified at a micro and a macro scale, as illustrated in Figure 3.9 (found in section 3.3). The four largest reservoirs in $SWAMP_B$, represented as red triangles, as well as the three district diversions, represented as blue arrows, are components that were verified. First the micro scale was verified- the operation of individual reservoirs with fixed inflows. This initial verification considered four “large” reservoirs, one for each of the Western Irrigation District (WID), and Bow River Irrigation District (BRID), and two reservoirs within the Eastern Irrigation District (EID). These reservoirs were chosen as it is the minimum number of largest reservoirs to contain at least one in each irrigation district. The four reservoirs were simulated with the same diversions in $SWAMP_B$ as in WRMM. By having the same diversions the only inaccuracies occurring would be with the reservoirs operation rules. Once the reservoir operations are seen to be represented adequately in $SWAMP_B$, then the accuracy of the model as a system was examined.

The macro scale considered the operation of the system as a whole. This verification was performed in two stages. First, the flow to the Oldman basin, as well as diversions to the irrigation districts, shown as blue arrows in Figure 3.9 (found in Section 3.3), were verified. The flow to the Oldman basin is not equal to the naturalized flow, due to operations of upstream reservoirs and water withdrawals. Verification of flow to the Oldman basin quantifies the ability of $SWAMP_B$ to allocate water considering these flow alterations. Similarly, verification of the irrigation district diversions illustrates $SWAMP_B$’s ability to prioritize allocations similarly to WRMM. Second, the four reservoirs verified at the micro level (fixed inflows) were then verified under inflows that were modeled by $SWAMP_B$. In this second stage errors can accrue not just from reservoir operations, but also from the feedback inherent to the surrounding licenses, demands and flow requirements. Once it was demonstrated that the system as a whole is adequate then the structure of $SWAMP_B$ is accepted.

With a structurally sound model, $SWAMP_B$ was then examined in comparison with historical data. Because $SWAMP_B$ is an emulation model, it is most important for it to emulate WRMM, and a verification against historical values is secondary. Here, the performance of the complete $SWAMP_B$ was compared by examining the operation of McGregor Reservoir, and flow in the Bow River. Because data for other large reservoirs (Crawling Reservoir, Bruce Lake and Lake Newell) were not available for a continuous period of more than a decade, it is difficult to verify a period representative of the $SWAMP_B$ simulation period. For this reason only McGregor reservoir was used to verify historical data.

All four verifications (structural, TransAlta, irrigation component, and comparison with historical records) utilized the error measures of R^2, RMSE, and Nash-Sutcliffe efficiency (NSE). Legates and Cabe (1999) recommended at least one dimensionless and one absolute error measurement when evaluating models, as some measure over-exaggerate errors with high-magnitude values and other over-exaggerate errors of low magnitude. By using these three error measures the error is represented both dimensionally and non-dimensionally. NSE is also useful as it compares the model's ability to predict over averaged observed values, with positive values indicating the model predicts better than just assuming average observed values. Aside from these error measures, graphical comparisons are utilized to better illustrate any biases not apparent in numerical error measures. Even if some error measures show poor performance in $SWAMP_B$, a graphical representation can still suggest a cause for these errors. In some instances (such as reservoir operation), the values of $SWAMP_B$ and WRMM may not match, but the trends will be important. The equations for these three error measures are shown in Equations 3.33, 3.34 and 3.35:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N}} \tag{3.33}$$

$$R = \frac{\sum_{i=1}^{N}(O_i - \overline{O})(P_i - \overline{P})}{[\sum_{i=1}^{N}(O_i - \overline{O})^2]^{0.5}[\sum_{i=1}^{N}(P_i - \overline{P})^2]^{0.5}} \tag{3.34}$$

$$E = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \tag{3.35}$$

Where O is observed values (WRMM for structural validation), P is predicted values ($SWAMP_B$) and $\bar{O}$ and $\bar{P}$ are the averages of both.

3.5 Climate and Streamflow Data

For the historical period of 1912-2001, climate and streamflow data were available from Environment Canada, with radiation, humidity and wind speed downloaded from the Canadian Weather, Energy, and Engineering Dataset (Environment Canada, 2015). The historical simulation period of the model was from 1928-2001, since this is the extent of the simulation period modeled by WRMM. In other words, 1928-2001 is the extent of the period in which direct comparisons between WRMM and $SWAMP_B$ can be made. Precipitation, radiation, and wind speed data availability were variable across the Bow for the entire simulation period. Much of the data were unavailable during the earlier simulation period (e.g. before 1950). For this reason only precipitation and Temperature at Banff, Calgary, and Medicine Hat were considered. Multiple gauges were available for each location, so an average precipitation and temperature across all gauges within the specific location were used. Radiation data (for ET) is only available for Calgary and Medicine Hat from 1953 – current. Since earlier radiation data were not available, they were recycled during unrecorded periods. A summary of the data used is shown in Table 3.4.

Table 3.4- Summary of Climate and Streamflow Data Used by SWAMP$_B$

Model Component	**Gauge**	**Data Type**	**Source**	**Years Available**
TransAlta Inflow	05BE006	Naturalized Flow	Env. Canada	1912-2001
Highwood Inflow	05BL024	Recorded Flow	Env. Canada	1912-2001
Bearspaw Inflow	BPAW LOCL	Calculated Flow	WRMM	1928-2001
Elbow Inflow	05BJ001	Naturalized Flow	Env. Canada	1912-2001
Calgary Local	05BH004 - 05BH008	Recorded Flow	Env. Canada	1912-2001
Calgary Precip	3031093, 3031094, 3031102, 3031107, 3031108, 3036652	rain and snow	Env. Canada	1885-2012
Calgary Average Temperature	3031090, 3031093, 3031094, 3036652	Average Daily Temperature	Env. Canada	1885-2012
Calgary Dewpoint Temperature	3031093 (Calg Int A)	Dewpoint Temperature	CWEEDS	1953-2001
Calgary Solar Radiation	3031093 (Calg Int A)	Global Horizontal Irradiance	CWEEDS	1953-2001
Calgary 10m Wind speed	3031093 (Calg Int A)	Wind speed	CWEEDS	1953-2001
Medicine Hat Precip	3034480, 3034485, 3034488	rain and snow	Env. Canada	1884-2007
Medicine Hat Average Temperature	3034480, 3034485	Average Daily Temperature	Env. Canada	1884-2007
Medicine Hat Dewpoint Temperature	3034480 (Med Hat A)	Dewpoint Temperature	CWEEDS	1953-2001
Medicine Hat Solar Radiation	3034480 (Med Hat A)	Global Horizontal Irradiance	CWEEDS	1953-2001
Medicine Hat 10m Wind speed	3034480 (Med Hat A)	Wind speed	CWEEDS	1953-2001
Banff Precipitation	3050519, 3050520, 3050522, 3050526	rain and snow	Env. Canada	1888-2007
Banff Average Temperature	3050519, 3050520, 3050521, 3050522	Temperature	Env. Canada	1888-2007

In addition to modeling the scenarios over a historical period (1928-2001), a 30 year extreme dry period is considered (as discussed in Section 1.6). Based on projections of future the prairies are expected to have a reduced streamflow regime (Pomeroy et al. 2009). This reduced streamflow is represented using paleo records, assuming that conditions of the past can occur in the future. The advantage of considering such paleo records is that there is a suite of streamflow conditions available, which presents a realistic approximation of a worst case dry scenario that can be expected in reality. It is noted that non-stationarity in climate is a general consensus and that reconstructions of past climate may not necessarily hold true for future conditions. However, the use of such records provides a range of conditions required for a robust analysis.

Streamflow records preceding 1912 were reconstructed using paleo records. Paleo records provided a means to approximate data through the use of different proxies. Commonly, tree-rings are used to approximate past climate and hydrology. Some applications of tree-rings as proxies include precipitation, temperature, and palmer drought index. The annual growth of tree-rings can be correlated with annual hydrological variables, such as rainfall or stream-flow. Tree-rings are an especially useful proxy as the rings themselves can be easily demarked to annual increments.

Although tree-ring widths were seen as a good proxy for climate variables, there are several limitations. First, the width of tree-rings is based on a *limiting factor*, a physiological constraint on growth (Speer, 2010). With reconstructions it was assumed that the tree-ring width is limited by the hydrological variable of interest, such as moisture (ex- rainfall). In reality there can be multiple limiting factors, such as the interplay of temperature and moisture. Also of relevance is the *divergence problem*- reduction in tree-ring widths of northern forests due to CO2 cycles, drought, delayed snow melt and/or global dimming (D'Arrigo et al., 2008). Non-climate factors such as nutrients, pests, and CO2 concentrations can add additional noise to the data (Briffa et al., 1998). Thus a sufficient sample is required to ensure the quality of the reconstruction. Even with these limitations, tree-ring proxies serve as a useful approximation to past conditions.

Razavi et al (under review) developed several series of streamflow data for Southern Alberta using tree-rings. These tree rings serve as a good streamflow proxy, having $R^2 = 0.51$. Although trees in Alberta were used to approximate data as far back as 1100, trees available in the Bow are younger and only have reliable records from 1600 A.D. The gauge station at the confluence of the Bow and Oldman rivers (gauge #05BN012) was nearest to the tree-ring flow proxies provided by Razavi et al (under review), shown in Figure 3.11. Figure 3.12 shows the eleven annual streamflow reconstructions of the Bow River near the confluence of the Oldman basin. As seen here, there are severe sustained droughts occurring in paleo records- exceeding that of any of instrumental period (e.g. 1912-current). Even the severe drought of the 1930's was less severe than dry periods in the 1700's and 1800's.

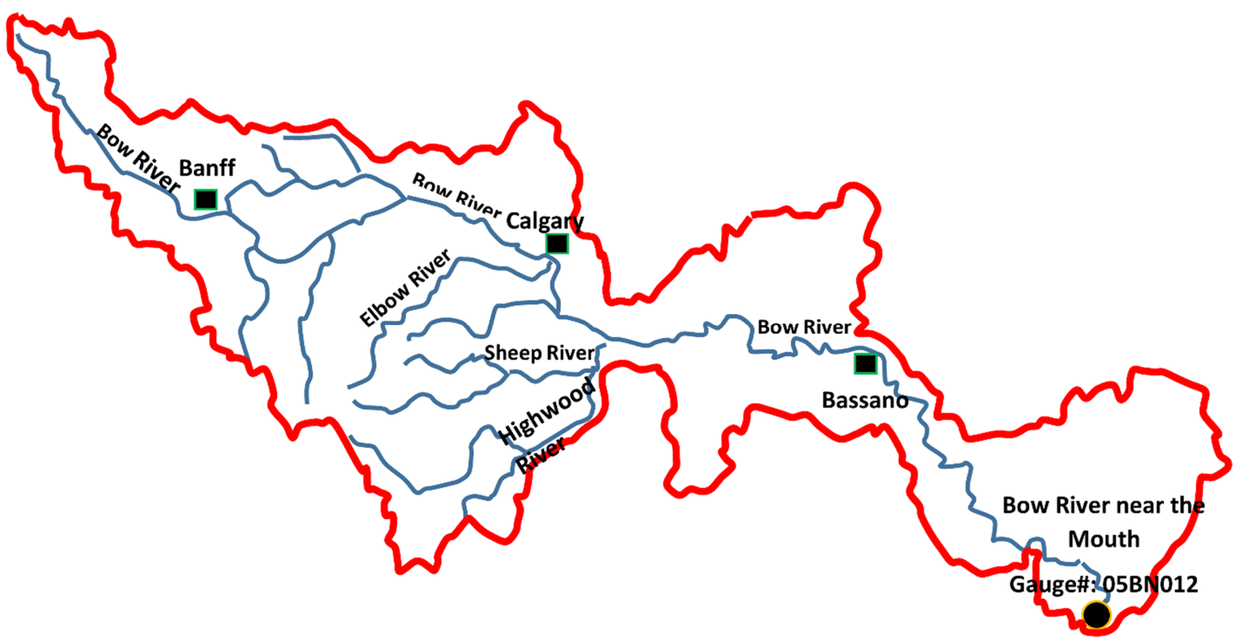


Figure 3.11- Map of the Bow Basin showing site of reconstructed flows and historical flow (circle) and cities (squares).

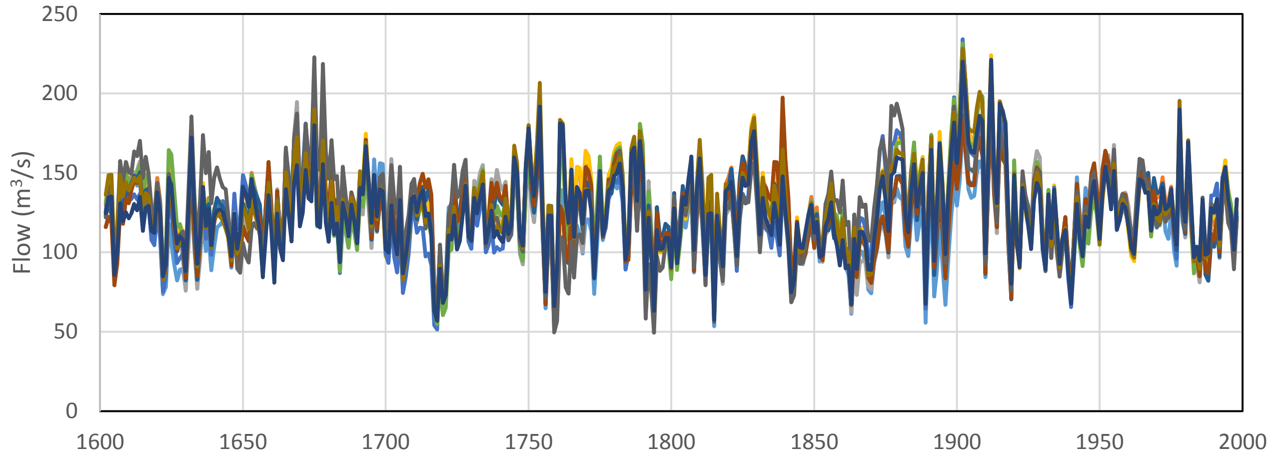


Figure 3.12- Time series of 11 paleo reconstructions of annual flow at gauge# 05BN012

In order for this reconstruction to be utilized by $SWAMP_B$, the annual flows were disaggregated to weekly values using the Stochastic Analysis, Modeling, and Simulation (SAMS) software. The SAMS software is a free software available by Colorado State University for statistical analysis (Sveinsson et al, 2007). Within this software are tools available for temporal downscaling. By using the Lane and Frevert (1990) method, weekly flows were estimated using SAMS (Sveinsson et al, 2007) according to equation 3.35:

$$Y_{v,\tau} = A_\tau Y_v + B_\tau \varepsilon_{v,\tau} + C_\tau Y_{v,\tau-1} \qquad (3.35)$$

Y_v is the observed flow in year v, $Y_{v,\tau}$ is the same year v but also within season (e.g. week) τ, $Y_{v,\tau-1}$ is the observed flow at year v and of the preceding week, ε is a random number that is normally distributed. Coefficients A, B and C are parameters calculated in SAMS to account for correlation, noise, and auto-correlation, respectively. These three parameters were calculated in SAMS using weekly naturalized flow data from gauge 05BM012 from 1928-2001. With these parameters, the 1600-1911 paleo annual streamflow data were disaggregated. Only one of the paleo disaggregated series was used in the proceeding analysis. The resulting Land and Frevert (1990) coefficients computed, as well as the weekly downscaled flows from 1840-1870, are provided in Appendix A. Figure 3.13 shows the results of the disaggregated series over the 30 year sustained drought from 1840-1870. A comparison with weekly average historical flows in Figure 3.14 illustrates that flow is significantly reduced during the 30 year paleo drought.

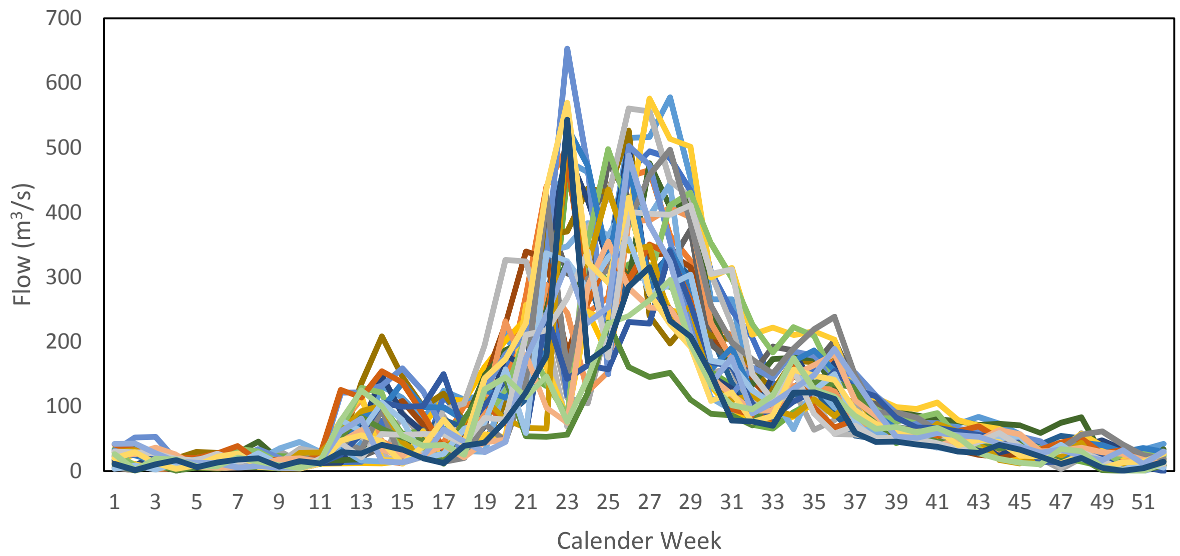


Figure 3.13- Weekly Disaggregated flows from 1840-1870

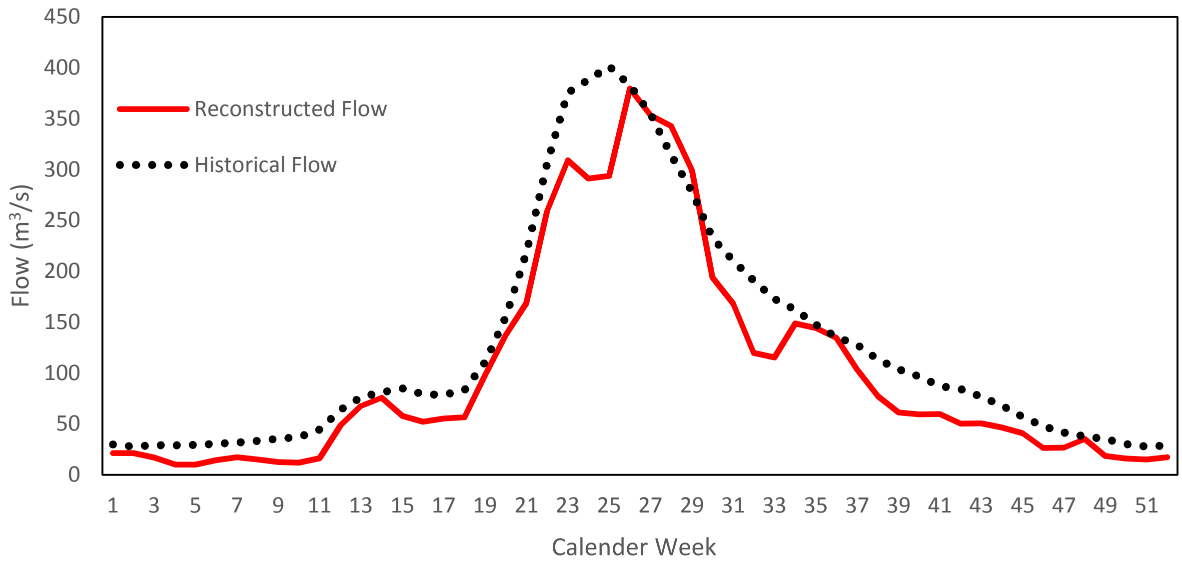


Figure 3.14- Comparison of the average weekly flows of the paleo drought (1840-1870) series and the historical (1928-2001) series

3.6 Scenario Design

In Chapter 1, the plans for Alberta to expand beyond the 1991 irrigation expansion limits- the maximum cropping area for each district deemed sustainable- were discussed. It was found that with this expansion, although deemed sustainable at that time (IWMSC, 2002), flows will not meet environmental flow requirements. With intensive crop water demands and alteration in streamflow due to the TransAlta reservoirs, the streamflow is below recommended levels during the summer and fall period. There were several solutions considered to restore the summer and fall streamflows for the Bow River. Table 3.5 illustrates five possible solutions to achieve this. These solutions include improving irrigation efficiency (S1), altering the flow released from the TransAlta Reservoirs (S2), combining improved irrigation efficiency with increases summer release from TransAlta (S3), implementing the recommended In-stream Flow Needs (IFN) (S4), and implementing the Water Conservation Objective (WCO) (S5).

Table 3.5- Possible scenarios to reduce Environmental Flow deficit

	Scenario	Application in Reality
	Baseline	Current operation
S1	Irrigation Efficiency	Implement Low Pressure and Micro Drip Sprinklers
S2	TransAlta Release	Alter Operations of TransAlta Reservoirs to increase summer flow
S3	S1 + S2	Combining increased summer flows with improved irrigation efficiency
S4	In-stream Flow Needs	Greater of 85% Natural Flow or 80% Exceedance stays In-stream
S5	Water Conservation Objective	55% Flow Stays In-stream

Scenario S1 considered fully implementing a micro-drip irrigation system, an advancement over the current mix of low pressure sprinklers and gravity irrigation (furrow and pipe). The baseline considered basin irrigation efficiency of 78%, based on reported values of 2014 (Alberta Agriculture and Rural Development, 2015). Potential solutions considered increasing efficiency up to 90%. The 90% efficiency is a hypothetical scenario, analyzing the impact of full implementation of micro-drip systems.

The TransAlta release was modified in $SWAMP_B$ by forcing an increased release in the summer period (calendar weeks of 22-40), with an equal reduction in release during the winter period (calendar weeks 45 to 17). All other weeks follow the base operational release specified in the methodology. This release was constrained by the minimum and maximum storage requirements of the reservoir, so this summer and winter alteration does not cause the lumped reservoir to spill or go below operational limits. Figure 3.15 illustrates that a 40% increase in summer and fall flows develops near natural flow conditions during these weeks (though significantly less during winter and early spring). This 40% summer release was considered for S2, as it best approximates natural conditions. Since the increased summer release considered is continuous and not discrete, a sensitivity analysis considered an array of values (discussed in section 3.7).

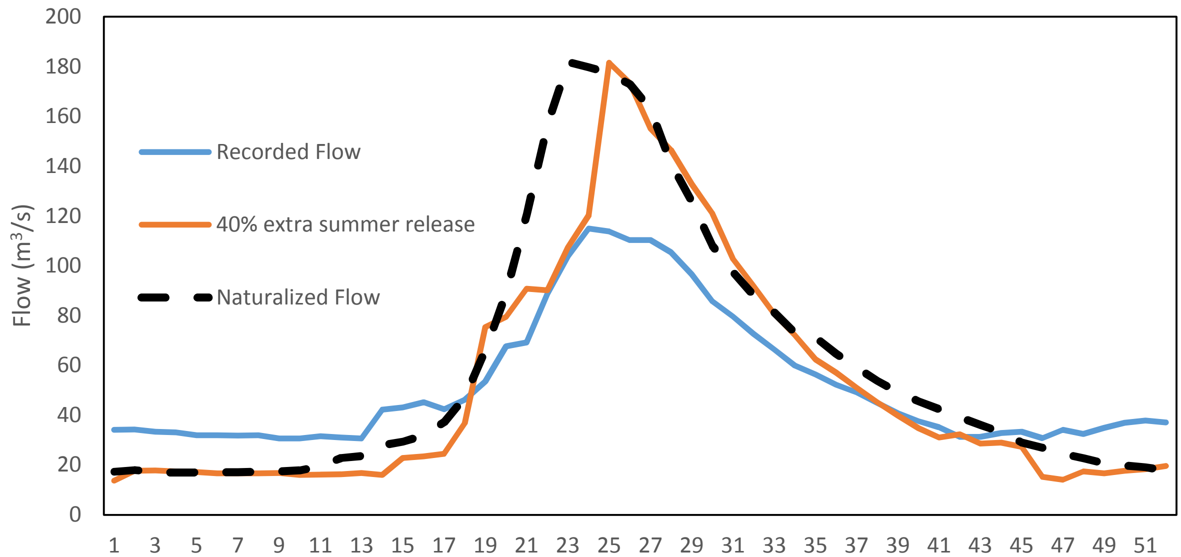


Figure 3.15- Release from TransAlta reservoirs under current and proposed operations.

Both the IFN (S4) and WCO (S5) were the policy interventions, defined in section 1.1. Briefly, the IFN could be thought of as an ideal situation for the environment, whereas the WCO was a compromise solution that is not as effective as the IFN but easier to implement. $SWAMP_B$ modeled both the WCO and IFN by giving environmental flows the highest priority, and setting their demand values to the WCO and IFN, respectively.

Not only was each of the five solutions evaluated by their ability to reduce streamflow deficits, but also the negative or positive impacts on other water uses. As water for irrigation is the highest priority in the Bow Basin, much of the tradeoffs will examine irrigation deficits and the impact of reduced yields on the economic return. Much smaller allocations are provided to Municipal uses, but the impact is still assessed. Although water is not consumed for hydropower generation, S2 (TransAlta Summer Release) will alter the timing of water release at the headwaters, which will affect hydropower generation. Thus, the aim of this analysis was to examine tradeoffs between water for the environment, irrigation, hydropower, municipal users, and the economic return as a whole. In order to perform such an analysis, performance indices were utilized.

3.7 Evaluation of Scenarios

For coherence, the tradeoffs and sensitivities were investigated in two parts. The management solutions, those involving irrigation efficiency and operation of the TransAlta reservoirs (S1, S2 and S3), were first evaluated by a Sensitivity analysis. Both irrigation efficiency and the percentage increase in summer release from the TransAlta reservoirs were incrementally varied in combination, while all other controls were held constant. This analysis served to show the effects of both irrigation efficiency and TransAlta release on the environmental flow and economy. This kind of analysis was also significant, because it illustrated if there was any optimal combination of these two solutions. After the sensitivity analysis, the impacts on hydropower production and crop water demand and shortages as consequences of S1, S2 and S3 were examined. Second, the impact of the policy solutions (S4 and S5) considered the tradeoffs of water allocated to irrigation, municipal users and the environment. Since the two policy solutions are mutually exclusive, there was no Monte-Carlo analysis to examine combinatorial effects.

$SWAMP_B$ was developed as a simulation model, having the strength of simulating combinations of conditions and constraints specified by the user. The drawback, as mentioned in Chapter 2, is that there is no means of picking a best solution- something that optimization models can do. Instead, a framework was provided to interpret the tradeoffs that are seen in the analysis. There are several ways to do this. Davis et al. (1972) illustrated Bayes' decision making by providing a framework for hydrological design. Although the study valued the ability of this approach to quantify uncertainty in decision making, the framework did not allow for multiple objectives and the outcome is dependent on the statistical distribution used. Multi-attribute utility theory (MAUT) allows for one to develop utility functions for evaluate multiple objectives. Hall and Borgomeo (2012) praised MAUT for its ability to represent risk aversion and decreasing marginal utility, apparent in many water management problems. Keeny and Wood (1977) were able to incorporate 12 attributes to evaluate different water resource system plans. These authors note that their preferred solution was different than David and Duckstein (1975) who performed the same analysis with ELECTRE. As seen with these two studies, the preferred solution was highly dependent on chosen values of attribute weights. The major flaw with MAUT was the uncertainty of user preferences, and the difficulty of incorporating a realistic number of stakeholders in developing utility functions (Hall and Borgomeo, 2012).

An alternative to MAUT to evaluate scenarios are performance indices. Hashimoto et al. (1982) developed three indices to evaluate water resources systems, which are the reliability index, resilience index and vulnerability index. Although the performance indices still requires user preferences, they provide a standardized measure of system flexibility, and magnitude of expected consequences. By identifying thresholds to various indices, Blackmore and Plant (2008) suggested water resource systems can be designed to fit within bounds of sustainability and vulnerability, and the ability to adapt. By combining all three indices to one comprehensive index, the sustainability index (SI), decision makers can readily assess tradeoffs without spending resources to analyze weights and numerous attributes (Sandoval-Solis et al., 2011). With these advantages inherent to the SI index, it was used to evaluate the five solutions against baseline conditions.

As there are multiple ways to define or represent these three indices, the specific implementation is discussed in detail below. Following this discussion of the three indices, the specific implementation of the SI is then mentioned. The reliability, resilience, vulnerability and sustainability indices are defined in equations 3.36, 3.37, 3.38 and 3.39 respectively:

Reliability (Rel): The likelihood of a success, or probability of there being no shortage.

$$Rel = \frac{Count(D_t = 0)}{n} \tag{3.36}$$

Count ($D_t = 0$) is the number of times that the shortage (D_t) is zero (e.g. demand fully satisfied), and n is the number of times there is a demand greater than zero. Only demands greater than zero were considered to prevent any biases towards a high reliability.

Resilience (Res): The recoverability or ability of a system to adapt. Probability of no shortage when a shortage occurred in the previous time step.

$$Res = \frac{Count(D_t = 0\ follows\ D_t > 0)}{n} \tag{3.37}$$

Count ($D_t = 0$ follows $D_t > 0$) is the number of times there is a shortage, immediately followed by no shortage.

Vulnerability (Vul): The severity of a consequence. This indicator can be represented in several ways. Hashimoto et al. (1982) specified Vul as the maximum failure/shortage magnitude to be expected in any series of failures/shortages. Alternatively, Loucks and van Beek (2005) defined Vul as the expected magnitude of shortage when a shortage does occur. This work uses Loucks and van Beek's (2005) formulation, emphasizing the average rather than maximum shortage.

$$Vul = \frac{\frac{\sum D_t > 0}{Count(D_t > 0)}}{Mean(Demand)} \quad (3.38)$$

$\sum (D_t > 0)$ is the summation of all shortages over the simulation period. The ratio of total shortages divided by the number of times a shortage occurs provides an expected shortage value. This expected shortage is divided by the average demand value to provide a unitless value between 0 and 1.

This study combined the above mentioned indices to one comprehensive index, the Sustainability Index (SI) (Sandoval-Solis et al., 2011). This score was computed for each scenario, for each of the three dimensions to be scored (Environment, Irrigation, and Municipal use) as defined in Equation 3.39:

$$SI = [Rel * Res * (1 - Vul)]^{1/3} \quad (3.39)$$

The advantage with this is that the index is unitless and scalable between 0 and 1. Because of the cubed root, the value of SI is easily interpreted (e.g. if Res, Rel, and (1-Vul) each equal 0.1, then SI equals 0.1). The weights of the three indices were assumed equal due to lack of information with regard to stakeholders' preferences.

Chapter 4 Model Verification

This chapter discusses the results of the verification process. There are three parts that will be discussed here. First the structural verification of $SWAMP_B$ is discussed. The structural verification assesses how well $SWAMP_B$ emulates WRMM, using the same water demands and assumptions. Next the irrigation component is verified in terms of how well crop water demands generated in $SWAMP_B$ compare to those of WRMM. Since there were many assumptions with regards to the soil moisture balance, a sensitivity analysis explores the impact these assumptions could have on model results. Following the irrigation component, the TransAlta component is verified- assessing the calibration and validation of the TransAlta reservoir release. Last, a verification considers the comparison of $SWAMP_B$ to observed historical data. 4.1 Structural Verification

4.1.1 Micro-Structure Verification

This first verification considered the four "large" reservoirs with fixed inflows from WRMM, thus only examining the micro-structure. Figure 4.1 and Figure 4.2 show both the scatter plots, as well as the weekly averages, of the storage (MCM) of each of these reservoirs. The error measures and the narrow scatter show that Bruce Lake, McGregor Reservoir, and Lake Newell are emulated well by the $SWAMP_B$ model. Crawling Reservoir is not emulated as well, seen by the bias and scatter illustrated in Figure 4.1. This bias in Crawling Reservoir is better illustrated in Figure 4.2, as Crawling Reservoir is under-filled in $SWAMP_B$ during peak storage. This likely reflects that water is redistributed amongst the reservoirs in EID with more water going to the smaller reservoirs. Even though Crawling Reservoir performs the poorest out of the four reservoirs, it still results in reasonable error measures. With the four largest reservoirs operating satisfactorily, the system as a whole is examined next.

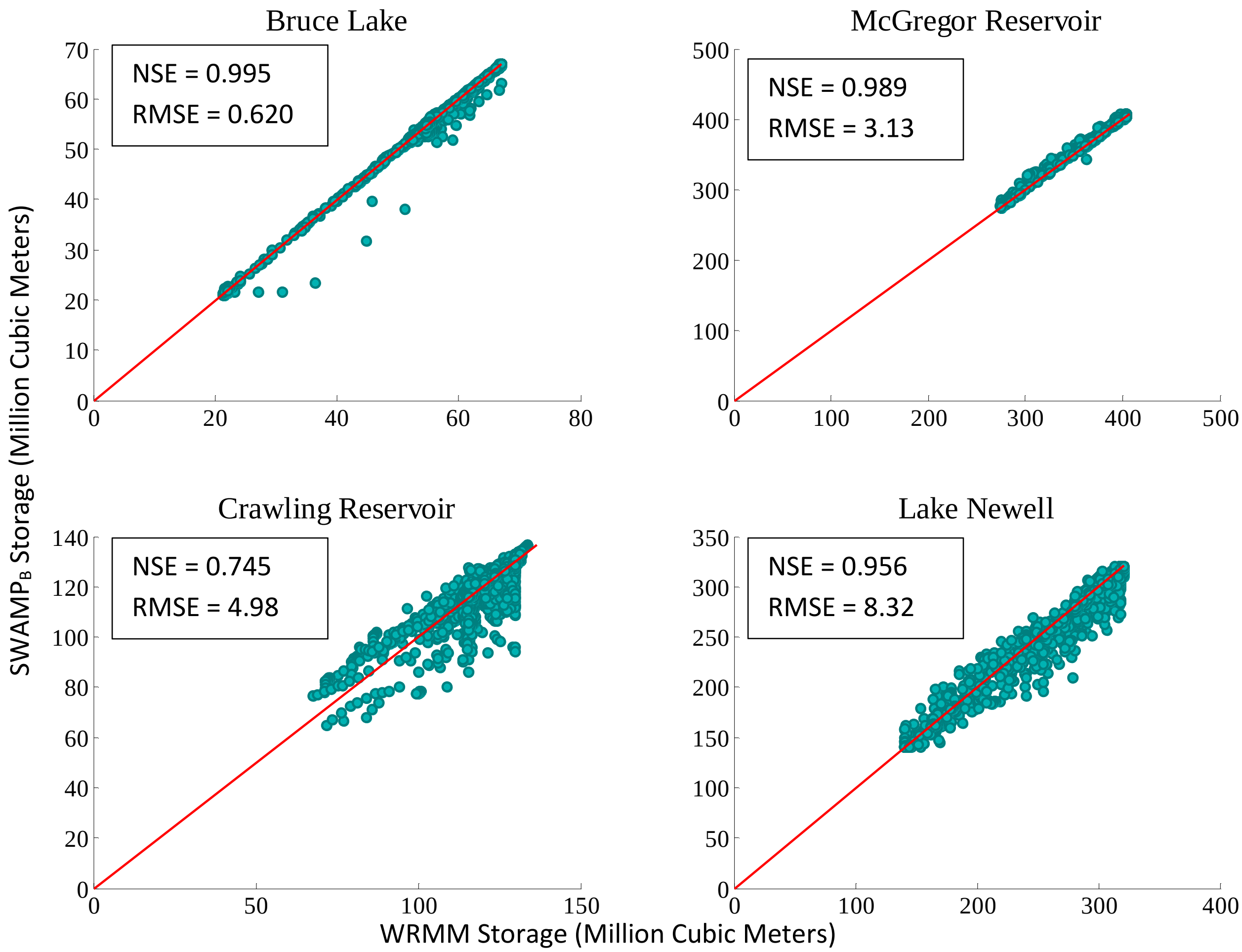


Figure 4.1- Scatterplot and error measures comparing $SWAMP_B$ against WRMM from 1928-2000. Each plot represents one of the large reservoirs in the Bow Basin. Dots represent weekly storage output from the two models and the 45 degree red line shows position of agreement.

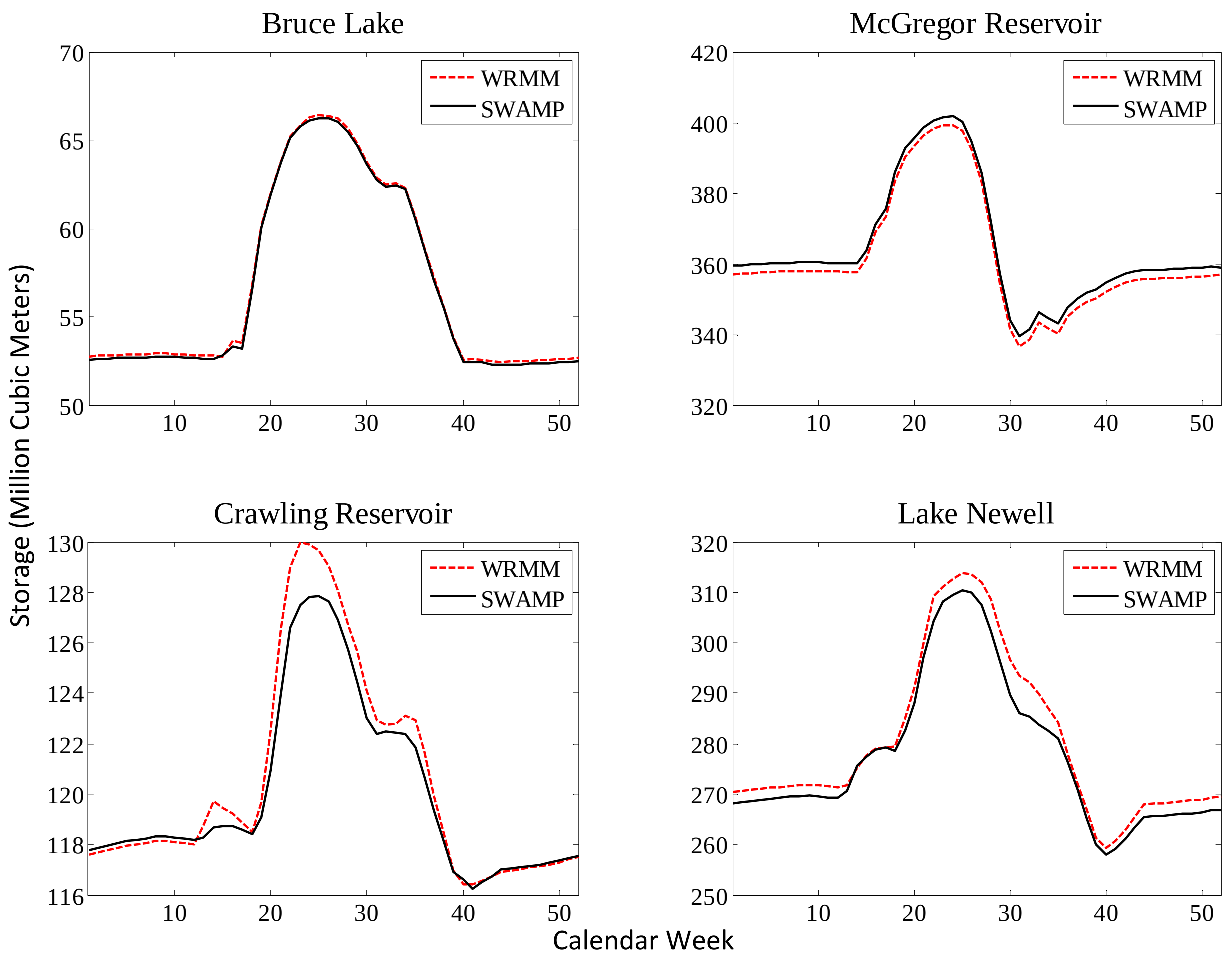


Figure 4.2- Average weekly storage, comparing $SWAMP_B$ against WRMM from 1928-2000. Each plot represents one of the four largest reservoirs in the Bow Basin

4.1.2 Macro-Structure Verification

Emulation of the three diversion flows and the flow to the Oldman basin was first verified in the macro-structure. The four scatter plots in Figure 4.3 show that $SWAMP_B$ is a relatively good emulator of WRMM for these flows. The fit is especially good for the diversion to Oldman with an NSE value of 0.975. The other three flows are emulated with less accuracy. Even though there appears to be much scatter in the plots, the error measures are reasonable with NSE values of 0.906, 0.886, and 0.830. Because there are many points on the plots (3796 scatter points) the visual impression of the plot can be misleading. Many of the points along the 45 degree line of agreement are overlapping, but cannot be shown as such. The error measures suggest that the majority of points lie near the 45 degree line, but the plots do not represent the density of overlapping points.

Examination of the weekly average flows in Figure 4.4 shows the cause of inaccuracies in the diversion to WID and EID. The error in the Diversion to WID is mainly caused by over allocation during calendar weeks 17 – 30. As seen in Figure 4.4, $SWAMP_B$ attempts to satisfy the license requirements during this period. This is a reflection of the modeling philosophy, as $SWAMP_B$ is not an optimization model, but instead aims to satisfy demands by priority. The priority of the WID Diversion license is higher than the other three 'macro' flows, thus, there is a bias to fulfill the WID water requirements. Although $SWAMP_B$ follows the trend well in the diversion to BRID, it does not accurately model the peak supply during the beginning and middle of the season. Diversion to EID is also accurately emulated in $SWAMP_B$, but shown in Figure 4.4 to under allocate during the last few weeks of the diversion period. From these results, it can be seen that $SWAMP_B$ sufficiently emulates the major diversion and flow to the Oldman Basin.

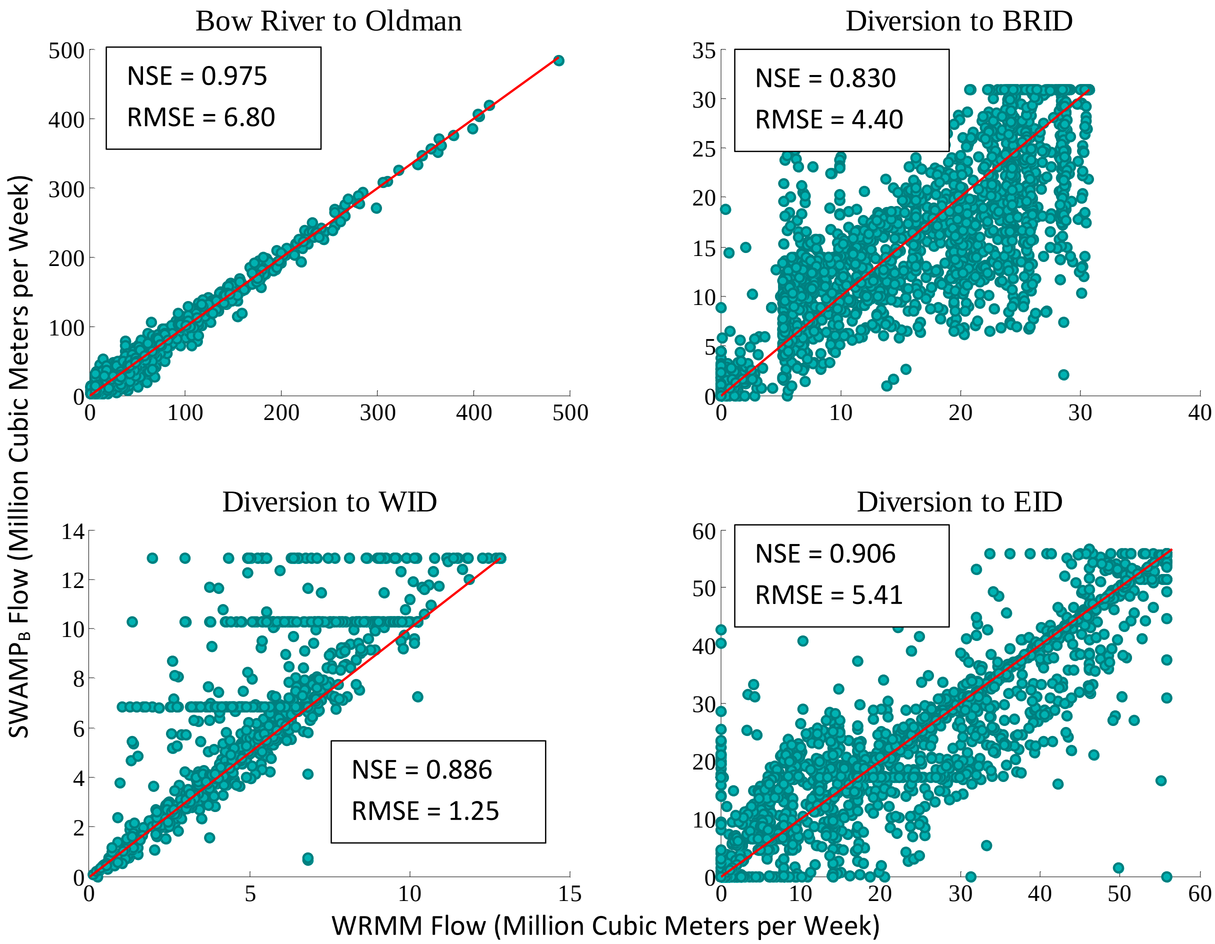


Figure 4.3- Scatterplot comparing SWAMP$_B$ against WRMM from 1928-2000. Each plot represents one of the four macro flow components. Dots represent weekly flow output from the two models and the 45 degree red line shows position of agreement.

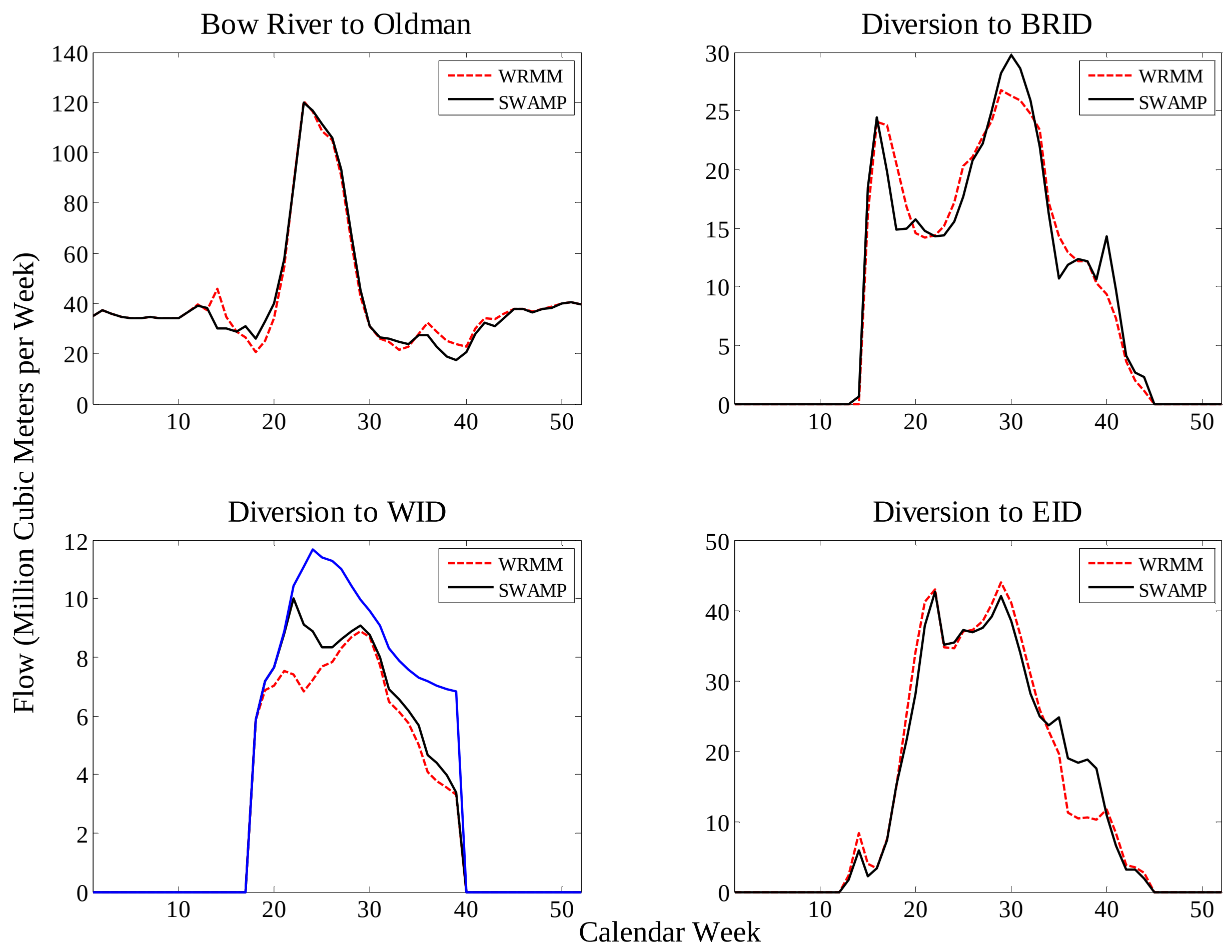


Figure 4.4- Average weekly flows, comparing SWAMP$_B$ against WRMM from 1928-2000. Each plot represents one of the four macro flow components. The blue "ID" line represents the Ideal license- or the maximum diversion during the specified week.

The analysis so far verified the operations of the reservoirs when isolated (micro-structure), and that the four flows were also emulated well. Flows were shown, for the most part, to be modelled similarly by SWAMP$_B$ and WRMM, with small differences. Reservoirs with forced district diversions also proved accurate, with only a small difference between both models. The final component of the macro-scale structural verification considered the reservoirs' performance with SWAMP$_B$ modeling the district diversions. Any inaccuracies seen in this next part should be due to the inaccuracies in the reservoir operation scheme in addition to errors in the flows. A comparison similar to the previous section is used, but with the diversions and reservoir operations modeled in $SWAMP_B$.

Figure 4.5 and Figure 4.6 illustrate that $SWAMP_B$ model no longer emulates the four large reservoirs as well once the four diversions are no longer fixed. This further deviance of accuracy is the combined effect of $SWAMP_B$'s ability to emulate the three district diversions and the flow to Oldman, as well as the operation of reservoirs. As seen in the weekly average storage in Figure 4.7, the McGregor reservoir is modeled with the best accuracy. Although the three other reservoirs are seen to have considerable inaccuracy in this plot, this error is not always present.

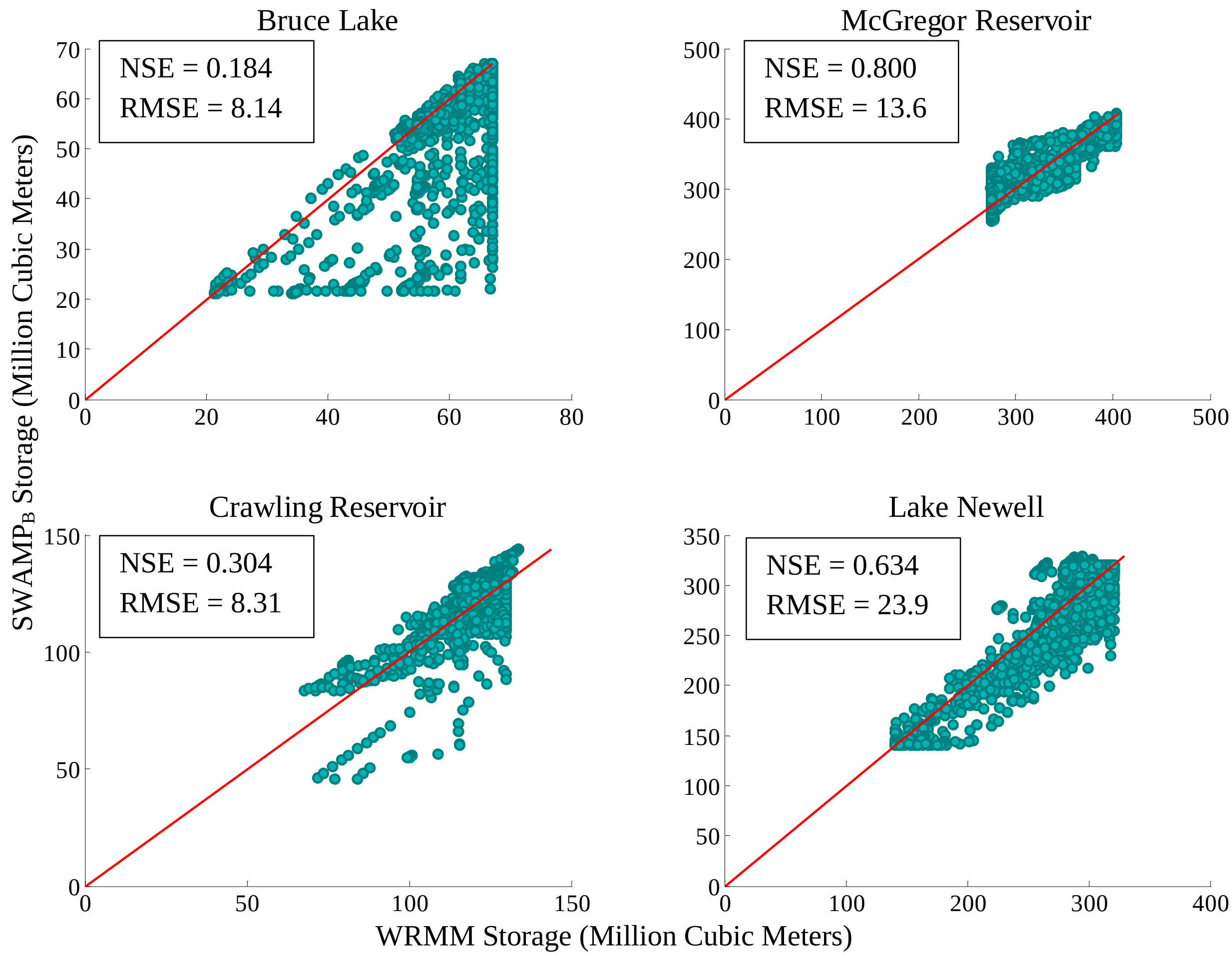


Figure 4.5-Scatterplot comparing $SWAMP_B$ against WRMM from 1928-2000. Each plot represents one of the largest reservoirs in the Bow Basin. Dots represent weekly storage output from the two models and the 45 degree red line shows position of agreement

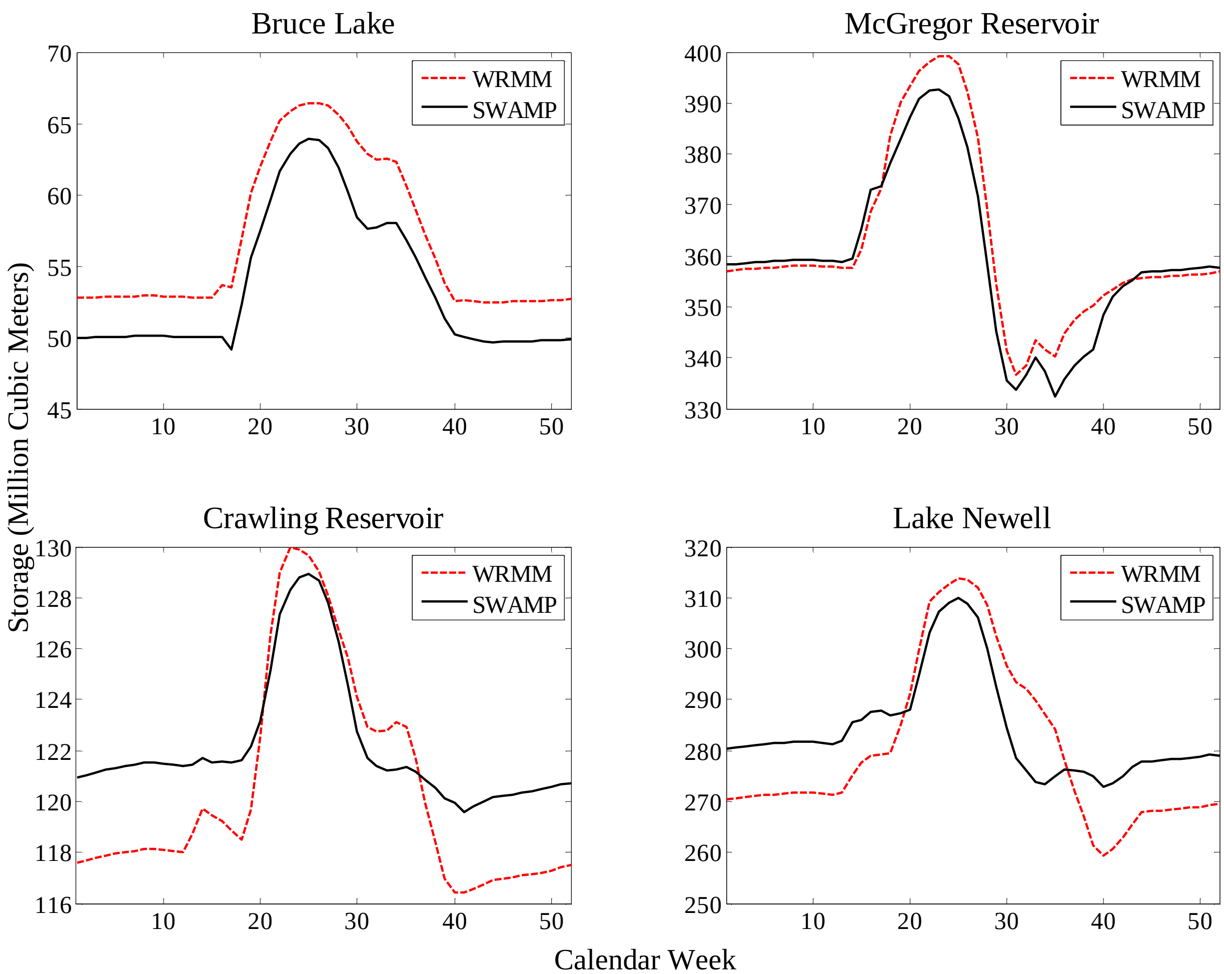


Figure 4.6- Average weekly storage, comparing SWAMP$_B$ against WRMM from 1928-2000. Each plot represents one of the four largest reservoirs in the Bow Basin

When examining the time series of Bruce Lake, Crawling Reservoir, and Lake Newell in Figure 4.7, the trends are quite reasonable. Discrepancies between the two models are not due to the operation rules themselves, but the simplification in SWAMP$_B$. Since an optimization scheme with penalties is translated to a hierarchal system of "IF-THEN-ELSE" statements, optimal values are not always arrived at. This is seen as the reservoirs ability to remain with operational limits, and provide well for demands, but still have different storage values. Bruce Lake only exhibits inaccuracy during dry periods (e.g. 1929 – 1940), where SWAMP$_B$ allows for less storage than

WRMM- although still above the minimum storage zone. For most other periods the behavior of Bruce Lake is in agreement between the two models. The opposite is true for Lake Newell, as it is able to match the dry periods, but $SWAMP_B$ over allocates to the reservoir during the normal and wet periods. Although Crawling Reservoir does not appear to follow the same storage trends in both models, it will be shown next that it still allows the model to function well as a system. Not only should the reservoirs themselves operate similarly, but their ability to supply different water demands is important as well.

It should be kept in mind that the modeling philosophies of $SWAMP_B$ and WRMM are different- as $SWAMP_B$ allocates resources on explicit "IF-THEN-ELSE" decisions, and WRMM employs quantitative penalty values that are minimized. With these different approaches to representing water allocation rules, the results are different. Since altering the penalty values in WRMM, without changing the ranking of priorities, can produce different solutions- one could develop different optimal solutions for different sets of penalties. The same cannot be said for $SWAMP_B$, as there is no numerical weighting to the priorities. This difference in philosophy between the two models means that the results of WRMM are not necessarily a true representation of reality, and $SWAMP_B$ needs not to be as close as possible to WRMM to be considered accurate. Instead, WRMM should be thought of as a baseline for assessing $SWAMP_B$'s performance.

The WRMM is not necessarily a perfect representation of reality and it may not be logical to compare $SWAMP_B$ to WRMM. However, historical data for all components represented in $SWAMP_B$ are not readily available, and in many cases WRMM is the best alternative to use as a source of data. Therefore, comparing the results of $SWAMP_B$ against WRMM is considered here as a baseline comparison to ensure that the input data are handled in a similar way by both models.

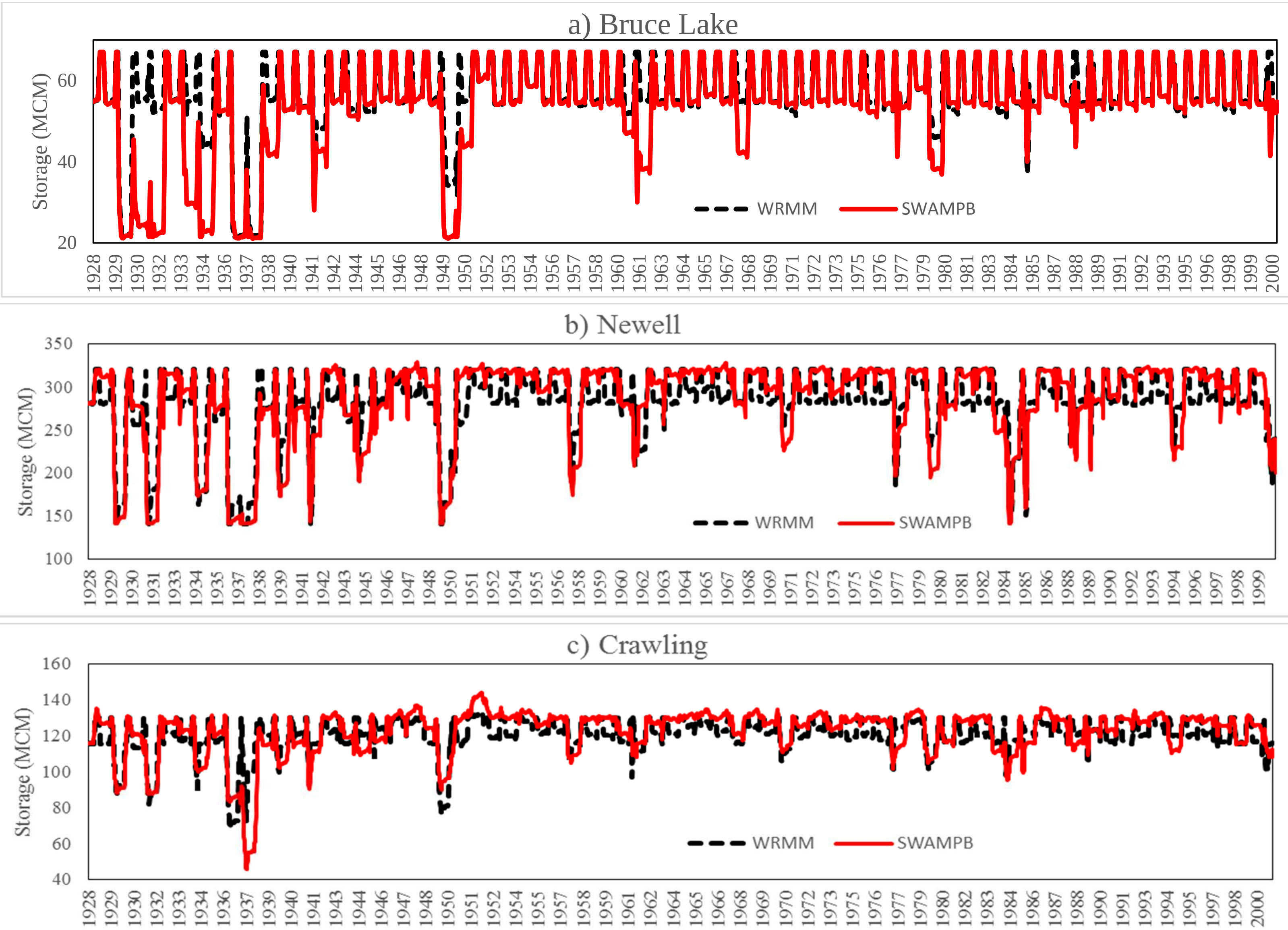


Figure 4.7- Time-series comparing reservoir storage of WRMM against $SWAMP_B$ for a) Bruce Lake, b) Lake Newell, and c) Crawling Reservoir. The comparison uses weekly data over the entire simulation period

All of the reservoirs in the Bow River Basin, with the exception of the TransAlta reservoirs, operate to store and release water for the irrigation districts. The performance of the two models can not only be evaluated in terms of the operation of the reservoirs, but also in $SWAMP_B$'s ability to meet water demands in the same fashion as WRMM. If demands can be met similarly by both models, then the overall structure is still valid. Thus, it is shown in Figures 4.8, 4.9, and 4.10 that the reservoirs in $SWAMP_B$ provide irrigation water to individual farm demands almost exactly as in WRMM for the WID, BID, and EID, respectively. From this result, the reservoirs in $SWAMP_B$ can be shown to perform the same function as WRMM, and therefore $SWAMP_B$ operations are structurally verified.

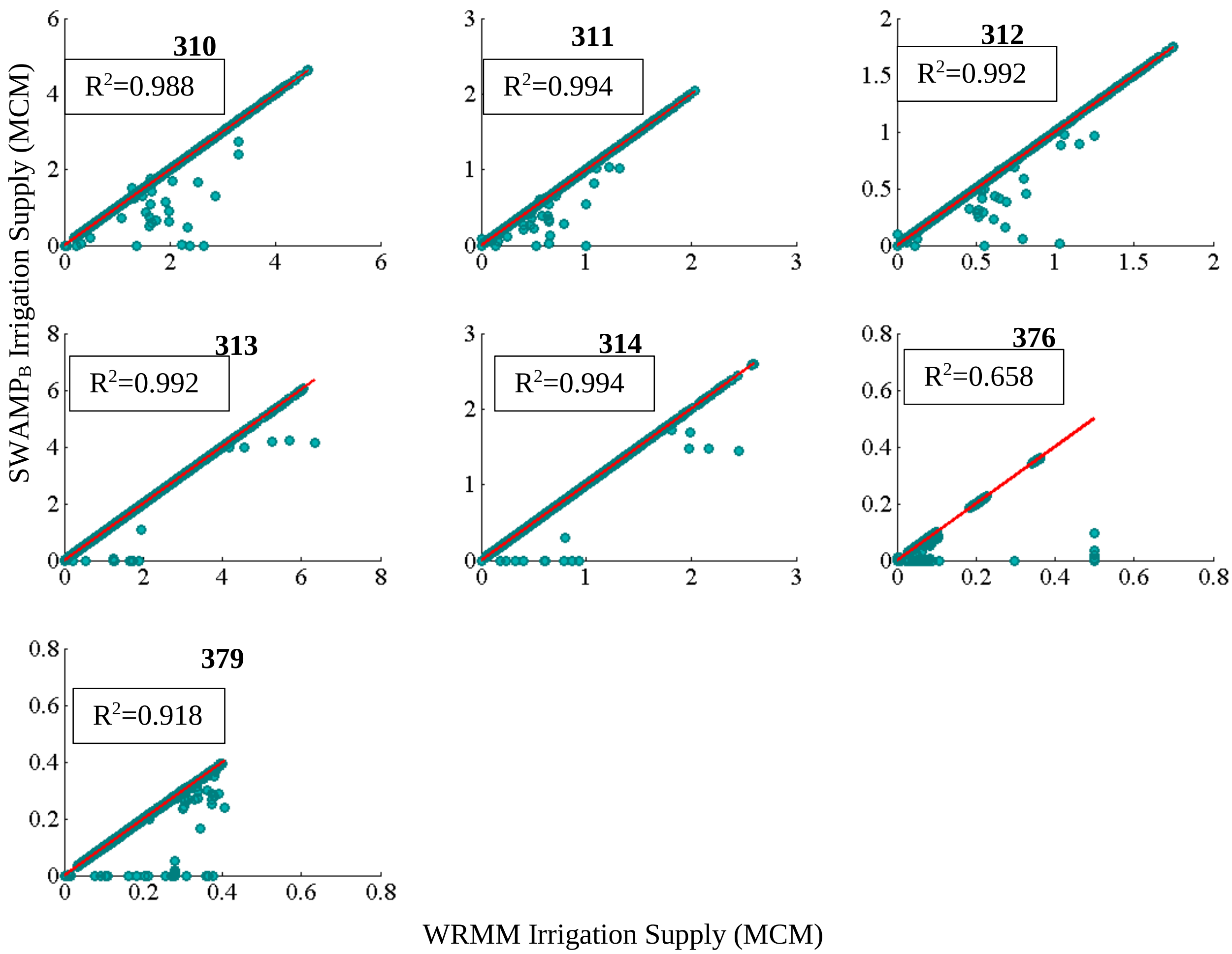


Figure 4.8- Scatter plot and R-squared measures, comparing individual farm supplies for the Western Irrigation District. Three digit numbers indicates farm ID used in WRMM

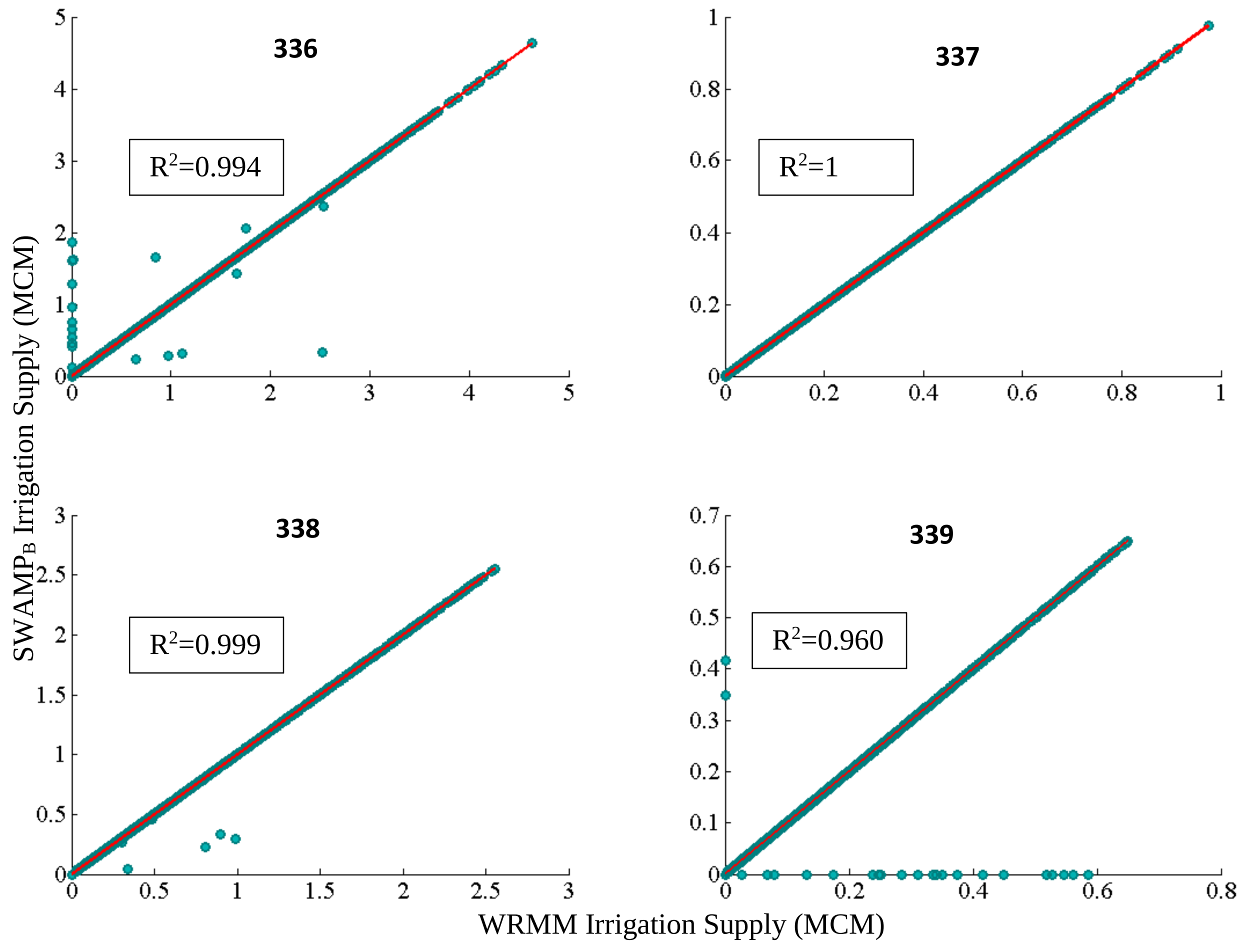


Figure 4.9- Scatter plot and R-squared measures, comparing individual farm supplies for the Bow River Irrigation District. Three digit numbers represent farm ID from WRMM

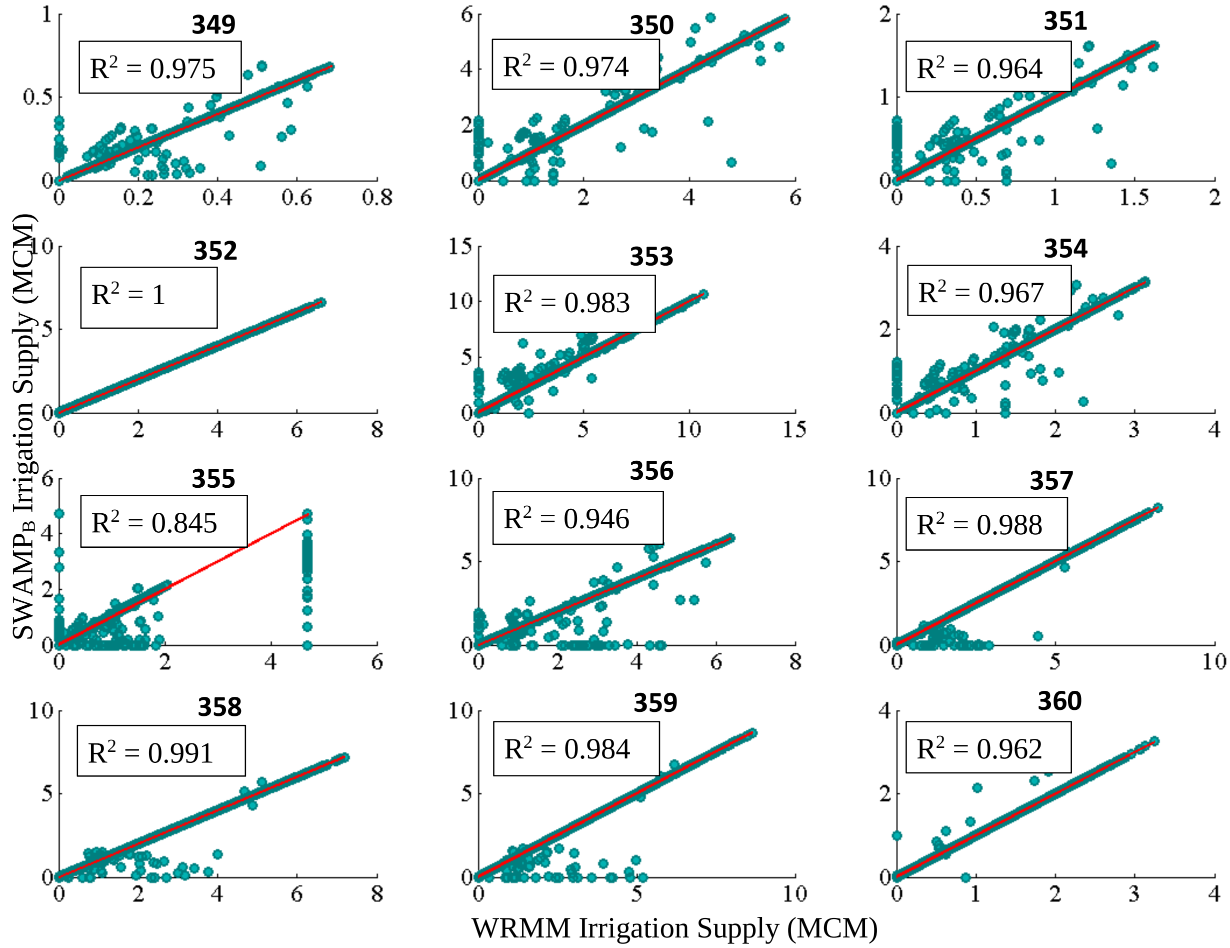


Figure 4.10- Scatter plot and R-squared measures, comparing individual farm supplies for the Eastern Irrigation District. Three digit numbers represent farm ID from WRMM

4.2 Irrigation Model Verification

With the $SWAMP_B$ model structure verified, the water demand and supply is examined next. A major component of $SWAMP_B$ is the irrigation sub-model. Unlike the verification in the previous section, the assumptions made in the irrigation sub-model have no baseline to compare to since there was no crop water demand calculation provided within WRMM. Although the irrigation demand values were present in WRMM, the method and assumptions utilized by WRMM were not available. This section will first compare the validity of the current assumptions in $SWAMP_B$ with the overall irrigation water demands. Then a sensitivity analysis will investigate the impacts of different assumptions in the model. Some of these assumptions include the irrigation trigger, runoff, snow sublimation and redistribution, ET equations and the return flow

The crop water demand was explained in Chapter 3, but is largely a function of the soil moisture trigger to irrigation. This is the percentage of field capacity that the model aims to maintain if sufficient water is available. Although requiring crop water demands to maintain soil moisture at field capacity is optimal, this is not done in neither $SWAMP_B$ nor WRMM for reasons explained in Chapter 3. The effect of the soil moisture trigger on the irrigation water demand is significant, as shown in Figure 4.11. By altering the soil moisture trigger between 75% and 90% of field capacity there is more than a two-fold increase in crop water demand. This difference is large because the soil moisture deficit is cumulative, allowing the previous demand deficit to be added to the current crop water demand.

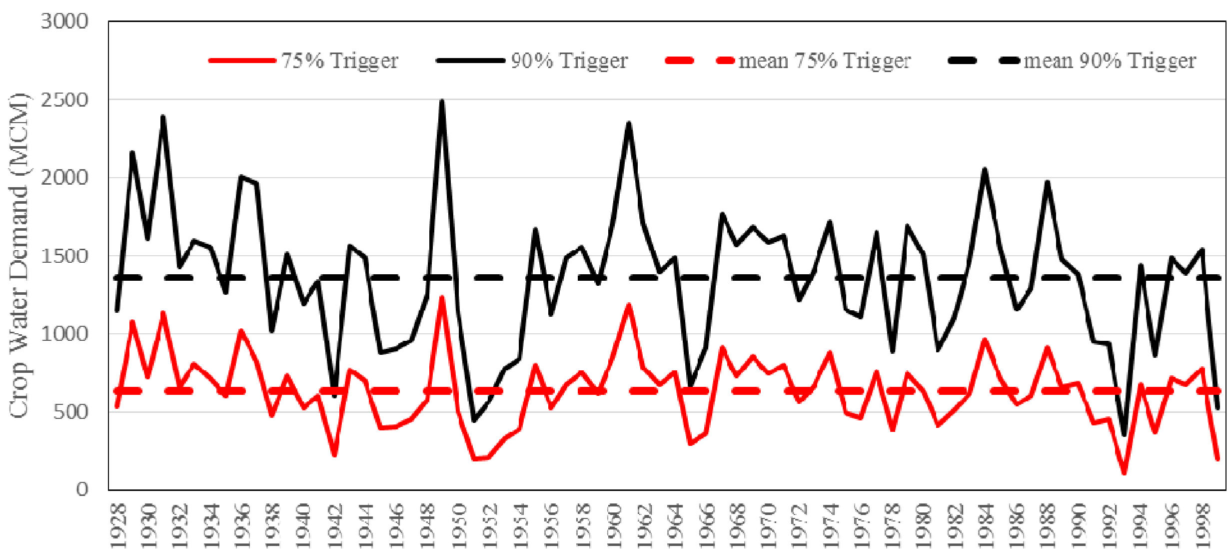


Figure 4.11- Annual crop water demand of Bow Basin utilizing a 75% and 90% soil moisture trigger

Because the crop water demand is quite sensitive to the soil moisture trigger, it is important to set a realistic trigger in $SWAMP_B$. In order to approximate the demands in WRMM, the soil moisture trigger was set to a value between 0.75 and 0.9 for each irrigation district, as discussed in Chapter 3. Figure 4.12 shows a good agreement between the crop water demand of $SWAMP_B$ and WRMM when trigger values of 0.82, 0.75 and 0.9 are used for the Western Irrigation District, Eastern Irrigation District, and Bow River Irrigation District, respectively.

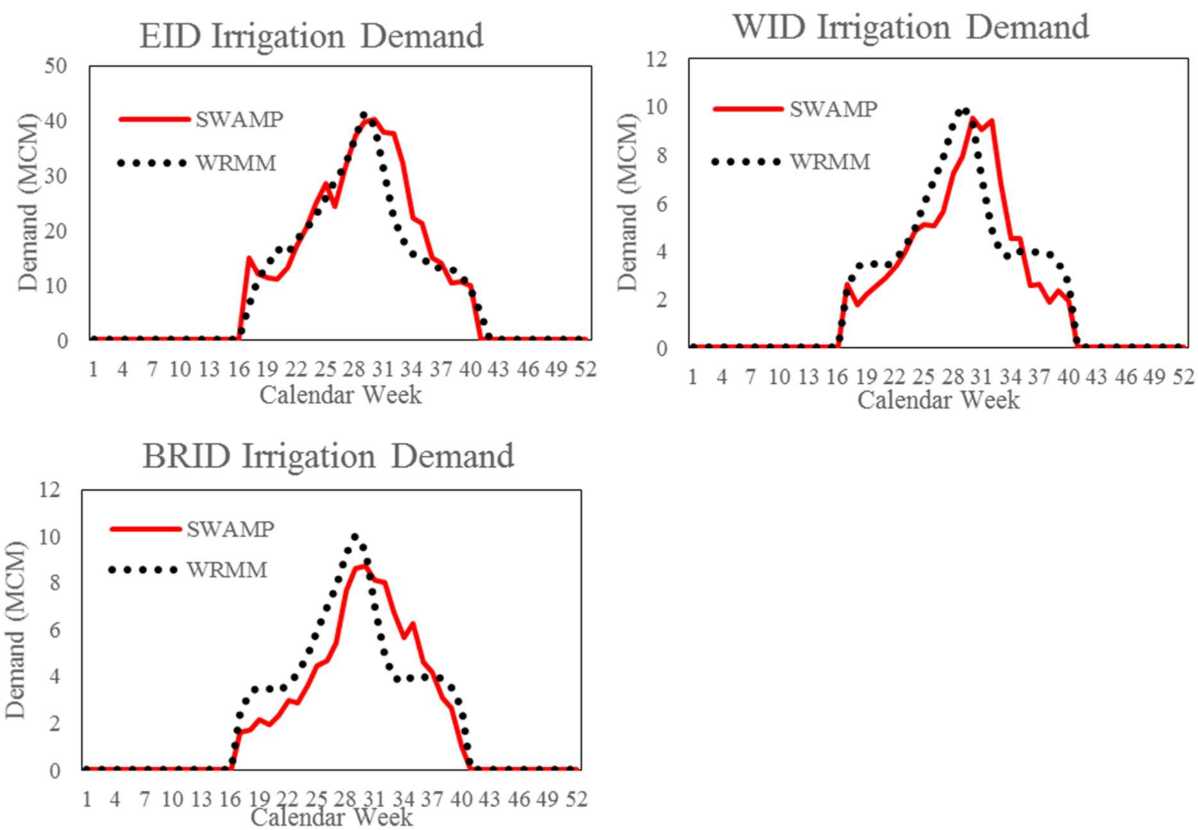


Figure 4.12- Comparison between WRMM and $SWAMP_B$ of the Average Crop Water Demand for each of the Irrigation Districts

The chosen soil moisture triggers for EID, WID, and BRID allow the crop water demands of $SWAMP_B$ to match closely with WRMM, considering the average trend. The peak crop water demand in $SWAMP_B$ is shifted approximately one week later. Since this shift is minor, and the general trend matches, the crop water demands in $SWAMP_B$ were considered acceptable. The largest variance is seen with BRID, as the demand is skewed with higher demands later season. These discrepancies are most likely due to different crop, and crop water demand assumptions used in $SWAMP_B$ and WRMM. Specific crops, AET determination and infiltration and runoff used to generate WRMM's demand are not provided. It is also important to remember that the current simulation assumes the same crops for all years, when in reality the percentage of each crop planted will differ from one year to the next.

As shown in this section, the irrigation water demand and crop yields are dependent on numerous mechanisms. The runoff, return flow and snow accumulation are all simplified to reduce the computational burden and data requirements of the model. With these simplifications come many assumptions that impact the model results. Also, the Penman-Monteith potential ET requires data that may not be available in all locations, so a simplified formulation of potential ET was considered. Previously in this section the irrigation outputs of $SWAMP_B$ was compared against WRMM as a verification. The next step will assess potential uncertainties due to these simplifications. Although these sensitivity analyses do not assess whether the hydrological processes are realistic, they assess how much uncertainty they contribute to $SWAMP_B$.

There are variety of equations that are suitable for determining the reference crop evapotranspiration (ET_0). The Penman-Monteith equation utilized by $SWAMP_B$ requires much data-temperature, radiation, wind speed, and humidity- which may not be available in all locations, or may be unreliable. Simplified equations can reduce these sources of uncertainty from missing or poor quality data. Two such equations are compared: The Hargreaves (Maule et al., 2006) and Modified Hargreaves (Farmer et al., 2011) equations. The Hargreaves equation (ET_H) is adapted to the Canadian prairies and shown in equation 4.1. An adaptation of the Hargreaves equation from Farmer et al. (2011), shown in equation 4.2, includes precipitation.

$$ET_H = 0.00094 * (T_{max} - T_{min})^{0.5} * \left(T_{avg} + 17.8\right) * R_a \tag{4.1}$$

$$ET_{MH} = 0.00053 * R_a * \left(T_{avg} + 17\right) * (T_{max} - T_{min} - 0.0123 * P)^{0.76} \tag{4.2}$$

T_{min}, T_{max}, and T_{avg} are the minimum, maximum and average daily temperatures (°C) respectively; R_a is the daily extraterrestrial radiation (MJ/m^2day), and P is daily precipitation (mm). ET_H and ET_{MH} are the Hargreaves and Modified Hargreaves potential evapotranspiration (mm/day), respectively. The reference ET from the Hargreaves and Modified Hargreaves are compared to that of the Penman-Monteith method in Figure 4.13. These two equations provide close estimates to the Penman-Monteith method used. Minor differences are apparent during winter months, which is insignificant as crops are not grown during this period.

A further examination of these equations is observed in Figure 4.14, with the effect on irrigation water demand. As expected, different ET methods produce different irrigation demands. Although both the Hargreaves and Modified Hargreaves equations produce lower irrigation demands for most years, the difference is minor (less than ten percent difference from Penman-Monteith). Interestingly, the annual economic return in Figure 4.15 follows the same trend but magnified- with Hargreaves and Modified Hargreaves having a higher economic return as the irrigation demand is less (thus easier to satisfy). In some instances there is a $50M difference in return that results from different ET equations, illustrating that even minor changes in ET can be significant to the economic return. Decision makers would likely be concerned with choosing an appropriate ET method to ensure the economic return predicted by $SWAMP_B$ is reasonable. By having multiple ET methods available decision makers have more flexibility in using $SWAMP_B$, being able to choose the method that fits within their data constraints (e.g. if wind speed or Rn data are poor, a simplified alternative method can be used).

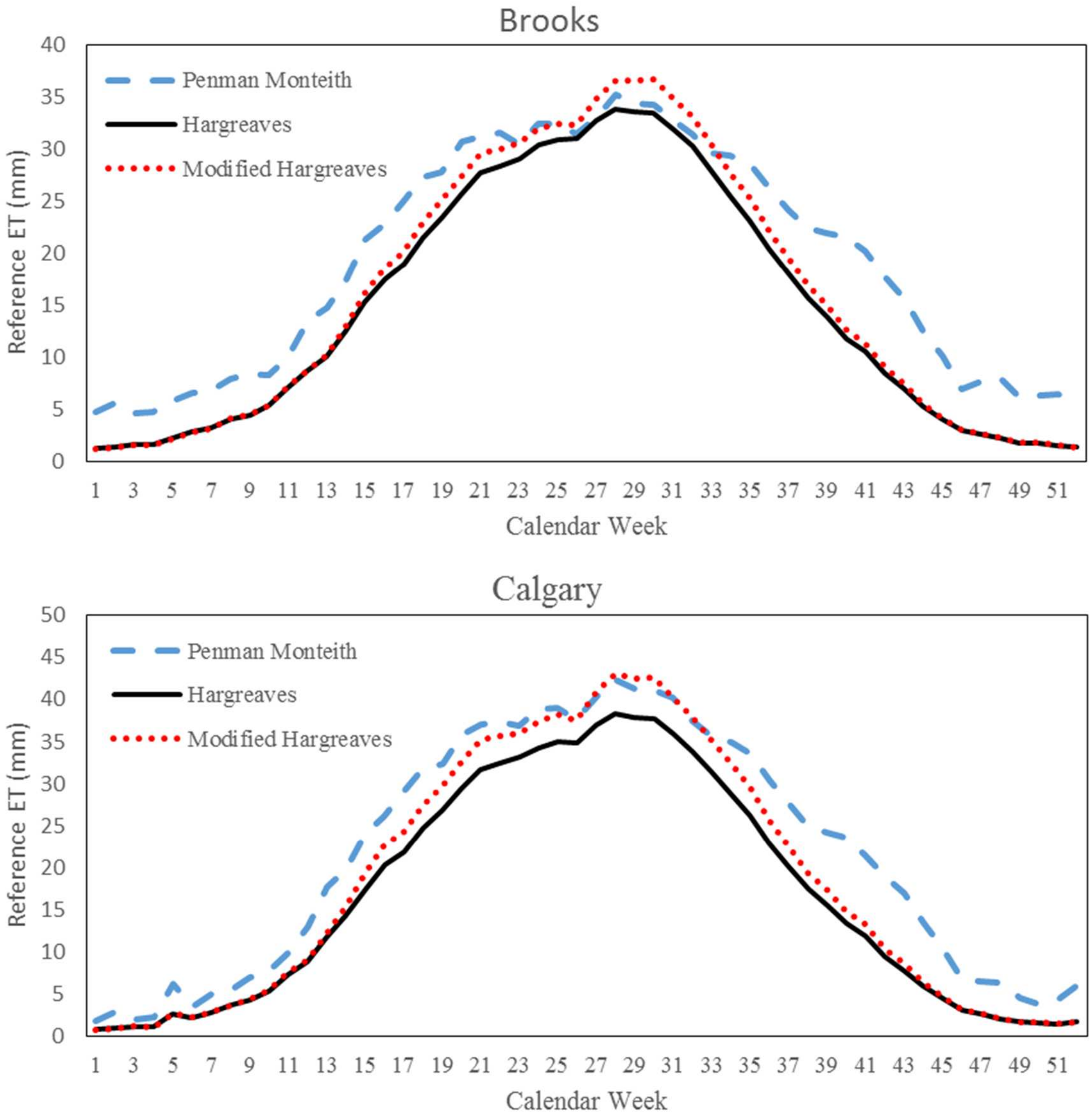


Figure 4.13- Comparison of the average weekly Reference ET for Brooks and Calgary

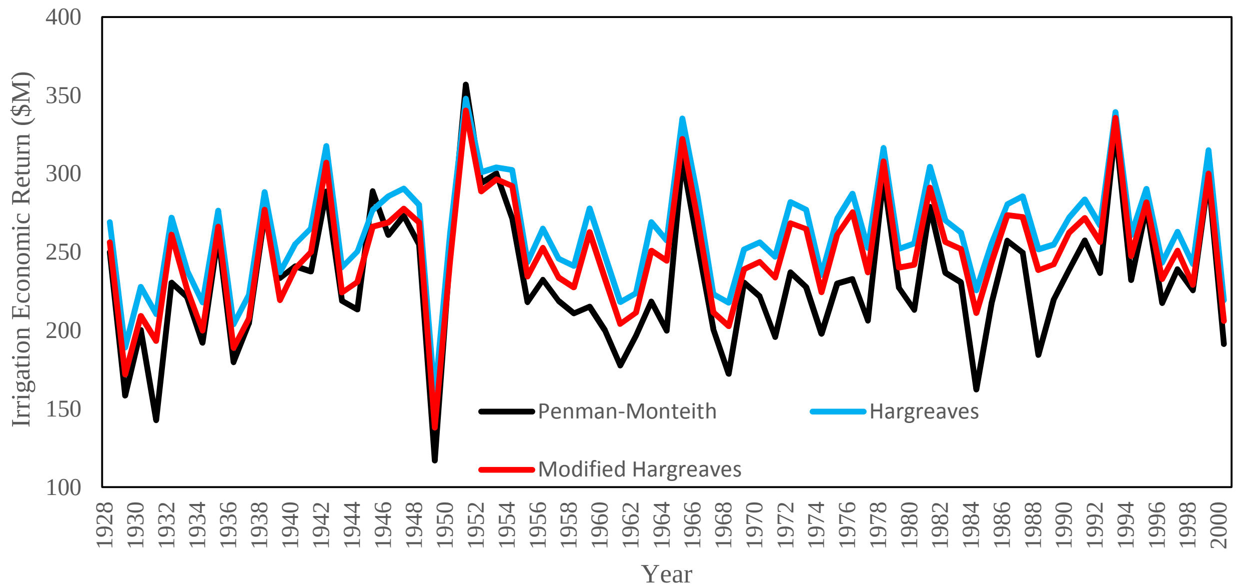


Figure 4.14- Annual Irrigation Economic Return under baseline conditions utilizing different reference ET equations

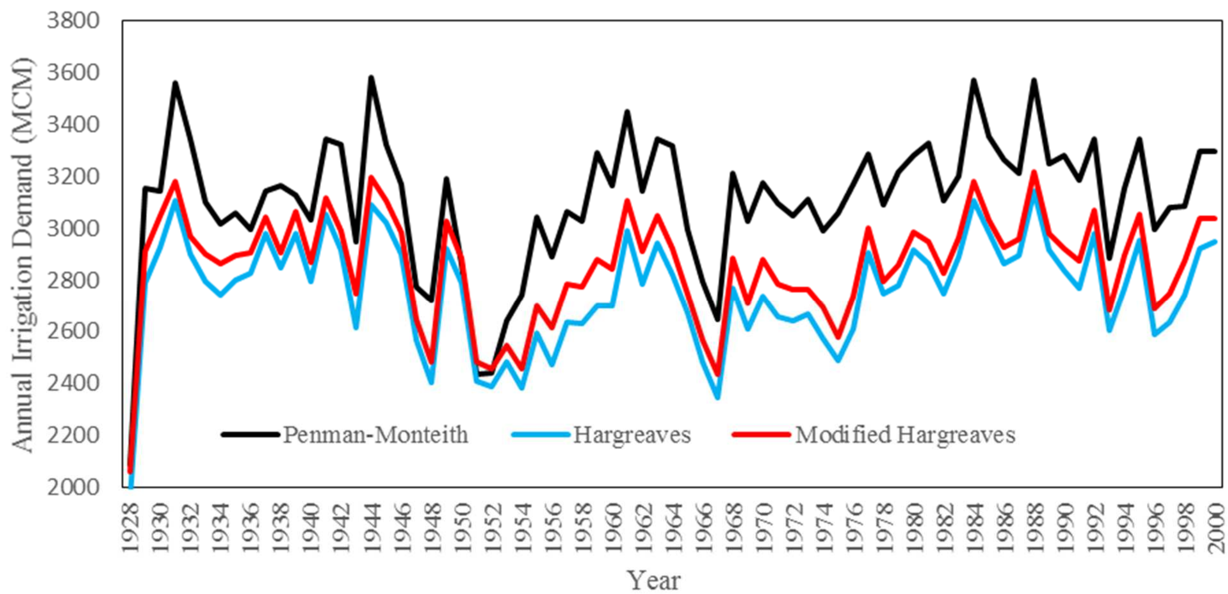


Figure 4.15-Annual irrigation demand under baseline conditions utilizing different reference ET equations

Another source of uncertainty with the irrigation component is the simplified runoff equation. As mentioned previously, this equation was simplified to reduce computation burden and data requirements of the model. The runoff is significant, in that the soil moisture, irrigation demand, economic return and environmental flow are affected. To examine these effects in the uncertainty of the runoff formulation in the model, under historical conditions, $SWAMP_B$ was run with incremental values of runoff. These incremental values specify a fixed percentage of runoff that occurs, regardless of soil conditions or rainfall. For example, if the runoff percentage was specified as 5%, then at every time step 95% of the precipitation would infiltrate and the remaining 5% would be runoff. As the Baier and Robertson (1966) method averages approximately 2% runoff across the historical period in the Bow basin, the bounds of this sensitivity was set between 0% and 20% runoff.

Figure 4.16 illustrates the average weekly irrigation demand on a seasonal basis for each of the irrigation districts. The magnitude of irrigation demand is significantly impacted by incremental differences in the runoff, in most cases with the potential to increase irrigation demand. Since runoff directly determines the quantity of precipitation that contributes to soil moisture, it is expected that a greater percentage of runoff would equate to larger irrigation demands. The increased irrigation demands then result in greater crop water shortages, as shown in Figure 4.17 and less flow in the Bow River, shown in Figure 4.18. Similarly, this variability in irrigation demand carries over to the irrigation economic return as shown in Figure 4.19. Although in reality some of the additional runoff would contribute to streamflow, thus providing more available water for irrigation, this mechanism is not provided in $SWMAP_B$. Although the crop water demand is quite sensitive to runoff, the variability in runoff has minimal effects on stream flow- with reductions in flow concentrated to peak streamflows. The impact on the economic return is minor, with only small decreases in return with increasing runoff. Figure 4.19 illustrates the impacts of runoff on economic return.

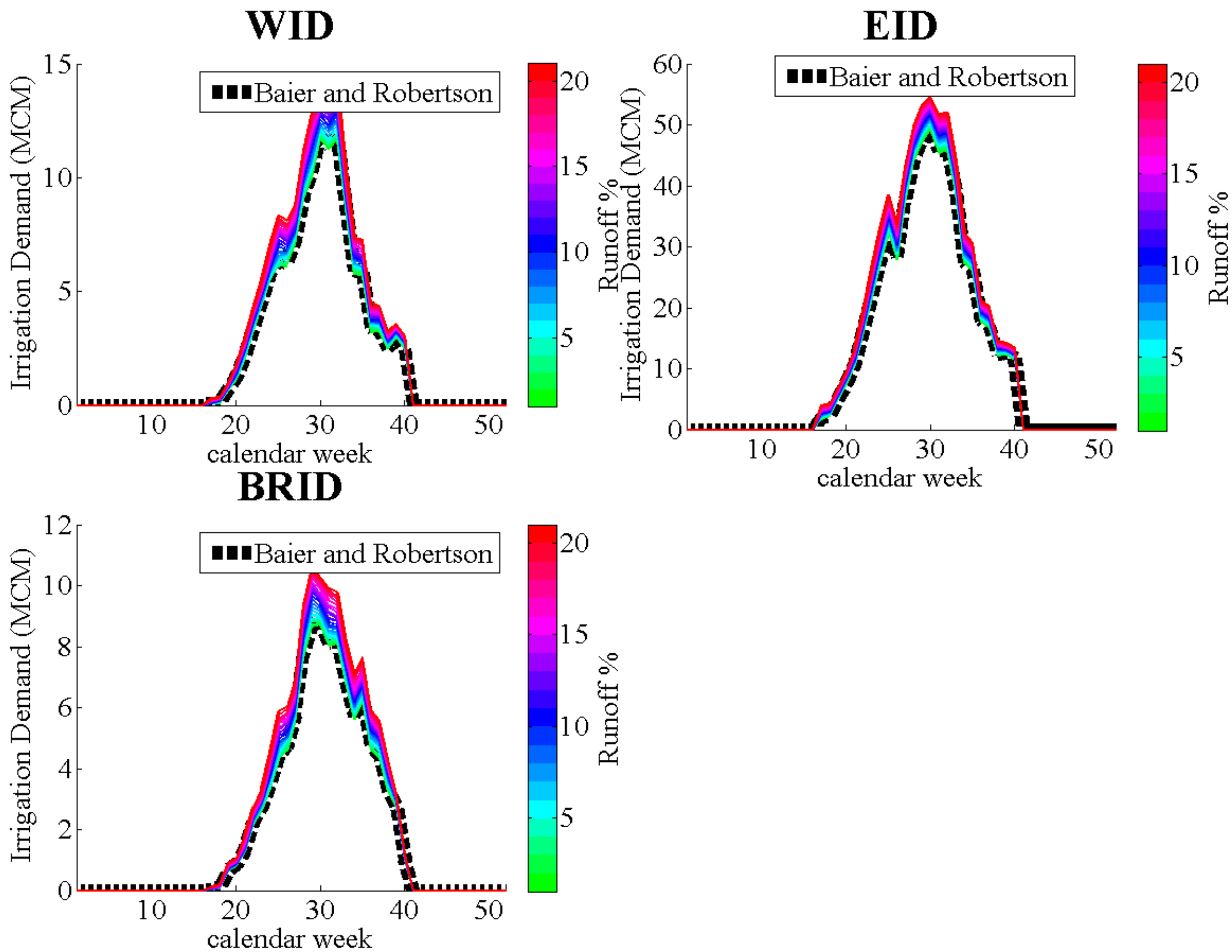


Figure 4.16- Sensitivity of irrigation demand to runoff under baseline conditions with incrementally increasing runoff percentage

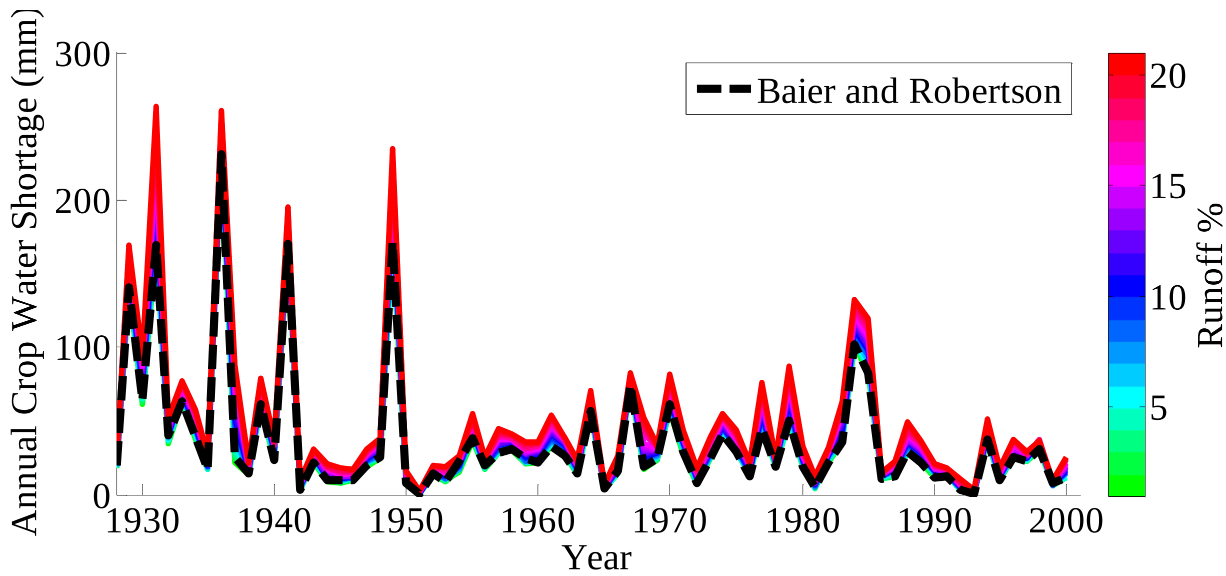


Figure 4.17 Crop water shortage under baseline conditions with incrementally increasing runoff percentage

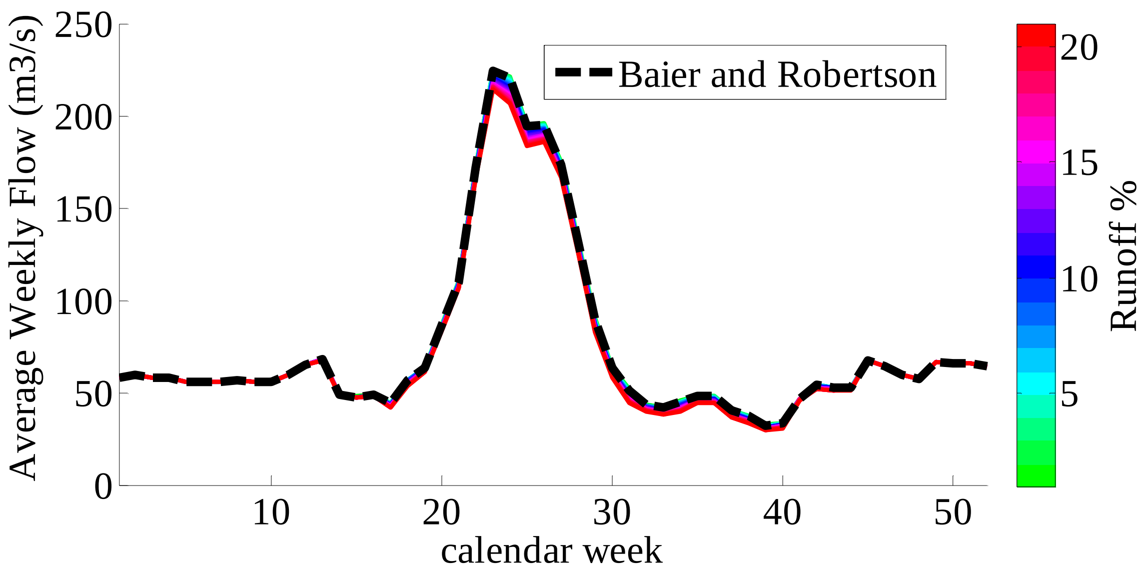


Figure 4.18- Bow River below Bassano streamflow under baseline conditions with incrementally increasing runoff percentage

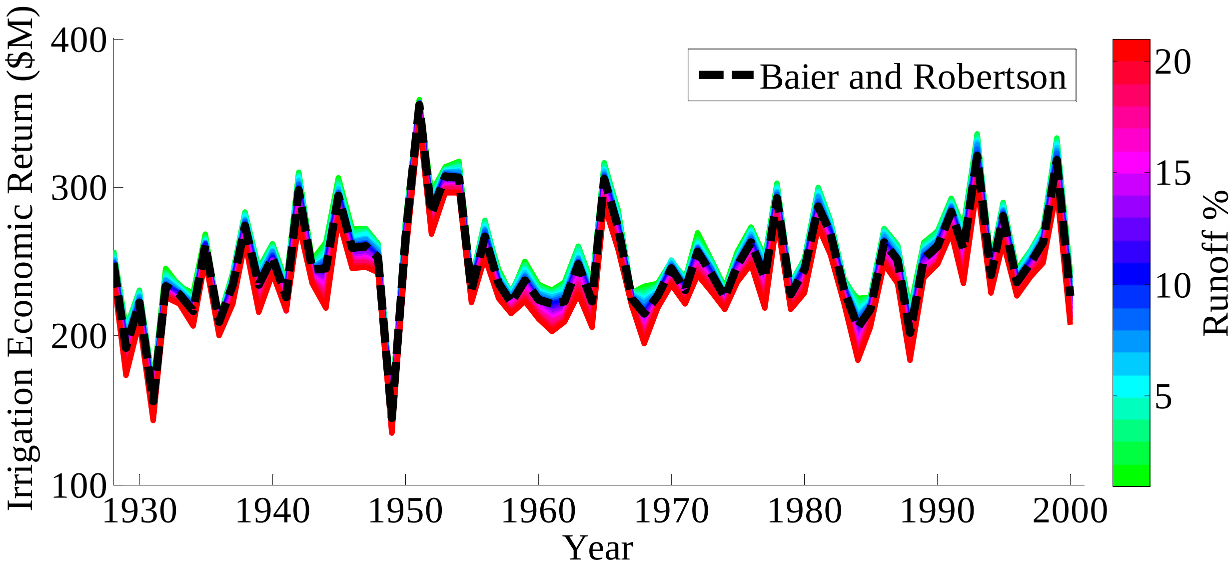


Figure 4.19- Irrigation economic return under baseline conditions with incrementally increasing runoff percentage

The simplifications of the Baier and Robertson (1966) runoff formulation were shown in Figures 4.16 – 4.19 to impact simulation results of $SWAMP_B$. Future work on $SWAMP_B$ should consider this sensitivity, and a more thorough approximation of runoff could produce better results. Though the soil moisture was most significantly impacted, this approximation has minor effects on the economic return and stream flows.

Assumptions in the rainfall mode were examined through sensitivity to runoff; now sensitivity to assumptions in precipitation to the winter mode is examined. Since the process of sublimation and redistribution requires many variables, it was simplified in a similar manner to the return flow. By default it was assumed the sublimation and redistribution of snow removed 75% of precipitation due to snow every week that snowfall occurred. This assumption, though highly simplified, does not affect the overall simulation results of $SWAMP_B$. In Figure 4.20 and Figure 4.21 the sublimation and redistribution was varied incrementally between 60% and 90% of the snowfall for every week- which is 15% greater or less than the default assumption. These two figures illustrate that deviating sublimation and redistribution by 40% has negligible effects on the irrigation economic return and the streamflow in the Bow River below Bassano.

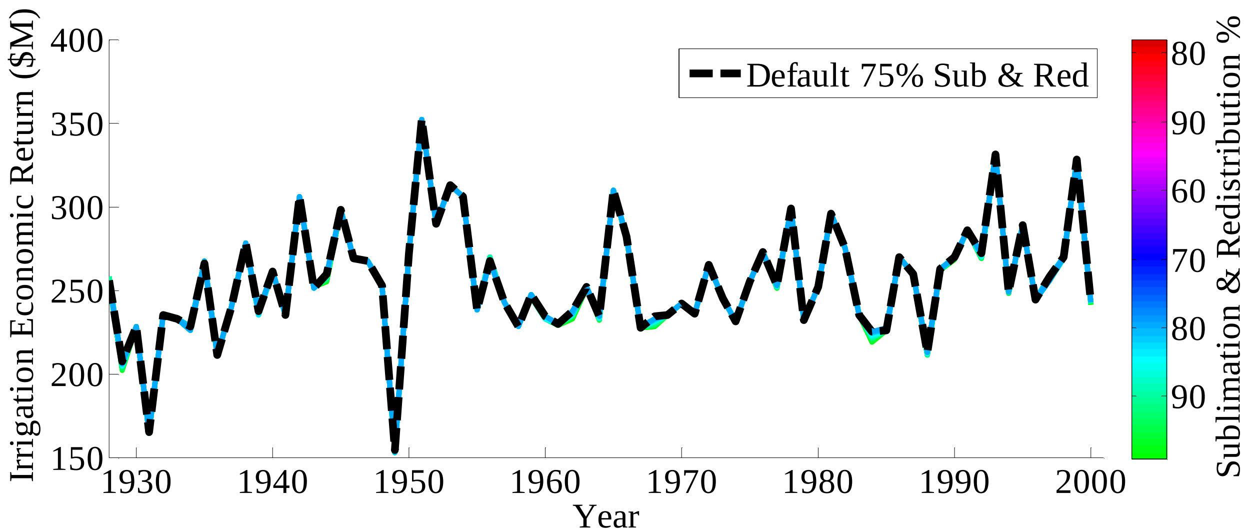


Figure 4.20- Irrigation economic return under baseline conditions with incrementally increasing sublimation and redistribution

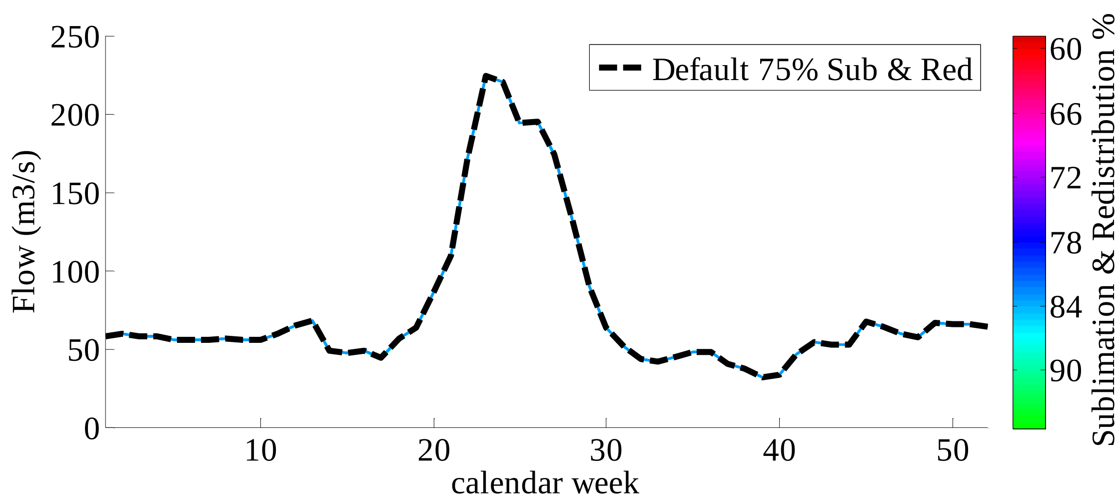


Figure 4.21- Streamflow of Bow River below Bassano under baseline conditions with incrementally increasing sublimation and redistribution

In addition to the reference ET equations and the summer and winter mode of precipitation, the return flow is also a base assumption in the model. $SWAMP_B$ specifies a runoff of 10% of the total irrigation supplied, which equates to the average return flow specified in WRMM. Though $SWAMP_B$'s return flow is similar as specified to WRMM, it is based on an assumption that does not reflect complexities in reality. Similar to the sensitivity of runoff, the return flow is incrementally varied between 0% and 20% of irrigation water supplied, with results plotted. This range represents the extremes of no return flow, to twice the assumed return flow, and the analysis considers a historical simulation period. Though return flow does not directly affect soil moisture, it contributes to water available in the model. It is shown in Figure 4.21 that varying the return flow between 0% (no return flow) and 20% (twice the default in $SWAMP_B$) has little effects on reservoir levels. Only Crawling Reservoir and Lake Newell see any impact from return flow, as they are furthest downstream and likely accumulate most of the flow returned. The impact on both the irrigation economic return and flow downstream Bassano is insignificant, as shown in Figure 4.22 and Figure 4.23 respectively. The flow downstream Bassano is not significantly affected by return flow since only WID's return flow reaches the Bow River downstream Bassano. Return flow from BRID contributes to the Oldman Basin and return flow from EID contributes to the Reddeer basin. These two other basins are outside the scope of the present work, so sensitivities within these basins are not presented.

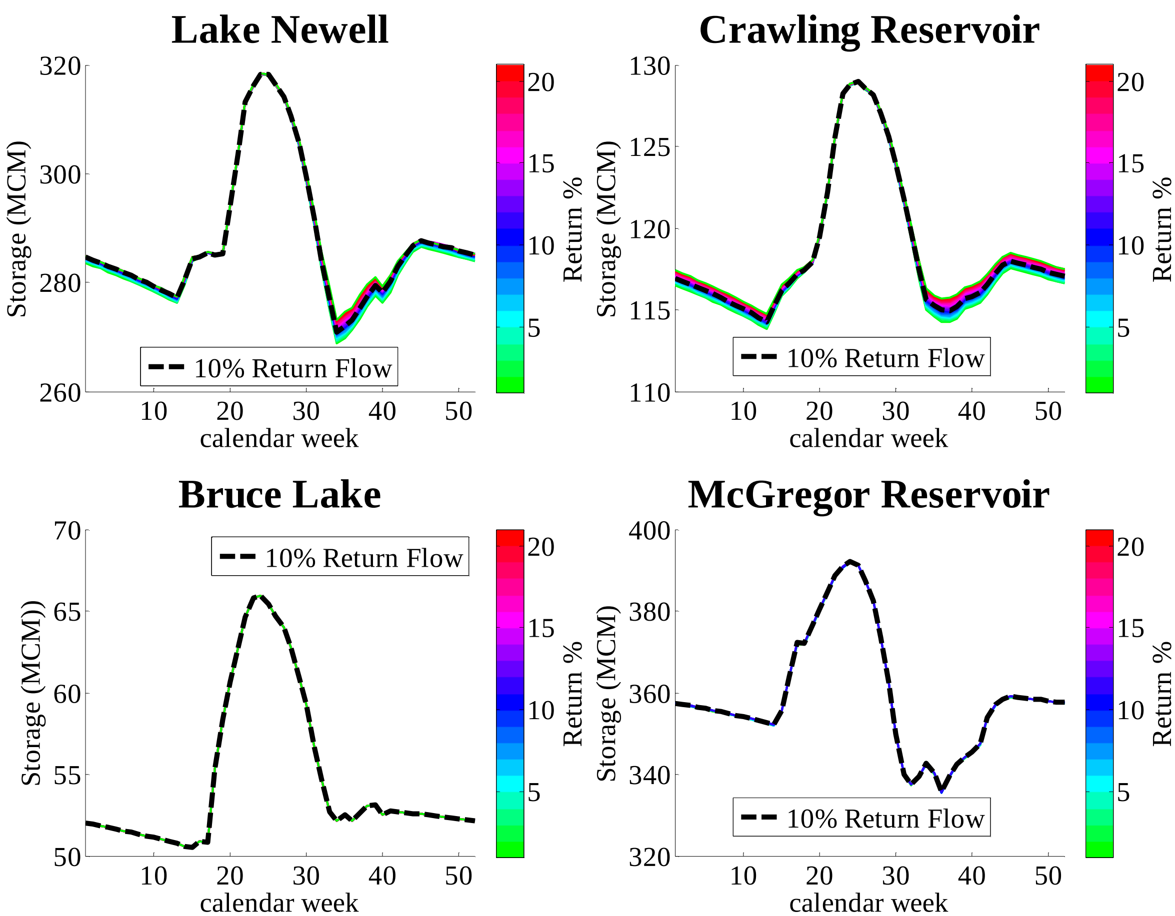


Figure 4.22- Reservoir storage under incrementally increasing return flow with baseline conditions

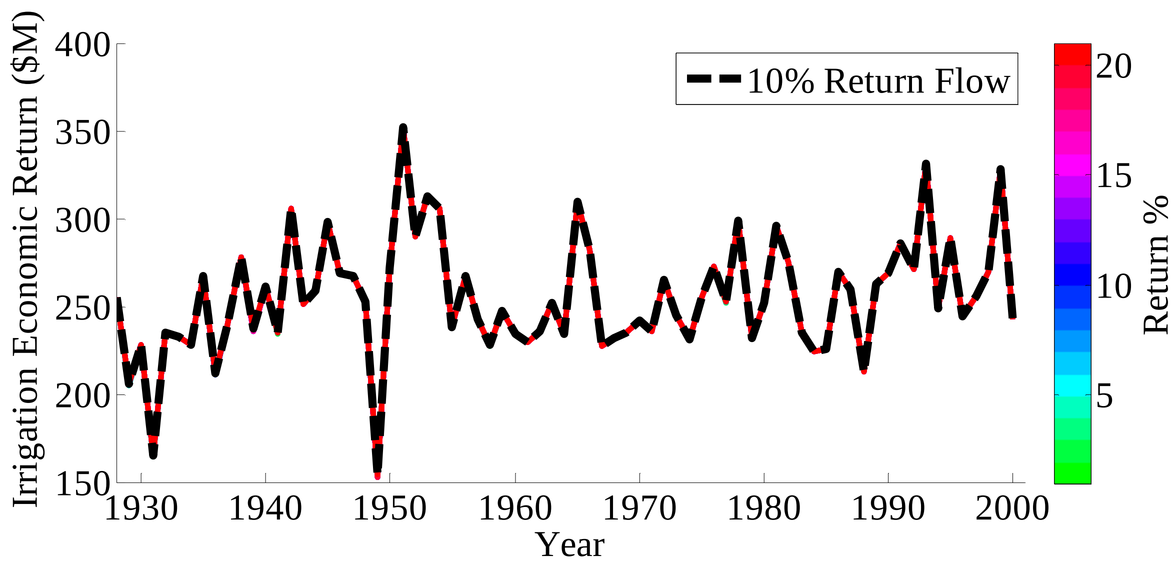


Figure 4.23- Irrigation economic return under baseline conditions with incrementally increasing return flow

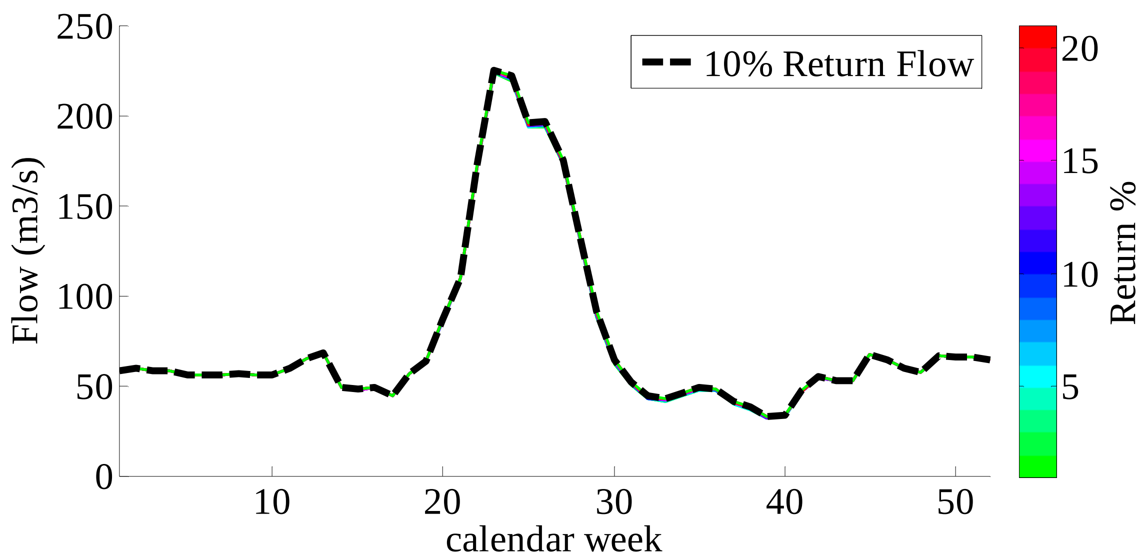


Figure 4.24- Streamflow of Bow River below Bassano under baseline conditions with incrementally increasing return flow

There were many assumptions in the irrigation component that were analyzed in this section. $SWAMP_B$ was found to be sensitive to assumptions made in the runoff formulation, and potential differences in potential ET. The irrigation demand was seen to be much greater with Penman-Monteith potential ET formulation as opposed to simpler Hargreaves and Modified Hargreaves. Conversely, the irrigation demand and irrigation deficits were of a lower magnitude with the assumptions made in $SWAMP_B$ for runoff, to what could potentially be the case. Similar results, but of the opposite effect, were observed when comparing the environmental flow and economic returns. As a whole, the return flow and snow redistribution and sublimation does not play a significant role in the irrigation component, and assumptions made in this regard will not significantly affect simulation results. These sensitivity analyses illustrate that limitations are present in $SWAMP_B$'s irrigation component, with the potential to alter simulation results. Although the simulation results may differ with a more comprehensive representation of these hydrological assumptions, the sensitivity analyses suggest only runoff could significantly alter simulation results.

4.3 TransAlta Verification

Although the simulated release from the TransAlta reservoirs is provided in WRMM, the model does not contain the operations of these reservoir nor the operational rules. This section discusses the calibration and validation of the lumped TransAlta model developed to simulate this release, as well as the approximated volume-area relationship. First the weekly storage of the lumped TransAlta system is compared to historical values to assess the validity of the constant relating volume to area. Next, the calibration and validation of the release in $SWAMP_B$ is compared to WRMM. Last, both $SWAMP_B$ and WRMM releases are compared with observed flow values.

Figure 4.25 plots weekly storage values of $SWAMP_B$ against historical values for the lumped TransAlta system. With fixed inflows and outflows, the deviance in storage from historical values and $SWAMP_B$ is mainly due to the assumed volume-area constant, relating precipitation and evaporation depth to their respective volume. As seen in Figure 4.25, the weekly storage in $SWAMP_B$ stays within the minimum and maximum storage bounds, and follows historical values well. Though this comparison is only available from 1955 and onwards (the TransAlta system wasn't complete until 1955), it still provides a continuous period of several decades. This comparison illustrates that although the assumption of a constant volume-area is highly simplified, it still provides a good estimate.

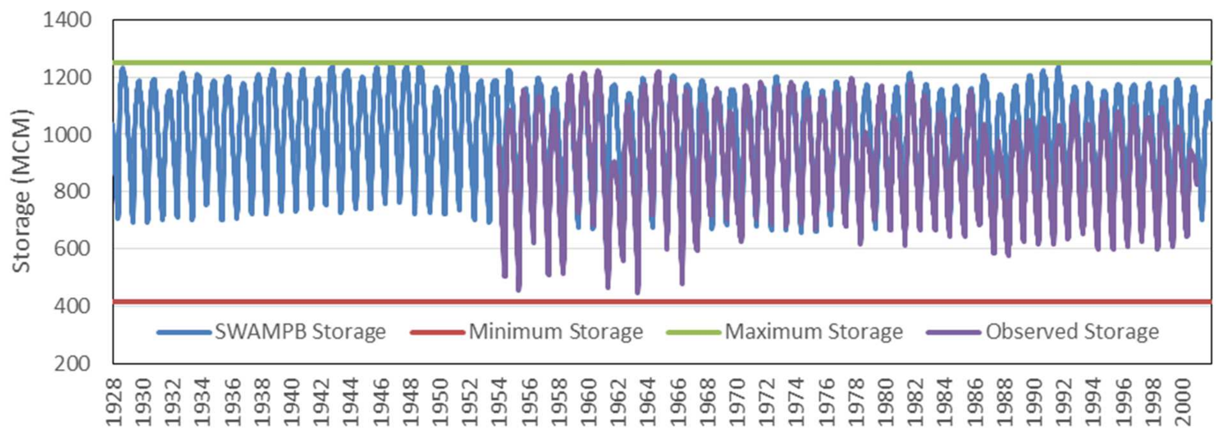


Figure 4.25- Weekly Storage of the lumped TransAlta reservoir system with fixed inflows and outflows, and assumed volume-area relationship

Release from the TransAlta lumped reservoir system was calibrated using weekly flow data from 1928-1975, and then validated for the period of 1976-2001. In order to take the seasonal operations of the reservoirs into account, individual equations were developed for 4-week periods. The calibration and validation R^2, as well as the release equations, are displayed in Table 4.1. Overall, the equation development is quite satisfactory, with some difficulties seen in the spring and fall periods (e.g. low R^2 for weeks 13-16 and 41-48). This difficulty is likely due to the variable operations at and around the spring thaw and winter freeze-up. The performance of the TransAlta sub-model to emulate WRMM is shown in Figure 4.26. The performance of the lumped reservoir system is very similar to WRMM.

Table 4.1- TransAlta Release Equations and Their Performance

Weeks	Equation	Calibration R^2	Validation R^2
1-4	$1.0021 * \text{Inflow(t)} + 9.23 * 10^{-4} * \text{Storage}(t-1) + 17.76$	0.9274	0.8970
5-8	$0.9877 * \text{Inflow(t)} + 6.227 * 10^{-4} * \text{Storage}(t-1) + 17.163$	0.9466	0.9575
9-12	$0.8965 * \text{Inflow(t)} + 0.0014 * \text{Storage}(t-1) + 16.815$	0.9095	0.8258
13-16	$1.0245 * \text{Inflow(t)} - 0.0534 * \text{Storage}(t-1) + 66.5756$	0.6206	0.6868
17-20	$0.5442 * \text{Inflow(t)} + 0.0798 * \text{Storage}(t-1) - 30.7486$	0.8795	0.9412
21-24	$0.4374 * \text{Inflow(t)} + 0.1289 * \text{Storage}(t-1) - 66.498$	0.9135	0.8437
25-28	$0.7039 * \text{Inflow(t)} + 0.1464 * \text{Storage}(t-1) - 138.1093$	0.9164	0.8809
29-32	$0.8488 * \text{Inflow(t)} + 0.099 * \text{Storage}(t-1) - 111.8725$	0.9635	0.9761
33-36	$0.865 * \text{Inflow(t)} + 0.0868 * \text{Storage}(t-1) - 99.813$	0.9355	0.9335
37-40	$0.9113 * \text{Inflow(t)} + 0.0864 * \text{Storage}(t-1) - 100.8302$	0.8930	0.8629
41-44	$0.9481 * \text{Inflow(t)} + 0.0286 * \text{Storage}(t-1) - 30.9472$	0.7620	0.7746
45-48	$1.002 * \text{Inflow(t)} - 0.021 * \text{Storage}(t-1) + 35.889$	0.6073	0.5992
49-52	$1.1052 * \text{Inflow(t)} - 0.0297 * \text{Storage}(t-1) + 51.7142$	0.7892	0.7046

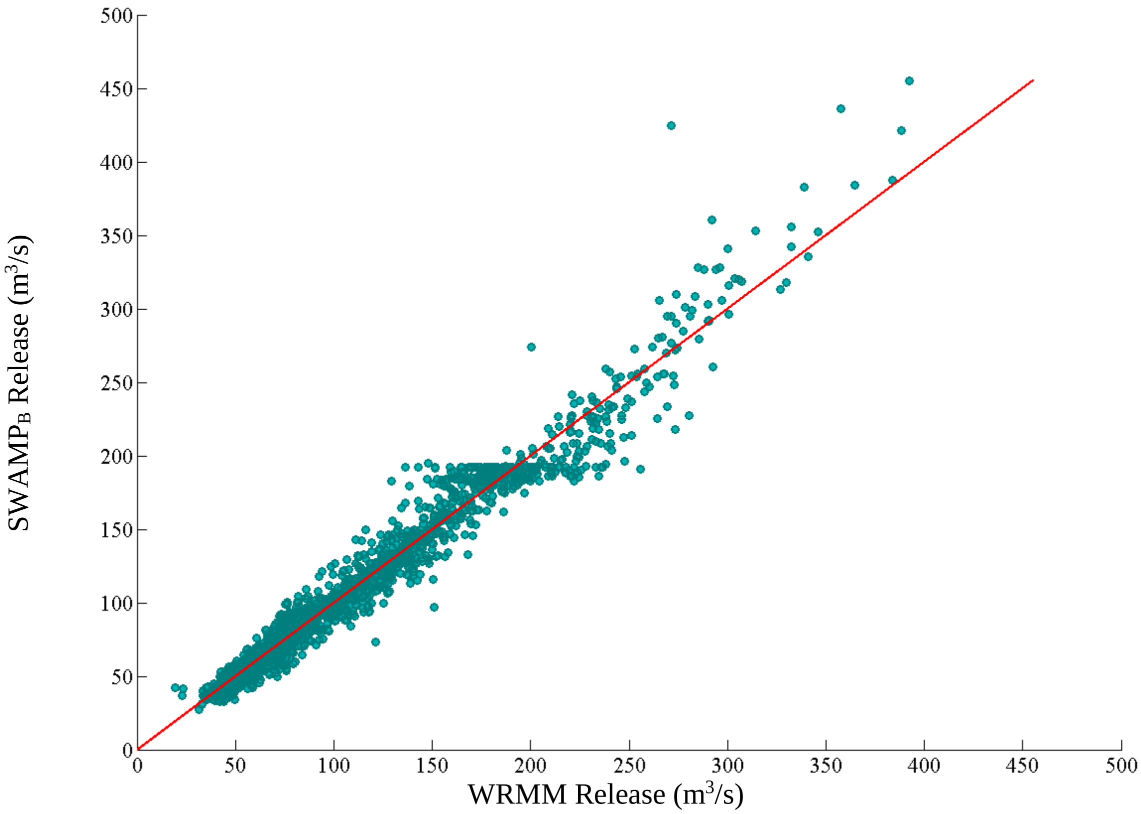


Figure 4.26- Scatter plot comparing the $SWAMP_B$ and WRMM weekly release from the TransAlta reservoirs

With $SWAMP_B$ shown to effectively emulate WRMM, in regard to the TransAlta releases, the models are then compared to observed records. Both $SWAMP_B$ and WRMM were compared with the historical release from TransAlta in Figure 4.27. Since all reservoirs considered in the TransAlta model were not in operation until 1955, older historical records could not be used. Further, not all years contained complete records, so a period from 1968-1977 was considered. From Figure 4.27 one can observe that both $SWAMP_B$ and WRMM match the historical flow quite well.

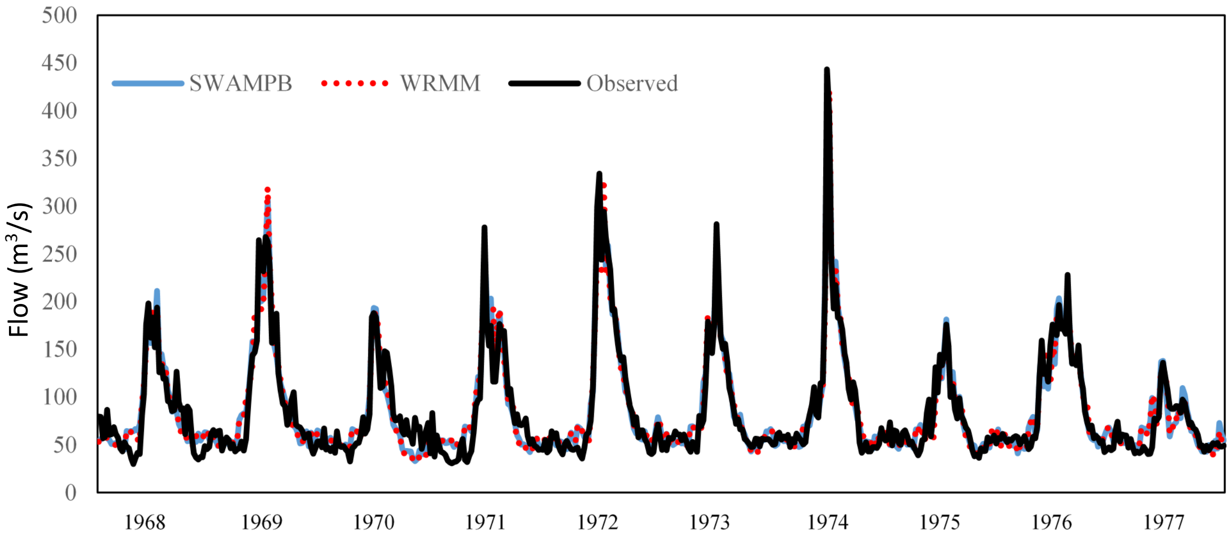


Figure 4.27- Weekly Release of TransAlta reservoirs from 1968-1977. Comparison of $SWAMP_B$ and WRMM against observed values

4.4 Verification with Historical Data

The previous sections verified $SWAMP_B$ as an emulation model- one that allocates water in the Bow in a similar manner as WRMM. Outputs of $SWAMP_B$ were compared against WRMM over the simulation period. This section shows comparison between both $SWAMP_B$ and WRMM against observed records. The primary purpose of this research was to emulate WRMM, so this section is a further examination of $SWAMP_B$. Since the assumed demands for both models are derived from licenses rather than the actual demands (water withdrawn) the allocation is not expected to precisely match with historical records. Errors between modeled and observed values are a function of uncertainty in the true water demands, and assumptions of the license values.

Unfortunately, all reservoirs in the Bow system (other than the TransAlta reservoirs) have limited elevation monitoring data available. For this reason, only McGregor reservoir was considered in this section, as it has the longest continuous record available. Both McGregor reservoir levels and flow downstream Bassano is compared to $SWAMP_B$ and WRMM in Figure

4.28. As seen, neither WRMM nor SWAMP$_B$ model McGregor reservoir's level very well for the period considered. In both cases the models over-estimate levels, likely because they are programmed to satisfy the reservoir rule curves if possible. On the other hand, flow downstream of Bassano was modeled quite well. These results illustrate that the models may not follow reality as they attempt to mimic rules that may not always be followed by reservoir operators. Still, they are valuable as the operations can be altered in the model, and the current models give users insight into the Bow system. Such applications of SWAMP$_B$ will be the subject of the following chapter.

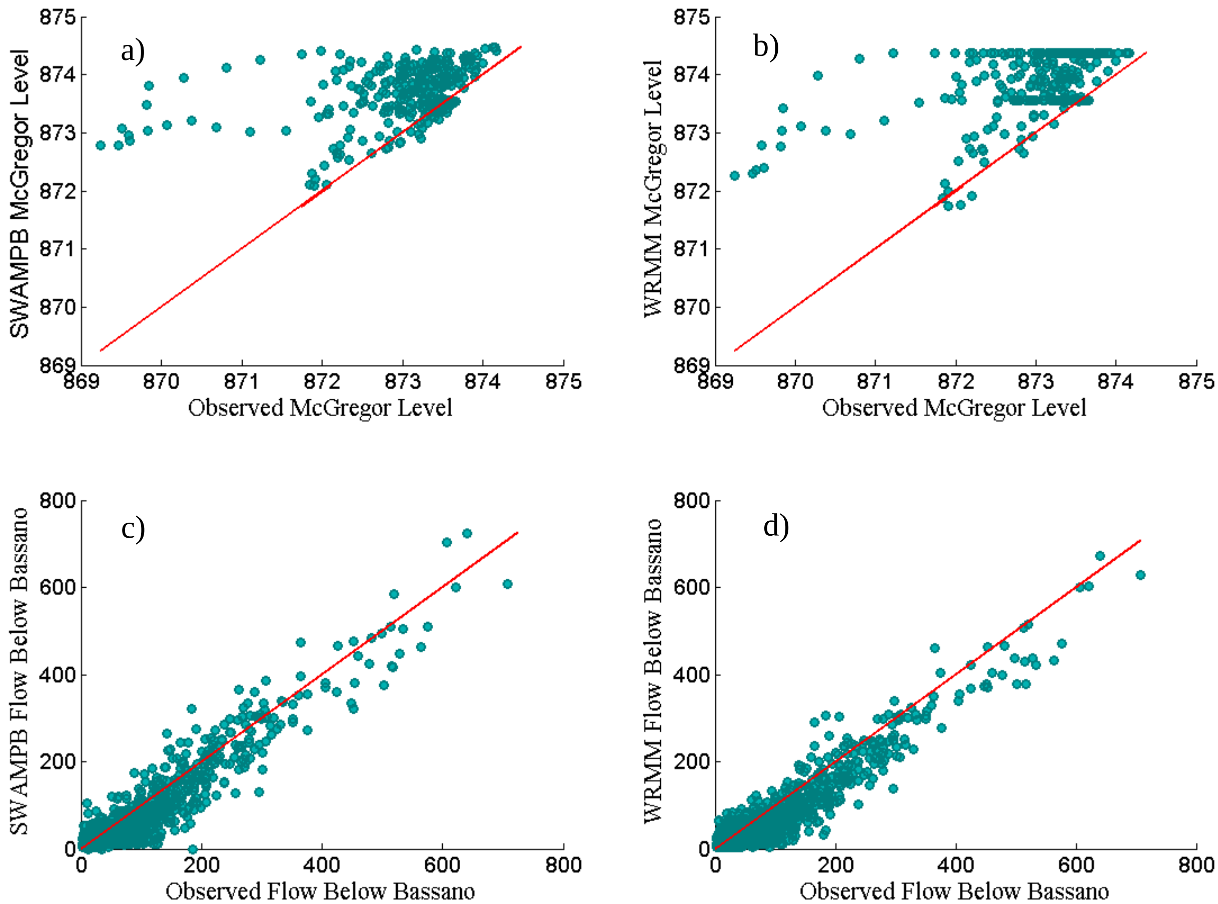


Figure 4.28- Comparison of WRMM and SWAMP with observed historical data: (a) and (b) compare reservoir level (m) of SWAMP$_B$ and WRMM respectively; (c) and (d) compare flow (m^3/s) of SWAMP$_B$ and WRMM, respectively

Chapter 5 Simulation Results

As discussed in Sections 1.1 (Background) and 3.6 (Scenario Design), there is competition for water use between various sectors- most notably the economy and the environment. The present section examines the efficacy of five scenarios to restore environmental flows while minimizing the burden on other sectors. First the three management scenarios, S1 (increasing irrigation efficiency to 90%), S2 (40% more water released during summer period from TransAlta reservoirs), and S3 (combination of S1 and S2) are examined, as these three require no adaptations to the license structure. In Section 5.2 the license structure is altered to accommodate for more environmental flow, as per the Instream Flow Needs (S4) and the Water Conservation Objective S5. All five scenarios, as well as the baseline, are then compared by using sustainability indices discussed in section 3.7 (Evaluation of Scenarios). Key tradeoffs considered hydropower and irrigation economic return (individually and combined), water use for municipalities, environmental flow and crop water shortages.

5.1 Implementation of Management Interventions

Scenarios S1, S2, and S3 were examined first as they have the potential to mitigate environmental impacts without enforcing any regulations to license holders. To evaluate the effectiveness of both scenarios, a sensitivity analysis was conducted, using the VENSIM software. By incrementally stepping through values, the TransAlta Release was increased between 0% and 40% of baseline flow, and the irrigation efficiency was varied between 80% and 90%. The TransAlta release was varied incrementally by steps of 1% and the irrigation efficiency by steps of 0.5% with all other controls held constant. The purpose of this sensitivity analysis was to determine if there is any optimal combination of S1 and S2, as well as to what degree the TransAlta release and irrigation efficiency affect the economic return and environmental flow. Similar to the scenario results discussed later, this sensitivity occurred over both the historical (1928-2001) and the 30 year paleo drought period. The lower and upper bounds of the TransAlta increased summer release approximate current conditions and natural summer flow conditions respectively. The results of this analysis are plotted in Figure 5.1 and Figure 5.2.

These two figures illustrate that the irrigation efficiency and the operations of the TransAlta lumped reservoir system do not have the same impact on the economy and environmental flow. A loose scatter on the bottom left plot in both figures suggests that streamflow is not very sensitive to increases in irrigation efficiency, whereas increasing summer release from the TransAlta reservoirs is shown to reduce environmental flow deficit. Although increasing irrigation efficiency does not affect environmental flow deficit significantly, it is shown to increase economic returns over both periods. An interesting point with these two figures is that increasing TransAlta summer release decreases economic return over the historical period, but increases economic return over the paleo reconstructed period. This suggests that the efficacy of the TransAlta operations is sensitive to the flow regime. During dry periods (e.g. reconstructed paleo series) the gain or loss of total economic return (hydropower and irrigation) is nearly negligible, as there is likely a shortage of water so there is little revenue to lose when releasing more water in the summer. On the other hand, the total economic return decreases over average conditions (e.g. historical period) as there is much to lose when releasing more water in the summer. . Further, this scatter is much tighter of the historical period, meaning that the economic return is much more sensitive to operations of the TransAlta reservoirs during the historical period- most likely because the reconstructed flows have less variance than historical flows. On average, the environmental flow deficit is still quite large, illustrating that these two solutions cannot restore environmental flow on the Bow River. The tradeoffs present with altering release from the TransAlta reservoirs are discussed next.

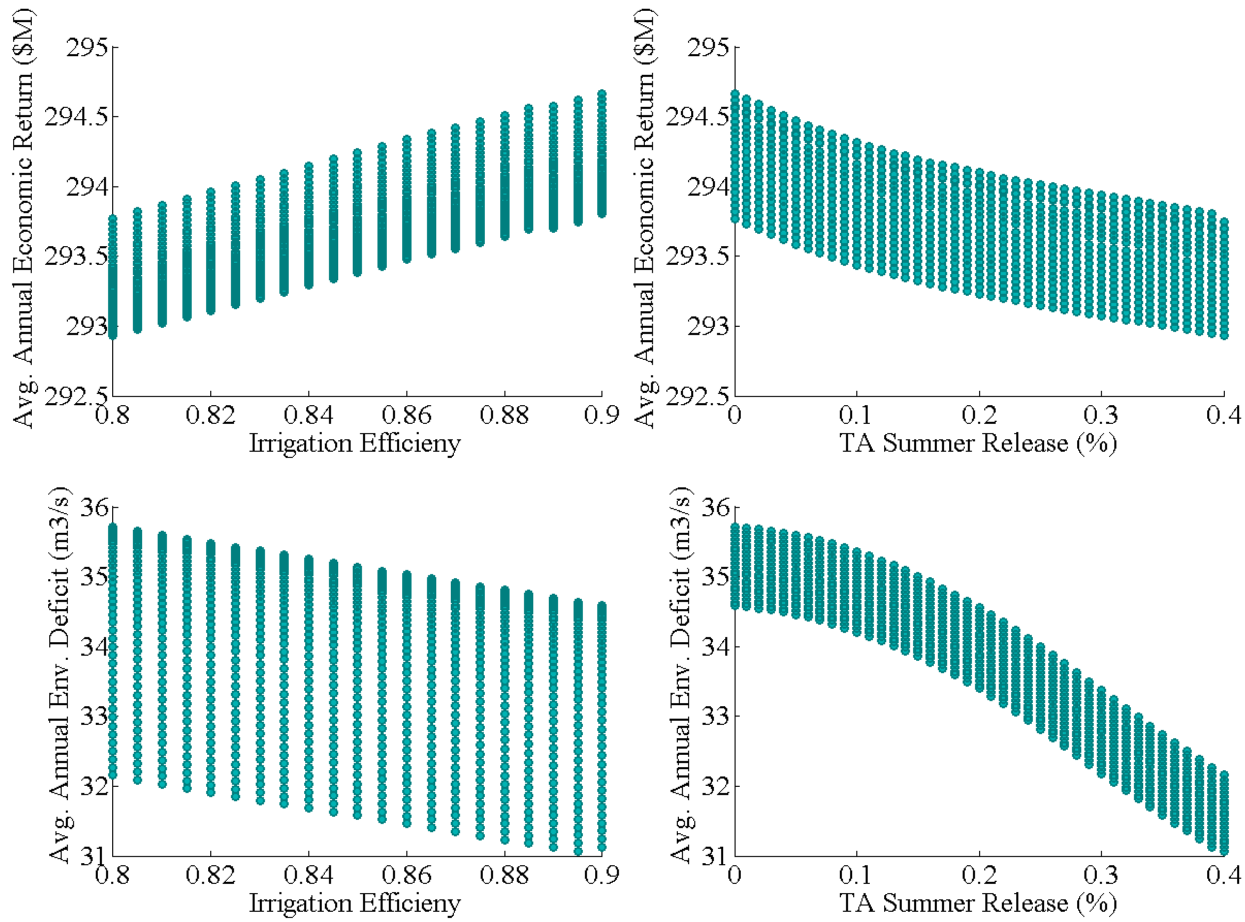


Figure 5.1-Scatter plots of varying irrigation efficiency and TA summer release over the historical period

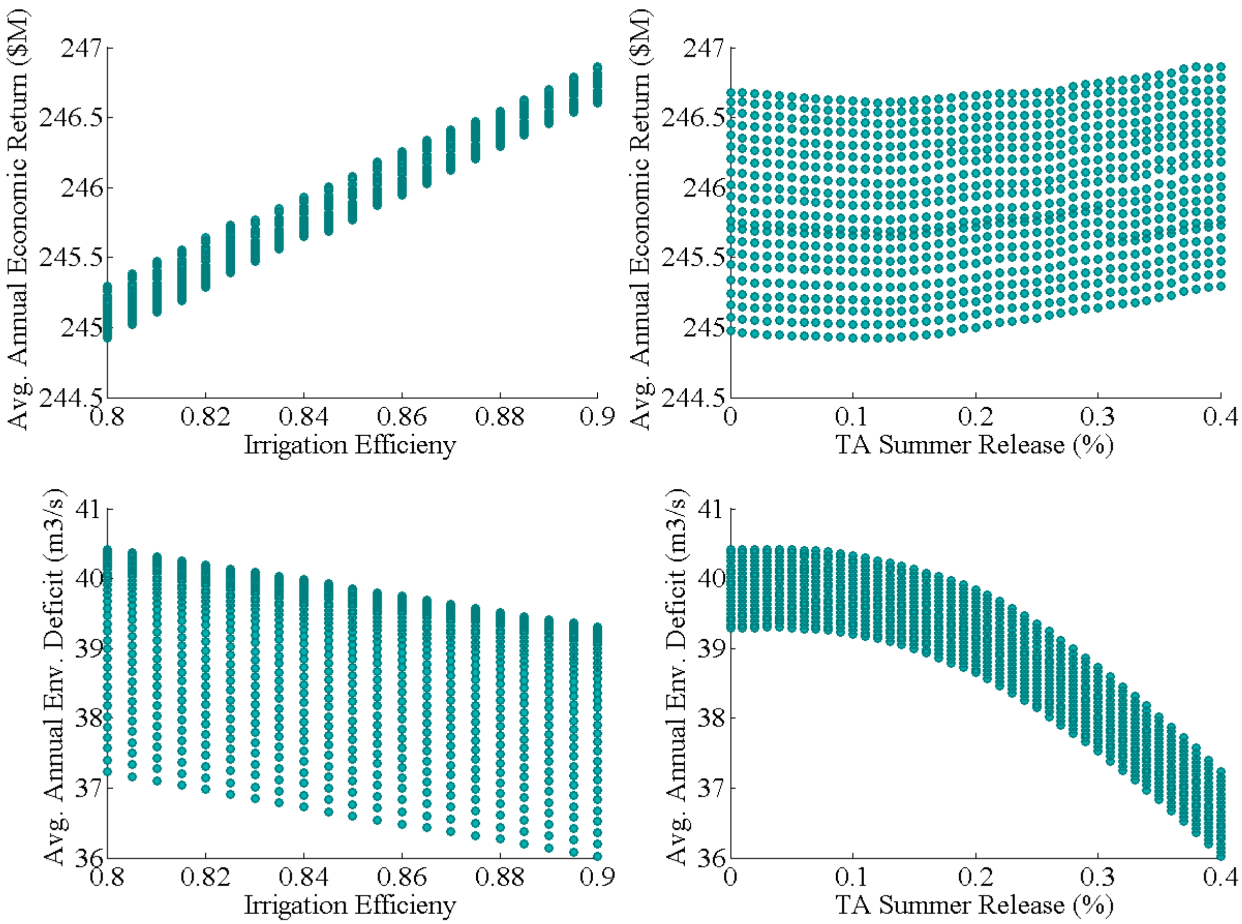


Figure 5.2-Scatter plots of varying irrigation efficiency and TA Summer Release over the paleo reconstructed period

The total economic return (irrigation and hydropower revenue) of the increased release during summer from the TransAlta reservoirs occur by two means. First, the hydropower revenue generated from TransAlta is a function of the timing and magnitude of reservoir release. By forcing more water to be released in the summer periods, there is less stored water to generate hydropower head, which reduces hydropower revenue. Second, by releasing more water in the summer months, there is more water in stream during peak crop water demands. This extra streamflow contributes to higher crop yields, generating more irrigation revenue.

Tradeoffs between the hydropower and crop revenue are apparent in Figure 5.3, comparing differential return of the TransAlta summer release scenario against the baseline scenario. Two things are apparent from this figure. First, there are many periods where losses from hydropower return are offset by gains in crop return. If one only considers the combined economic return, then it is apparent that releasing more flow in the summer is beneficial in some instances. Over the historical simulation period the gains in irrigation return do not offset losses from hydropower to a large enough degree for any overall net benefit. Conversely, the paleo reconstructed period has sufficient offsets by gains in crop return to produce a net benefit. Second, the economic gains and losses for the TransAlta hydropower and crop revenue have much inter-annual variability. Although variable, Figure 5.3 still illustrates that on average, over the entire simulation period (historical or paleo reconstructed), there is an economic gain to crop revenue and an economic loss to hydropower generation.

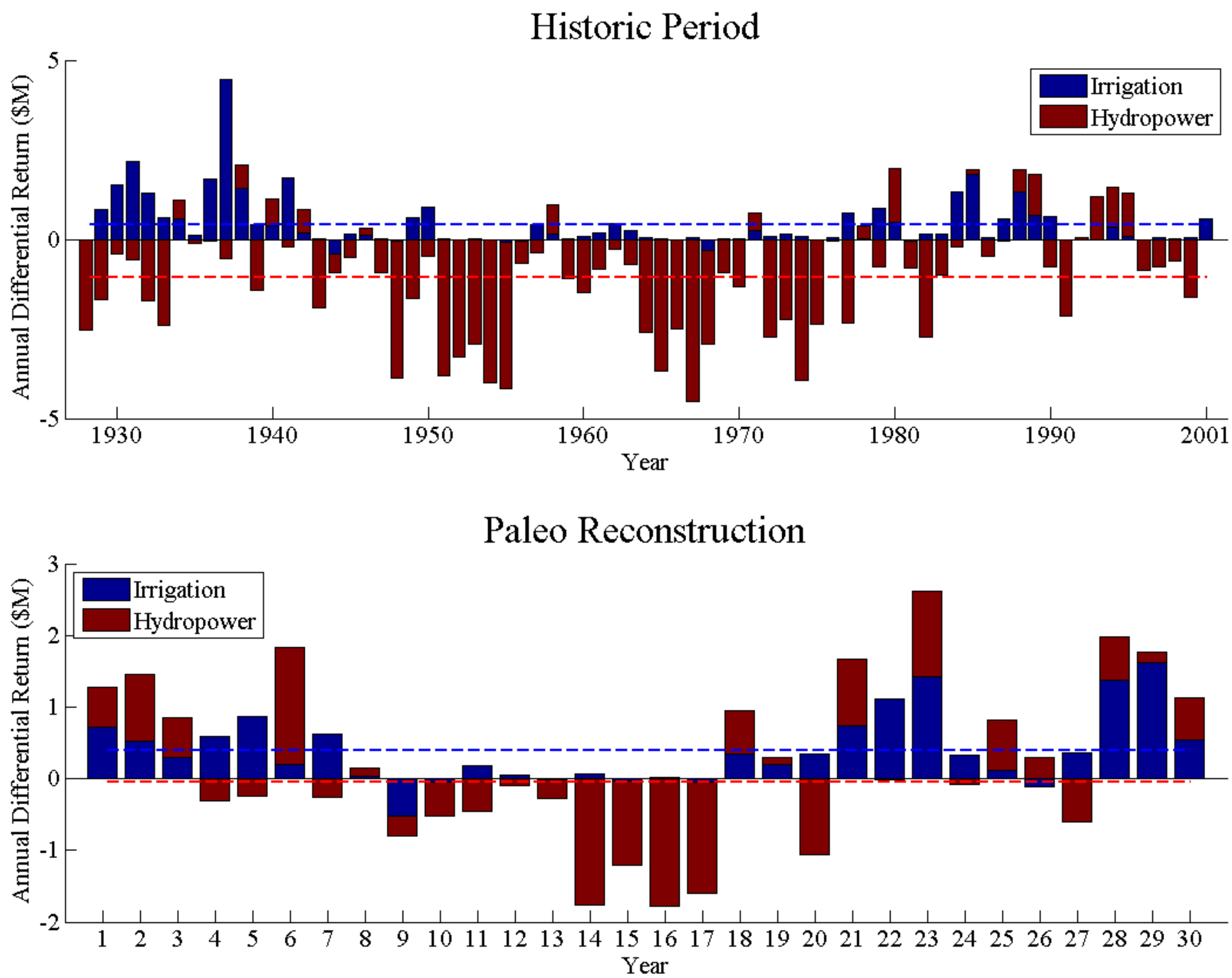


Figure 5.3-Annual Differential Return of the increased TransAlta summer release scenario in comparison with the baseline scenario. Bars represent cumulative annual values of the crop return and hydropower return, and dashed lines represent the average irrigation return and hydropower return over the entire simulation period.

The increased irrigation efficiency directly contributes to economic return because more water is available for crops. Because the crop water demand is not fully satisfied for most years, the gains in irrigation efficiency only serve to reduce the deficit and not restore environmental flow. As seen in Figure 5.4 and Figure 5.5, although minor, a crop water deficit persists in the majority of years during baseline conditions. The increased irrigation efficiency was shown to significantly reduce crop water shortages, with only three years having a shortage of more than 100 mm. This 100 mm deficit is a recommended threshold for most crops in Alberta, prescribed by IWMSC (2002). It was noted by IWMSC (2002) that irrigation deficits less than 100mm is financially insignificant as losses due to application are already accounted for (both in reality and in $SWAMP_B$'s calculation of irrigation demand), reducing the impact of 100mm deficit. Also irrigators can redistribute available water to higher value crops, further mitigating these small deficits. It may not be apparent in the bar graphs, but the increased summer release from the TransAlta reservoirs mitigates crop water shortages by a small amount. Table 5.1 summarizes the shortages across these three technical scenarios, highlighting that, as expected, the least shortage occurs when the TransAlta summer release is combined with the increased irrigation efficiency.

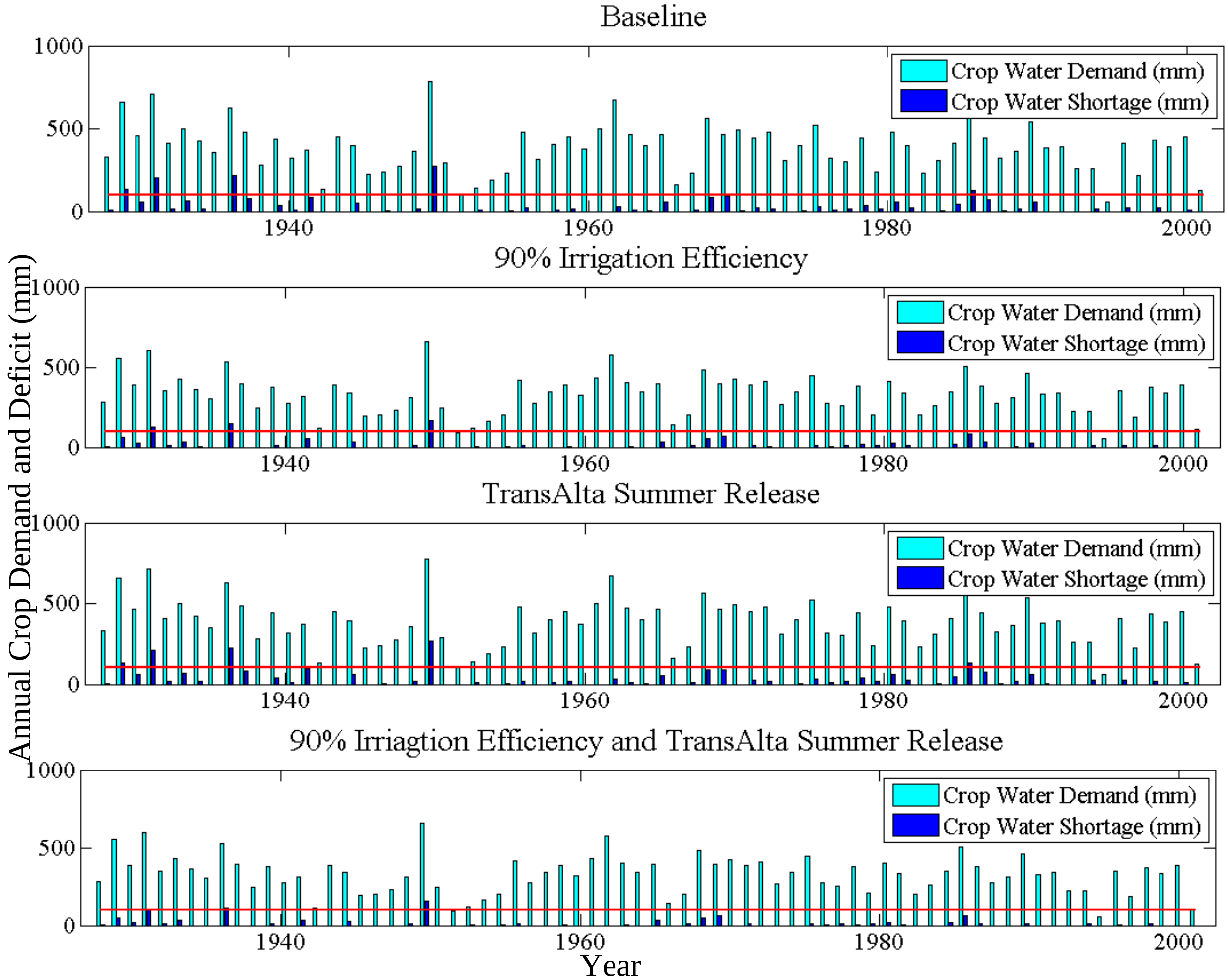


Figure 5.4-Total annual crop water demand and deficit over the historical simulation period. Depths are represented as the average values across all irrigation districts in the Bow Basin. The horizontal red line indicates the 100mm shortage threshold

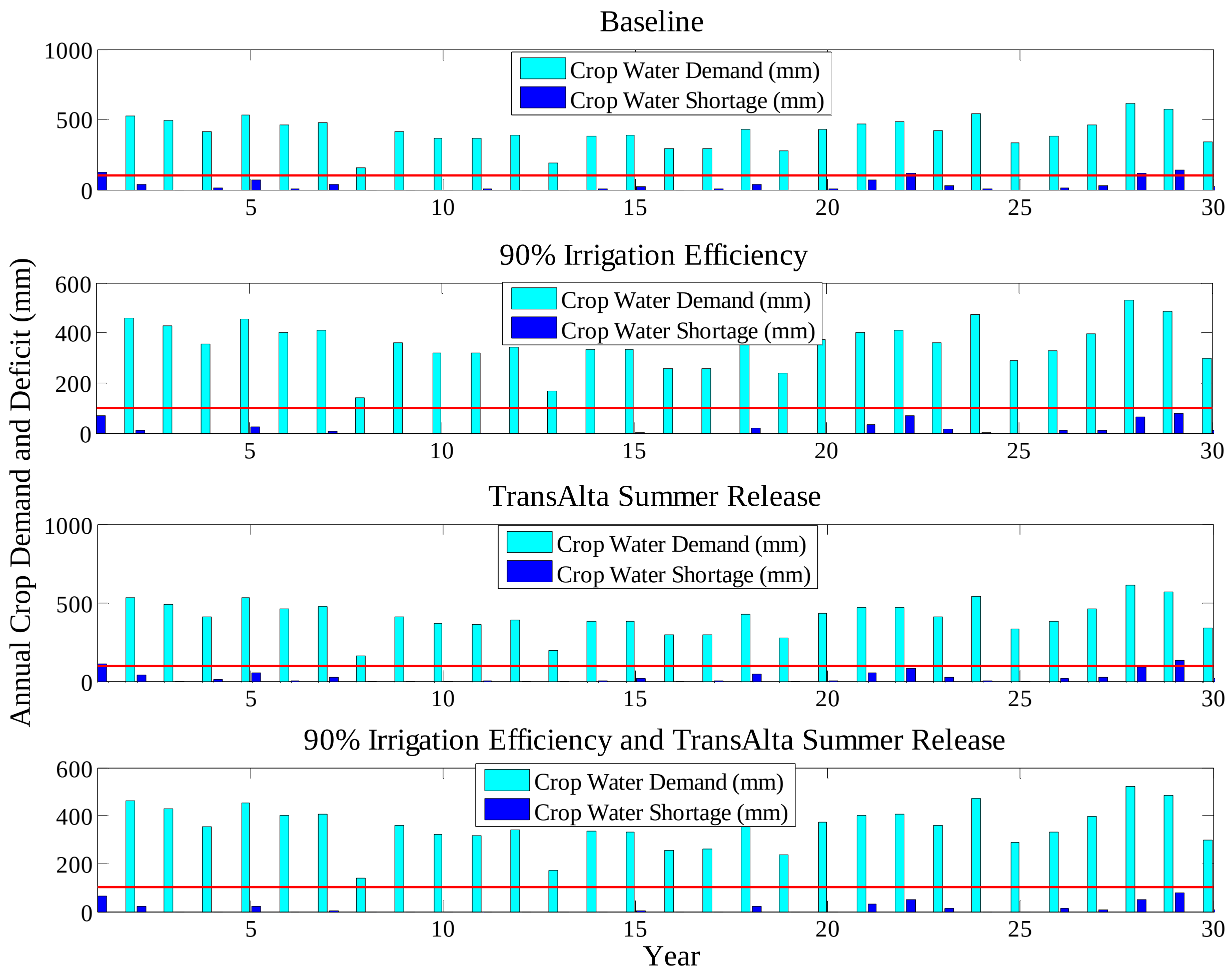


Figure 5.5-Total annual crop water demand and deficit over the paleo drought period. Depths are represented as the average values across all irrigation districts in the Bow Basin. The horizontal red line indicates the 100mm shortage threshold

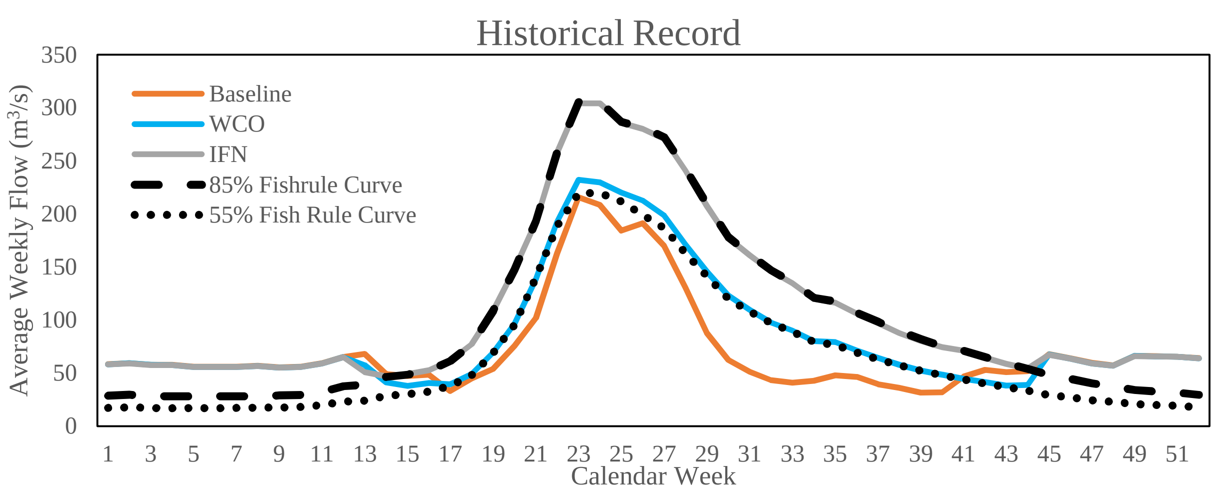
Table 5.1-Crop Water Deficit (mm)

Period	Baseline	90% Irrigation Efficiency	Summer TA Release	Combined
Historical	31.6	16.1	25.9	13.2
Paleo Drought	30.6	15.2	25.2	12.5

There is a negligible effect of these management solutions on the municipal water allocation. Currently, the water demands for municipal users are almost fully supplied during the baseline conditions. The three technical solutions provide negligible savings to the municipal users when they are already well supplied. Thus, results are not shown for the municipal allocation. In the next section, implementation of policy solutions, the impact on municipal allocation will be more prominent.

5.2 Implementation of Policy Interventions

The management solutions, increasing irrigation efficiency and altering the operation of TransAlta reservoirs, were seen ineffective at mitigating environmental flow deficit. Instead, the implementation of the IFN (S4) and WCO (S5) are observed to be more effective at reducing environmental flow deficit. As seen in Figure 5.6, both the IFN and WCO can be implemented in the model and guarantee sufficient streamflows. Even under severe drought conditions (bottom sub-plot), Figure 5.6 shows that both the WCO and IFN can be maintained.



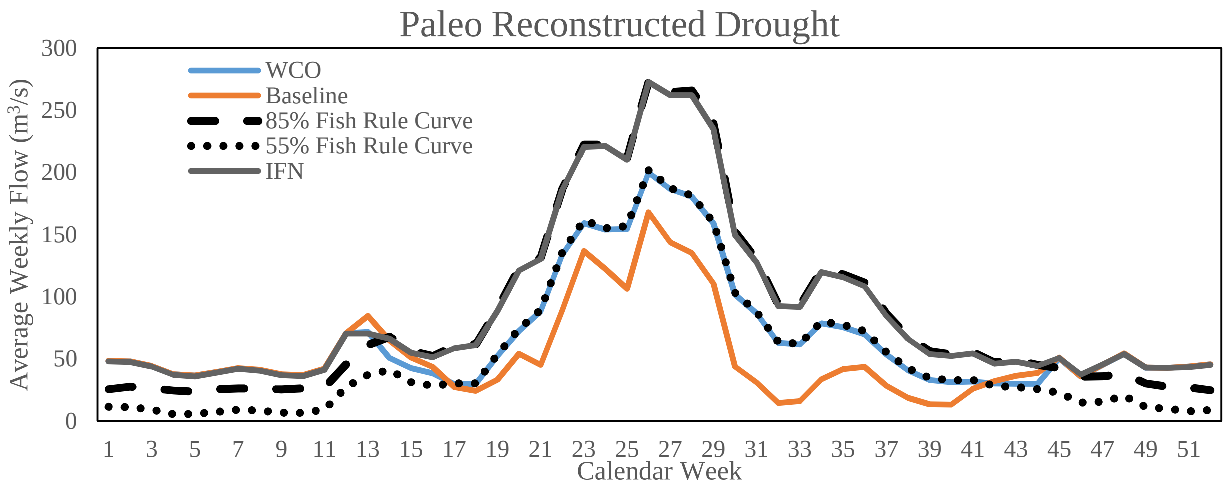


Figure 5.6-Average weekly flow downstream of Bassano over the historical record (1928-2001) the 30 year paleo drought reconstruction. Solid lines represent flows simulated by $SWAMP_B$; the dashed and dotted lines represent flow requirements estimated from fish rule curves

Unfortunately this newly-gained in-stream flow results in less water for crops and municipalities. Because the TransAlta reservoir operation rules are not altered for S4 and S5, and located furthest upstream in the basin. Since the TransAlta release is only a function of the regression equations presented in section 4.3, the release is not altered to accommodate environmental flow policy. By implementing these two interventions there are severe deficits to the economic return (from reduced crop yields), as seen in Figure 5.7. Economic loss here is defined as the amount of return lost from baseline conditions (no interventions); $0 loss would indicate the same economic return as baseline conditions. In both the historical and drought periods, economic losses can be as high as $60 million. Another important point seen in Figure 5.7, is that the IFN lowers economic returns substantially more than just the WCO. In some instances the loss from the IFN is over three times greater than the WCO. This illustrates that increasing environmental flow requirements from 55% of the Fish Rule Curve to 85% reduces the economic return by more than 20%. Thus, the additional mitigation to streamflow deficit with a stricter regulation comes at a price.

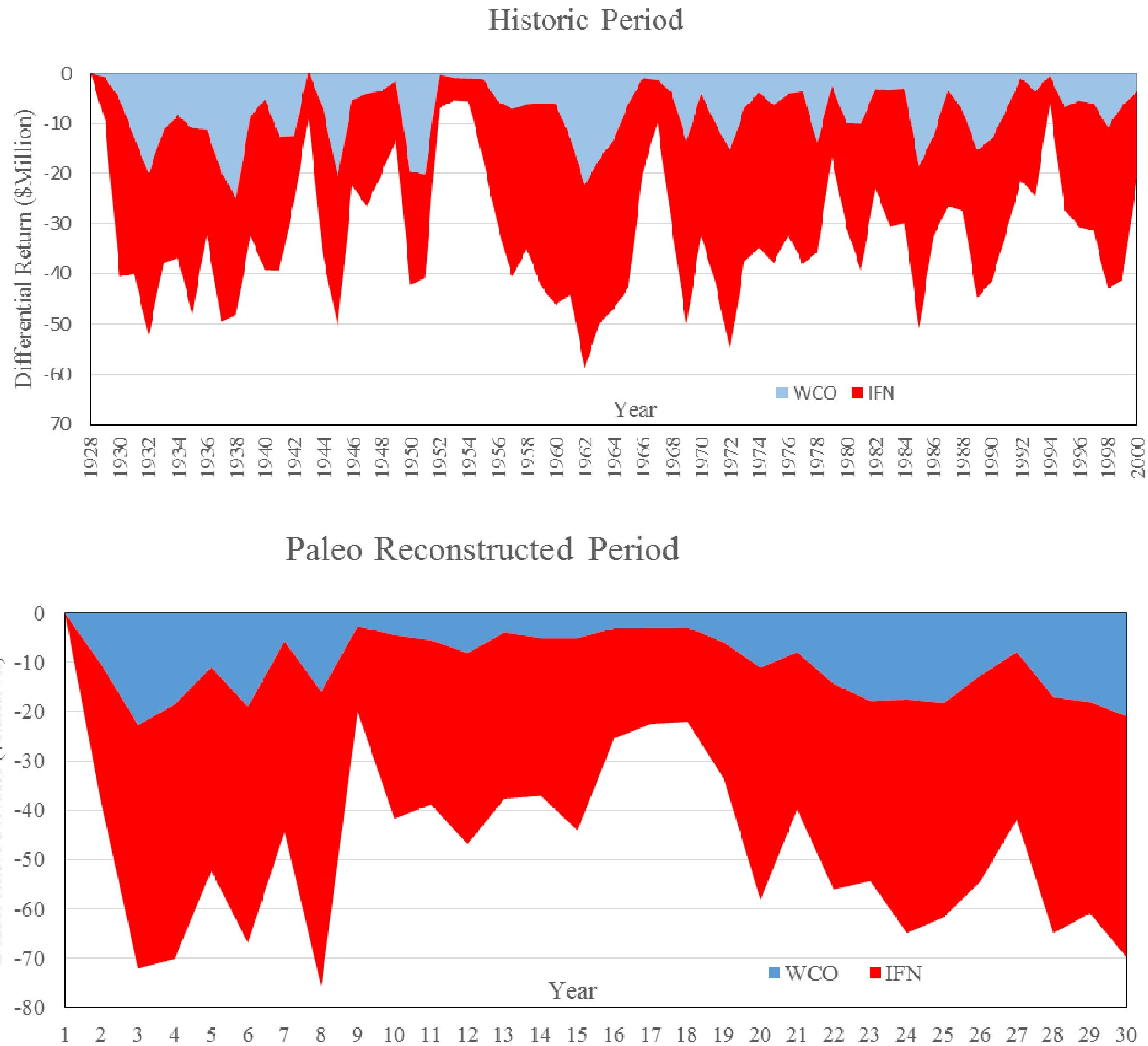


Figure 5.7- Differential economic return of irrigation of implementing the WCO or IFN. Simulated in SWAMP$_B$ over a) the historical simulation period (1928-2001) and b) the 30 year paleo drought reconstruction.

Economic losses from implementation of the two policy interventions were due to crop water shortage. By forcing water to remain in-stream there is less water available to irrigate crops, which reduces crop yields. Figures 5.8 and 5.9 illustrate that implementing the IFN substantially increases crop water shortage over the WCO. These findings are consistent across both the historical simulation period and the paleo reconstructed period. Both under normal and dry conditions, implementation of these two policies are seen to have dire effects on irrigation. In the previous section, *Implementation of Management Interventions*, both the irrigation efficiency and increased summer release from TransAlta were beneficial to irrigation. Here, with the implementation of the WCO and IFN, policy solutions are detrimental to irrigated agriculture.

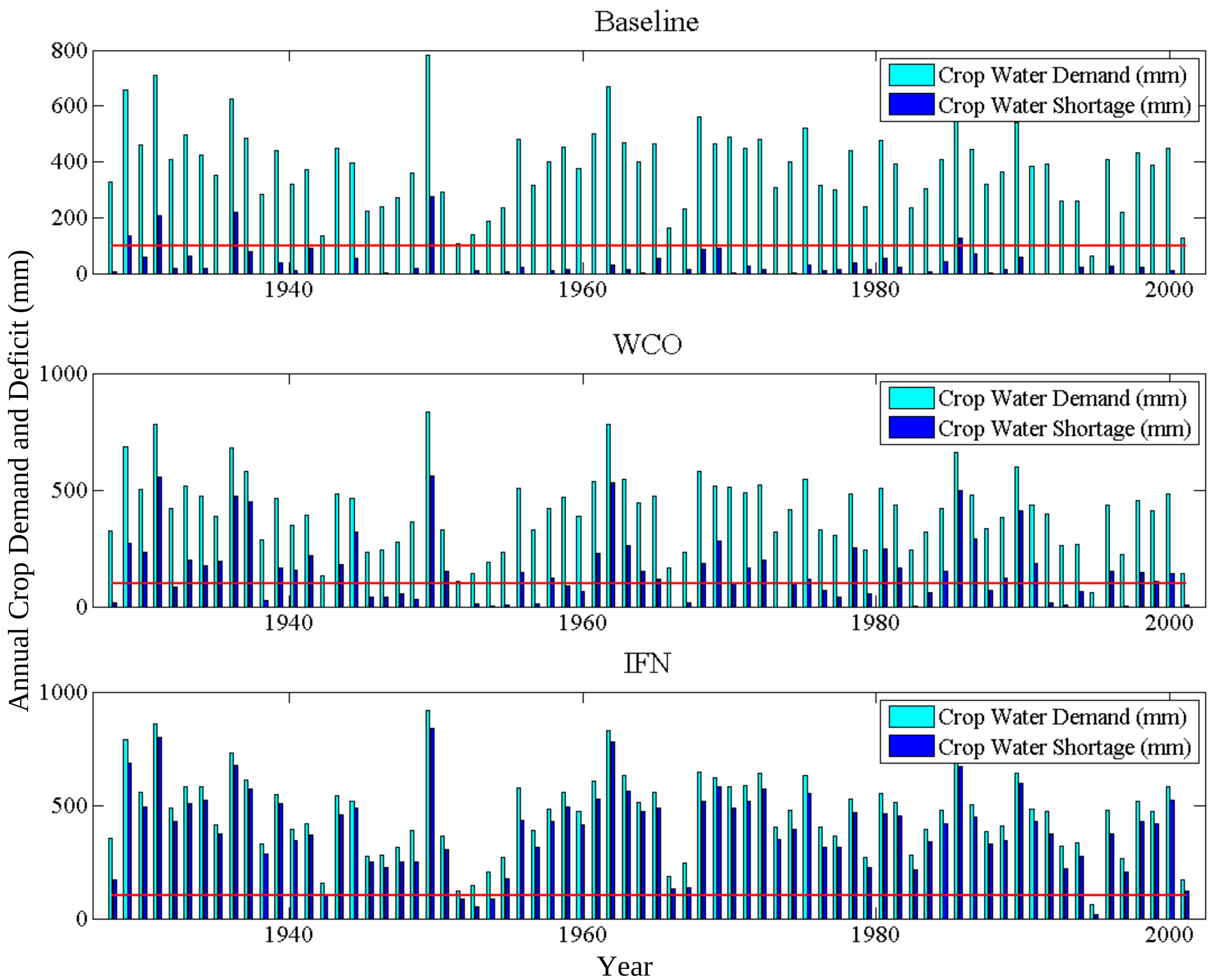


Figure 5.8-Total annual crop water demand and deficit over the historical period. Depths are represented as the average values across all irrigation districts in the Bow Basin. The horizontal red line indicates the 100mm shortage threshold

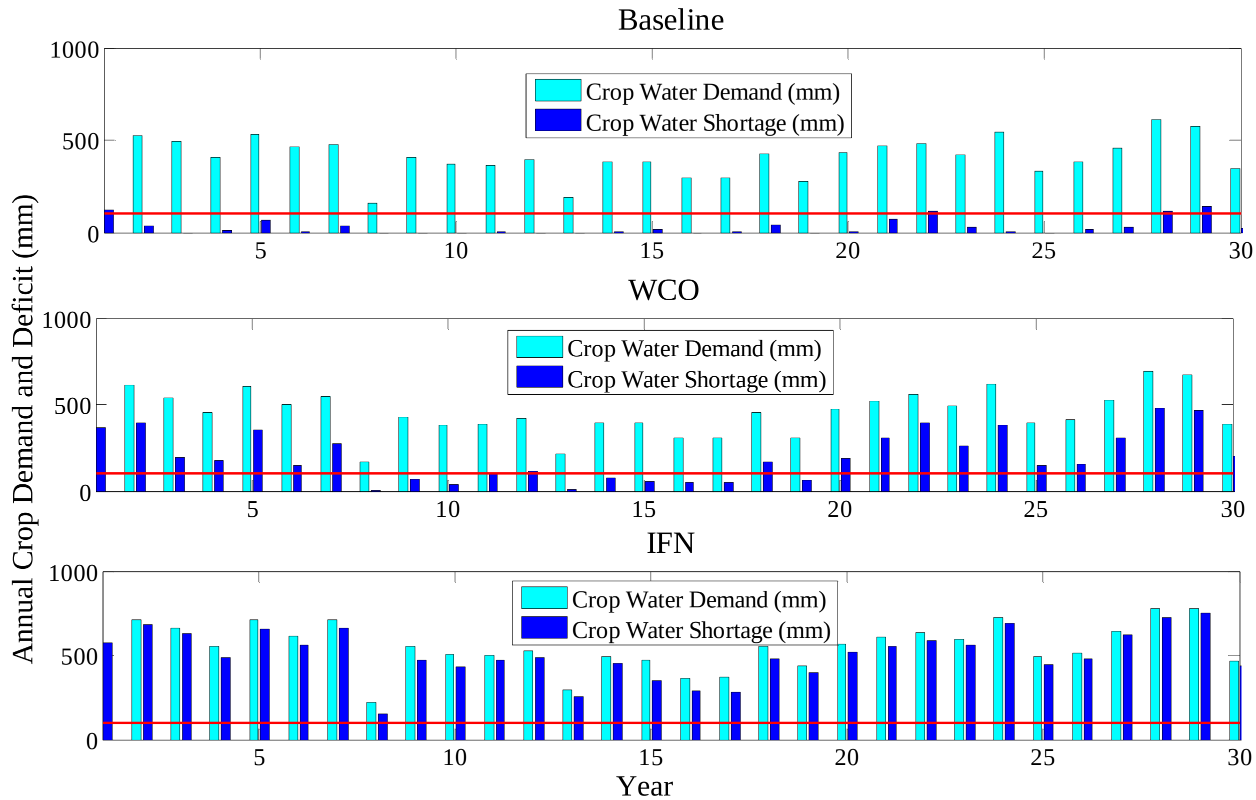


Figure 5.9-Total annual crop water demand and deficit over the paleo drought period. Depths are represented as the average values across all irrigation districts in the Bow Basin. The horizontal red line indicates the 100mm shortage threshold

In addition to the economic losses reported previously, the policy interventions can affect water apportioned to municipalities. Figure 5.10 shows that water apportioned to municipal uses is significantly decreased for both the historical and drought periods. Minor demands are still guaranteed in S4 and S5, but all Municipal users specified as Major demands are subject to shortage. Similar to the case with economic return, the IFN decreases water for municipal users significantly. From Figure 5.10 it may seem that there is more water supplied to municipal users under implementation of the IFN during the paleo reconstructed period than the historical period. This is not the case as there is more supply during the historical period than the paleo reconstructed period; even though there is less supply during the spring and summer weeks (weeks 17 – 40), there is much more over the fall and winter weeks. It is important to note that the municipal demands in both WRMM and SWAMP$_B$ have varying levels of priorities, across the entire spectrum of penalty demands in WRMM. Municipal demands classified as Minor demands in WRMM were still maintained, as these are demands both models always meet. The actual implementation of the IFN and WCO would likely make some accommodation for municipal demands not classified as "Minor demands", but the present simulation assumes all Major demands (including municipal demands) follow the set allocation priority structure.

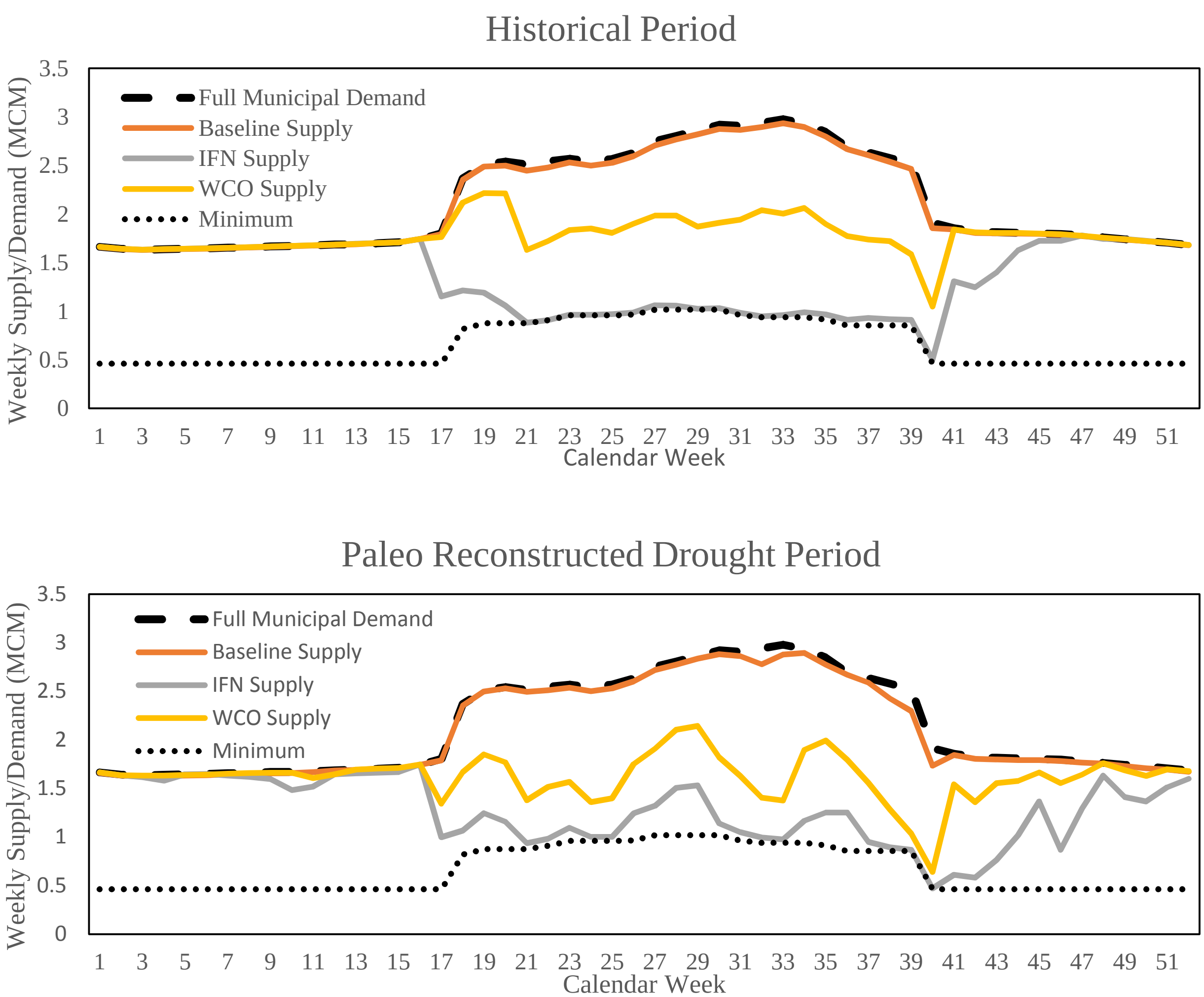


Figure 5.10- Weekly average municipal demand and supply as simulated in SWAMPB for a) the historical simulation period (1928-2001), and b) the 30 year drought paleo reconstruction

From the results presented, one can see that both the irrigation limits and environmental flow requirements cannot be satisfied. Under current operation, without enforcing environmental flow requirements, the streamflow deficits are large. Even when considering upgrades to the irrigation system or changes in the operation of the TransAlta reservoirs the streamflow is still inadequate. The proposed IFN and WCO bring streamflows to acceptable levels, but with a price. With enforced environmental flows there are large deficits to economic return and water available for municipal uses. A compromise is seen by using the WCO, as the economic and municipal consequences are much less than the full implementation of the IFN.

5.3 Sustainability Indices and Total Economic Return

The previous two sections examined the ability of each of the five solutions to mitigate environmental flow deficit, as well as the tradeoff with other sectors. It was found that the technical solutions (S1, S2, and S3), both mitigated environmental flow deficit and improved economic return. A tradeoff was seen between economic gains of improved crop yields versus economic loss to hydropower generation. The policy solutions, considering an IFN and WCO, are much more effective at mitigating environmental flow deficit, but at a cost. It was seen that there were crop water shortages and less water for municipal uses when water is left in stream. Each of these management interventions was applied in isolation to examine their efficacy. It is likely that a combination of policy (e.g. IFN) and technical (e.g. irrigation efficiency) interventions would yield different, perhaps better, results. The present analysis was only focused on the tradeoffs, and many figures in the previous two sections illustrated this well.

To rate an overall effectiveness of each of the five solutions, as well as the baseline, Sustainability Index (SI) values are computed as outlined in Section 3.7. Figure 5.11 clearly illustrates the tradeoff each of the solutions has on environmental flow, municipal allocation and irrigation allocation. The two policy solutions, S4 and S5, are considerably higher rated for environmental flow, and marginally score better for municipal allocation, but are severely lower rated for irrigation. The technical solutions, S1 – S3, score the weakest for environmental flow, but are most effective in the other two areas. The SI values for the municipal allocation is relatively low for S2 and S3 because the reliability score is very low, and with equal weighting of the three indices, lowers the resulting SI (see Appendix B). For example, in the historical simulation the average shortage to municipal demands (when shortages occur) is 0.03 MCM, which is between 1% and 2% of the overall demand. Since this very minor shortage occurs often (even though the shortage is insignificant), the reliability score is very low. On the other hand, the SI score of municipal demands is justifiably low for S4 and S5 as all three indices are affected. A summary of each of the four indices (Rel, Vul, Res and SI) for all the simulations are provided in Appendix B.

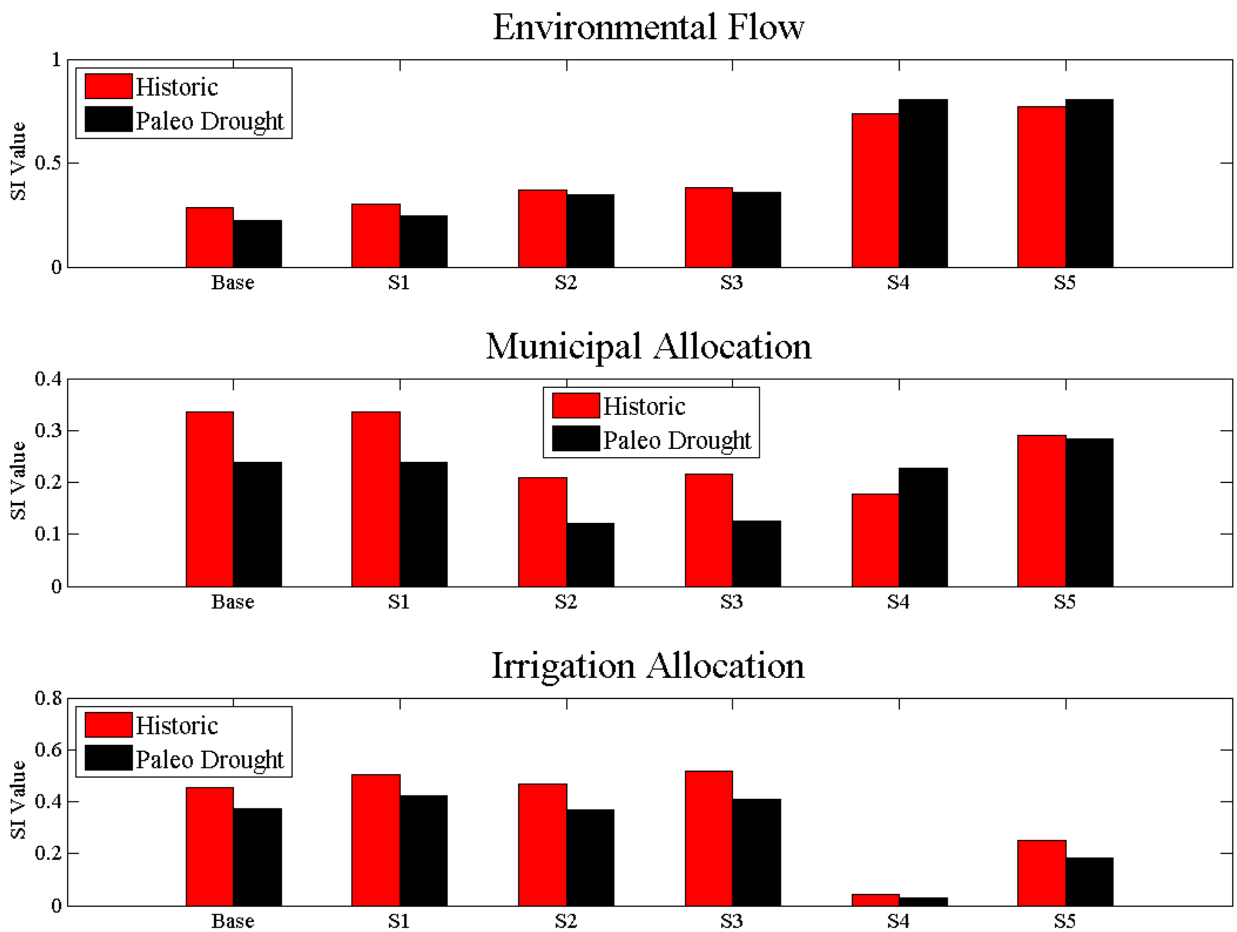


Figure 5.11- Sustainability Index (SI) for each scenario, considering both the historical period and paleo reconstruction. Separate plot for each of the three indicators

In addition to the SI scores, a summary of the average annual economic return for each solution is provided in Figure 5.12. As seen earlier, implementation of the IFN (S4) considerably damages the economic return. On average, the implementation of the IFN (S4) over the baseline incurs an additional loss of over $30 million annually. This is significant, considering implementing the WCO only results in an annual economic loss of less than $10 million.

The combined results of Figures 5.11 and 5.12 show a divide between solutions that are optimal for the economy, and those optimal for resolving environmental flow deficits. The SI indices clearly indicate that neither a policy implementation (S4 and S5) nor the technical solutions

(S1, S2, and S3) should be implemented without consultation with experts or consideration of other options. Although a preferred solution is not prescribed through this analysis, the tradeoffs of each are well illustrated. Decision makers can consult these tradeoffs provided by the $SWAMP_B$ model to make well informed decisions. Further, this analysis illustrates how $SWAMP_B$, an integrated hydro-economic model, provides a means to analyze different water management scenarios.

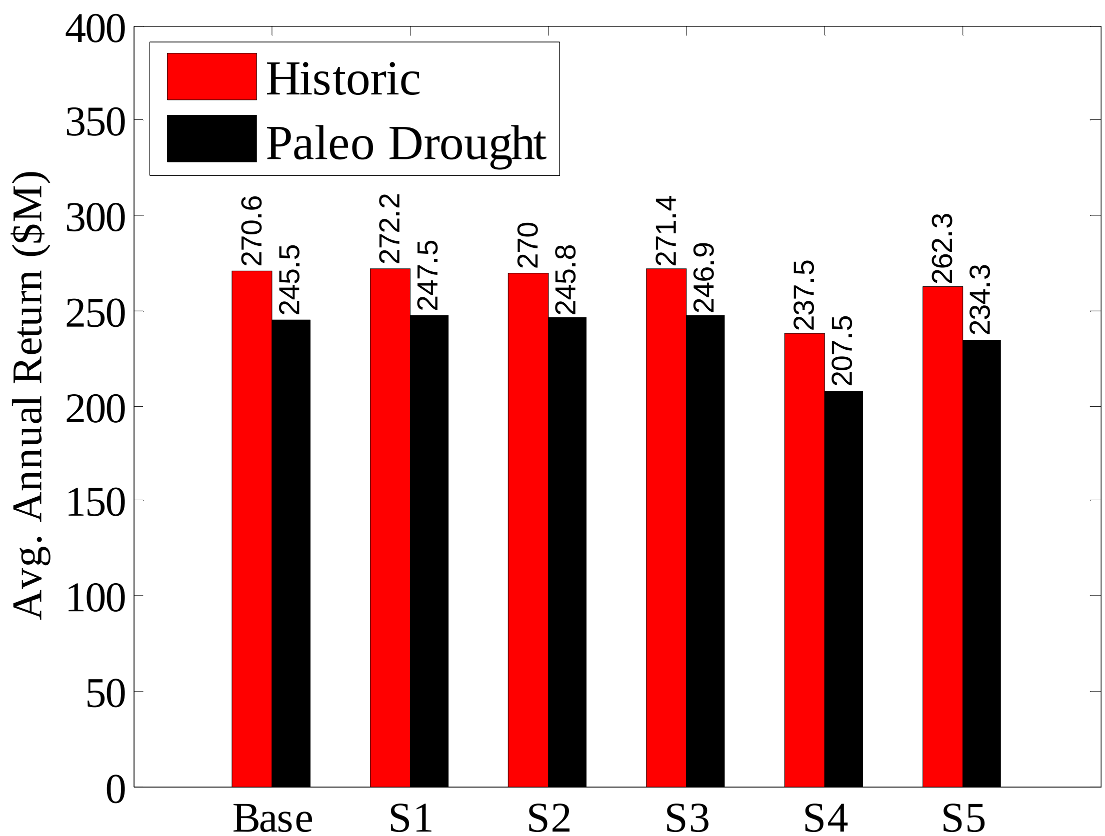


Figure 5.12- Average Annual Economic Return for the base scenario, and five solutions. Results for the historical and paleo reconstructed periods shown

The tradeoffs presented in this chapter are subject to much uncertainty in the model structure. These results only considered one set of assumptions in the irrigation component, and had uncertainty in the allocation structure. As seen in Section 4.2 (Irrigation Model Verification), the use of different ET equations and assumptions regarding runoff could affect the resulting economic return and streamflow simulated. Further, differences in reservoir levels and streamflows, as seen in the model verification, could also alter the allocation of water and affecting the economic return and stream flows. These numerous uncertainties would most likely propagate to the tradeoffs, altering the SI values and economic returns. Further work should investigate running these scenarios with improvements to the model structure, or different assumptions, and examine the results. Ultimately, this analysis is just one potential approximation of the effects of different management strategies and policies to better manage water resources.

Chapter 6 Conclusions

6.1 Summary

The integrated water resources emulation model, $SWAMP_B$, was developed in this research to provide decision support to water management in the Bow River Basin, located in Southern Alberta, Canada. This is a semi-arid basin, with water received from the headwaters of the Rocky Mountains. The majority of water resources are from surface runoff, primarily from snow and glacial melt water. This basin served as a prime candidate to be modelled by the SWAMP methodology, as it contains many complexities. Primarily an agricultural and hydropower dominated basin, the Bow basin was seen to have conflicting requirements for the water resources. $SWAMP_B$ was one implementation of a larger Sustainability-oriented Water Allocation, Management, and Planning (SWAMP) framework, which is an integrated water resources modeling framework. This model was able to link water allocation with hydrological principles, reservoir operation, crop growth and yield, as well as providing an economic valuation. As an emulation of the Water Resources Management Model (WRMM), $SWAMP_B$ utilized the same allocation priorities and system components. $SWAMP_B$ was developed in the System Dynamics environment, based on principles of feedbacks and causal loops. Such an environment was valuable as it was able to approximate complex feedbacks between water allocation decisions and the respective economic returns and crop yields. As a simulation tool, $SWAMP_B$ allowed a variety of scenarios to be examined. As the basin is already over-allocated, with diversions from the Bow River already exceeding healthy environmental limits, $SWAMP_B$ was used to analyze tradeoffs between water uses. Tradeoffs considered were conflicting uses between municipalities, hydropower, crop irrigation and environmental flow.

The operations of the TransAlta hydropower reservoirs were not included in WRMM, and were approximated as a black box model. These reservoirs were lumped together as one surrogate reservoir, with the release modeled as a linear regression of inflow and storage, with some approximations of seasonality. Irrigation water demand and yield was also a unique component for $SWAMP_B$ as WRMM did not model this. Using a simple water balance that considered infiltration, runoff, percolation and evapotranspiration, soil moisture was calculated for every week. From soil moisture and actual evapotranspiration, yield was determined as a factor of water stress. Economic valuations were considered based on the costs and revenue generated for both crop yields and hydropower generation.

$SWAMP_B$ was verified structurally, using the same components and water demand values utilized by WRMM. Four reservoirs were identified (located across all three irrigation districts) as being significantly larger than the others, and used as part of the structural validation. These reservoirs were first modeled in $SWAMP_B$ with fixed inflows to the district, and then again with the inflows modeled. Some deterioration of results were seen when inflows were not fixed, but the overall .performance was considered acceptable for basin-wide decision making purposes. Similarly, flow along the Bow River, and each of the diversions to the three irrigation districts were compared to WRMM. With the structure of the allocation model found to be adequate, a sensitivity analysis assessed the effects of different assumptions with the irrigation model. This analysis revealed that $SWAMP_B$'s simulation results are quite sensitive to runoff assumptions, and future work should address this (see section 6.3 and 6.4). With $SWAMP_B$ structurally sound, the model was verified against historical values of flow at the headwaters (e.g. release from the TransAlta reservoirs); the Bow River near the Oldman Confluence and lake levels at McGregor Reservoir. River flows matched well with R^2 exceeding 0.9 for both cases. McGregor Reservoir, on the other hand, was poorly matched by both WRMM and $SWAMP_B$. Since the operation rules prescribed in WRMM may not be fully implemented in reality, the reservoir levels modeled by

$SWAMP_B$ also had some discrepancies from reality. Though the model can be considered valid when assuming license demands, it does not have the ability to represent actual water withdrawals that differ from allotted license withdrawals.

This tradeoff between the environment, hydropower, irrigation and municipal water uses was examined over both a historical period (1928-2001) as well as reconstructed paleo-streamflows from tree-ring proxies. The paleo records provided annual streamflow proxies from 1600-present, which were then downscaled to weekly values. To test the robustness of the analysis, a 30 year dry period extending from 1840-1870 was utilized. Using these two records six different scenarios were analyzed; these solutions being a baseline scenario and five possible solutions to restore streamflow. Solutions considered were, increasing irrigation efficiency (S1), increasing summer release from the TransAlta hydropower reservoirs (S2), the combination of S1 and S2 (S3), implementing the Water Conservation objective (S4) and implementing the In-Stream Flow Needs (S5).

A Sensitivity analysis revealed that increasing irrigation efficiency does very little to mitigate streamflow deficits, as the irrigation efficiency is already quite high in the Bow, and the additional savings go towards furthering irrigation. This analysis proved that increasing release from the TransAlta reservoirs in the summer had significant implications for decreasing streamflow deficit, with very little consequences to the economy. The two policy solutions, implementation of the WCO and IFN respectively, were seen as most effective at reducing streamflow deficits. The issue with these two solutions was that they severely reduced economic returns through shortages of water to irrigation. Further analysis of all five solutions was provided through examining sustainability indices. These indices quantified the tradeoffs between municipal, irrigation and environmental water use. Although no one solution was prescribed, the indices provide a means to evaluate decisions.

6.2 Research Contributions

The work presented resulted in the development of the integrated water resources model $SWAMP_B$. This was an extension developed from the existing SWAMP methodology, and applied to the Bow Basin in Southern Alberta. $SWAMP_B$ was demonstrated as a valuable tool to assess water management strategies, likely being useful to future stakeholders. Because $SWAMP_B$ is fully coupled to both the economic and crop components, it provided a comprehensive tool to understand multiple dimensions of water allocation problems. Where many models were shown just to simulate the hydrology or allocation, or having to be compartmentalized into modules operating in isolation, $SWAMP_B$ has all components available.

The demonstration of $SWAMP_B$ in balancing environmental and economic tradeoffs in the Bow Basin gave insight into the complexities of water allocation. This case study illustrated the effectiveness of different technical and policy solutions to balancing environmental flow and the economy. Of interest was the effectiveness of altering the TransAlta hydropower reservoir operating rules. Not only does allowing more summer release reduce environmental flow deficits, but also has some minor economic gains when increased crop yields counterbalance losses from hydropower generation. Moreover, these analyses showed the importance of considering all aspects of a water resource system.

Not only was the development of $SWAMP_B$ seen to have practical uses to water managers, but provides scientific insight into model emulation. The successful emulation of a linear-optimization model towards a System Dynamics simulation model aided in closing gaps in the literature. Much of the emulation literature is concerned with reducing computational burden and/or data requirements of the model. This emulation, with $SWAMP_B$, illustrates that emulation is also a technique used to understand the structure and mechanics of a system, as well as improving the coherency of the model to the users.

6.3 Further Work

The $SWAMP_B$ model developed in this work was an extension of the overall SWAMP methodology applied to the Bow Basin. Also mentioned in the Scope (section 1.6) is the application of SWAMP already present in Saskatchewan ($SWAMP_{SK}$) and ongoing work to the Oldman basin in Alberta ($SWAMP_{OM}$). Future work with SWAMP will consider two things. First, the application of SWAMP to all of the SSRB will be achieved through completion of the Oldman Basin, and work towards the Red deer basin. This extension could also be applied to the North Saskatchewan River Basin (NSRB). Second, the separate applications of SWAMP ($SWAMP_B$, $SWAMP_{SK,}$ $SWAMP_{OM}$, etc.) will be linked as one coherent model. One could examine tradeoffs with apportioning water between provinces, and how the effects of one basin propagate to downstream basins.

As this is the first model construction of the Bow River Basin, there were many simplifications in the model. As noted in section 4.2 (Irrigation Model Verification) there were many assumptions in processes governing soil moisture, and in particular the runoff. It was shown in this section that the simulation results are sensitive to runoff. Further work should review these assumptions with the soil moisture and implement more sophisticated methods to improve the model accuracy.

Because the model is built in an SD environment, it would be quite simple to add new modules. The current $SWAMP_B$ only links the water resources (allocation and hydrology) with economic return, and crop demand and yields. These two elements provide much more context to decision making than just the water resources alone, however, there is still much more potential. Other modules, such as water quality and salinity, could provide for more thorough investigations. It is well known that more efficient irrigation methods can produce more salinity in soil, and this can have a burden to the productivity of the crop. Also, with return flow from agriculture, and reuse water from municipalities, water quality can degrade. Further analysis that considers water quality, and other potential modules, can provide much value.

6.4 Limitations

There are several limitations with the present work, both in the model development and the analysis. By building an optimization model in a simulation framework, the penalties of licenses cannot be represented numerically. Though this is not a limitation to the accuracy of $SWAMP_B$, it has the potential to producing results different from WRMM. Instead of optimizing a system based on a hierarchal set of penalties, $SWAMP_B$ specifies license relative to each other. These limitations in the modeling environment may change the results, but are unlikely to affect the overall conclusions of the case study investigated. Other limitations are in the weekly time step. Such a long time step requires the hydrology and crop growth to be simplified. For example, daily water levels in a reservoir could drop above or below operational limits, but if averaged over a week may seem as adequate. Also rainfall, when averaged over a week, reduces extreme values that could govern infiltration and runoff. Also, the long time step might be unrealistic when the future models are linked. Currently, the weekly time step allows the system to allocate water instantaneously as it is assumed the travel time is shorter than the simulation step. Once the travel time across the whole system is longer than the simulation time step, other directions must be considered- such as adding a routing component. Even with these limitations inherent to $SWAMP_B$ it is still shown as a valuable decision making tool.

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Appendix A: Downscaling of Paleo Reconstructed Stream Flows

Lane and Frevert (1990) Coefficients

Week	A	B	C
1	0.001659	6.57927	0.65821
2	0.001298	8.47909	0.566831
3	0.001059	6.2771	0.515555
4	0.000684	5.05387	0.262055
5	0.000674	5.68378	0.514304
6	0.00137	5.42043	0.705787
7	0.001687	5.44631	0.568254
8	0.001485	8.07325	0.551715
9	0.000513	6.57557	0.334483
10	-0.00072	9.55513	0.79387
11	0.000146	9.61118	0.530922
12	0.00628	25.1359	0.652675
13	0.007156	24.5408	0.638917
14	0.006157	29.7884	0.633836
15	-0.00044	26.058	0.575866
16	0.002958	19.9642	0.549415
17	0.004152	27.74	0.720899
18	0.006116	19.5173	0.484912
19	0.00789	24.1842	0.90457
20	0.01225	31.2263	0.818838
21	0.017506	47.7829	0.530476
22	0.020667	72.2275	0.812566
23	0.020685	100.867	0.6635
24	0.03783	54.3638	0.351497
25	0.045741	69.6605	0.275951
26	0.066291	53.6714	0.308993
27	0.033925	49.1613	0.508964
28	0.028132	36.1634	0.51742
29	0.014749	32.7109	0.654582
30	0.005894	18.8142	0.562078
31	0.008321	20.9377	0.652615
32	0.001251	24.2414	0.597957
33	0.007881	16.8373	0.59861
34	0.015396	22.9987	0.6295
35	0.01552	25.1322	0.436205

Lane and Frevert (1990) Coefficients

Week	A	B	C
36	0.005069	22.6283	0.806165
37	-0.00059	19.603	0.721075
38	0.00175	10.6194	0.65926
39	0.002097	8.75096	0.624118
40	0.001528	6.41194	0.848713
41	0.002974	6.07985	0.784265
42	0.001247	6.86981	0.774601
43	0.001261	7.65941	0.852922
44	0.002307	7.47105	0.687095
45	0.00202	6.71237	0.626267
46	0.001395	8.0223	0.52922
47	0.002245	9.57249	0.583047
48	0.003677	9.15636	0.54827
49	0.00027	8.57797	0.537021
50	0.000506	7.34969	0.573008
51	0.001806	6.75904	0.318944
52	0.000998	7.43353	0.686715

Paleo Reconstructed Flows 1840-1870 (m3/s)

Week	Total	Highwood River	Bearspaw Local	Elbow River	Ghost River
1	30.58492	3.083022	0.546979	1.442085	13.42567
2	61.70042	6.219527	1.103446	2.909188	27.08426
3	29.34742	2.958279	0.524847	1.383737	12.88246
4	6.222379	0.627228	0.111281	0.293386	2.731399
5	20.49763	2.066203	0.366578	0.966468	8.997719
6	31.34799	3.159941	0.560626	1.478064	13.76064
7	37.98966	3.829434	0.679405	1.79122	16.67609
8	34.77301	3.50519	0.621878	1.639555	15.2641
9	52.71543	5.313822	0.942759	2.485544	23.14017
10	22.44761	2.262764	0.401452	1.058409	9.853687
11	33.45526	3.372358	0.598312	1.577423	14.68565
12	40.37806	4.07019	0.722119	1.903834	17.72451
13	23.33111	2.351823	0.417252	1.100067	10.24151
14	22.32999	2.250908	0.399348	1.052864	9.802058
15	148.8021	14.99956	2.661168	7.016052	65.31876
16	81.18782	8.183896	1.451958	3.828023	35.63852
17	140.0387	14.11618	2.504443	6.602853	61.47192
18	65.94157	6.647043	1.179295	3.109159	28.94597
19	137.078	13.81774	2.451494	6.463255	60.17227
20	205.5965	20.72454	3.676875	9.693919	90.24944
21	254.932	25.69766	4.559187	12.02009	111.9059
22	425.0692	42.84783	7.60191	20.0421	186.59
23	187.5346	18.90386	3.353856	8.842294	82.32089
24	173.1965	17.45855	3.097434	8.166249	76.02699
25	381.8579	38.49205	6.829122	18.00468	167.6218
26	505.0093	50.90595	9.031554	23.81129	221.6808
27	489.1962	49.31197	8.748754	23.0657	214.7395
28	534.5256	53.88126	9.559421	25.20299	234.6374
29	403.7128	40.69506	7.219973	19.03514	177.2153
30	250.7783	25.27895	4.484902	11.82425	110.0826
31	263.5137	26.56271	4.712661	12.42472	115.673
32	135.258	13.63428	2.418945	6.377441	59.37336
33	143.1336	14.42816	2.559792	6.74878	62.83048
34	207.5176	20.9182	3.711232	9.7845	91.09274
35	105.4297	10.62753	1.885498	4.971034	46.27984
36	129.8937	13.09355	2.323011	6.124516	57.01864
37	169.7121	17.10732	3.03512	8.00196	74.49747
38	81.23052	8.1882	1.452721	3.830036	35.65726
39	80.7051	8.135237	1.443325	3.805262	35.42662
40	72.58726	7.316942	1.298146	3.422504	31.86318

41	69.82276	7.038275	1.248706	3.292158	30.64967
42	52.96716	5.339197	0.947261	2.497413	23.25067
43	50.75218	5.115922	0.907649	2.392976	22.27837
44	53.86685	5.429888	0.963351	2.539833	23.6456
45	42.35743	4.269714	0.757518	1.997162	18.59338
46	31.45582	3.17081	0.562554	1.483149	13.80797
47	4.683274	0.472083	0.083755	0.220817	2.055788
48	32.55766	3.281878	0.582259	1.5351	14.29164
49	14.23953	1.435373	0.254659	0.671397	6.250637
50	35.1623	3.54443	0.62884	1.65791	15.43498
51	27.59755	2.781889	0.493553	1.30123	12.11433
52	9.834645	0.991352	0.175882	0.463706	4.317053
53	27.0406	2.725747	0.483592	1.27497	11.86985
54	43.40251	4.37506	0.776208	2.046437	19.05213
55	31.3231	3.157432	0.56018	1.476891	13.74971
56	12.98511	1.308926	0.232225	0.612251	5.699995
57	9.022572	0.909493	0.161359	0.425416	3.960583
58	6.28231	0.63327	0.112352	0.296212	2.757707
59	10.82055	1.090733	0.193514	0.510191	4.749829
60	21.8167	2.199167	0.390168	1.028662	9.576742
61	6.533686	0.658609	0.116848	0.308065	2.868052
62	6.28231	0.63327	0.112352	0.296212	2.757707
63	18.47091	1.861905	0.330333	0.870907	8.10806
64	19.22296	1.937713	0.343782	0.906366	8.438182
65	20.47983	2.064408	0.36626	0.965628	8.989906
66	19.60106	1.975826	0.350544	0.924194	8.604155
67	26.51564	2.67283	0.474204	1.250218	11.63941
68	116.9591	11.78971	2.091688	5.514644	51.3408
69	184.9429	18.64262	3.307507	8.720097	81.18325
70	180.2341	18.16796	3.223295	8.498075	79.11625
71	265.4331	26.75619	4.746988	12.51522	116.5155
72	333.9906	33.66693	5.973067	15.74773	146.6098
73	389.7034	39.28289	6.969431	18.3746	171.0657
74	363.1668	36.60795	6.494852	17.12339	159.4171
75	299.0833	30.1482	5.348787	14.10184	131.2868
76	408.0506	41.13232	7.29755	19.23967	179.1194
77	295.8307	29.82033	5.290618	13.94848	129.859
78	519.1911	52.33551	9.285181	24.47997	227.9061
79	527.0287	53.12556	9.425348	24.84951	231.3465
80	410.8842	41.41796	7.348227	19.37328	180.3633
81	400.5433	40.37557	7.16329	18.8857	175.824
82	217.9237	21.96715	3.897334	10.27515	95.66062
83	155.8244	15.70742	2.786754	7.347155	68.4013

84	118.7282	11.96804	2.123327	5.598059	52.11738
85	120.6452	12.16128	2.15761	5.688444	52.95886
86	139.3934	14.05114	2.492903	6.572429	61.18867
87	174.1257	17.55222	3.114053	8.210064	76.4349
88	149.7038	15.09044	2.677293	7.058565	65.71455
89	93.66899	9.442023	1.67517	4.416512	41.1173
90	87.97997	8.868558	1.573428	4.148274	38.62002
91	90.41302	9.113815	1.616941	4.262993	39.68805
92	96.25077	9.702272	1.721343	4.538244	42.25061
93	83.42182	8.409087	1.49191	3.933356	36.61916
94	77.67318	7.829613	1.389102	3.662306	34.09572
95	66.93667	6.747351	1.197091	3.156078	29.38278
96	51.04199	5.145136	0.912832	2.406641	22.40559
97	34.99972	3.528042	0.625933	1.650244	15.36361
98	21.69171	2.186569	0.387933	1.022769	9.521878
99	50.51581	5.092096	0.903422	2.381831	22.17461
100	40.04728	4.036847	0.716203	1.888238	17.57931
101	16.33636	1.646738	0.292158	0.770263	7.171069
102	24.31718	2.451221	0.434887	1.14656	10.67436
103	30.07319	3.031438	0.537827	1.417957	13.20104
104	22.90353	2.308722	0.409605	1.079906	10.05382
105	24.92109	2.512097	0.445687	1.175035	10.93946
106	48.81976	4.92113	0.873089	2.301862	21.43011
107	42.31715	4.265654	0.756797	1.995262	18.5757
108	14.81819	1.493703	0.265008	0.698681	6.504649
109	10.29637	1.037895	0.18414	0.485476	4.519733
110	36.17189	3.6462	0.646896	1.705512	15.87815
111	31.55367	3.180673	0.564304	1.487762	13.85092
112	12.05945	1.215616	0.21567	0.568605	5.29366
113	18.55772	1.870656	0.331885	0.875	8.146168
114	7.353854	0.741283	0.131516	0.346736	3.228076
115	21.6214	2.179481	0.386676	1.019454	9.491013
116	22.50172	2.268219	0.402419	1.060961	9.877443
117	23.97298	2.416525	0.428731	1.130331	10.52327
118	128.2197	12.9248	2.293073	6.045585	56.28381
119	50.99897	5.140799	0.912062	2.404612	22.3867
120	35.79654	3.608363	0.640183	1.687814	15.71339
121	192.1409	19.36819	3.436236	9.059484	84.34292
122	128.7306	12.9763	2.30221	6.069674	56.50808
123	156.1829	15.74356	2.793166	7.364058	68.55866
124	271.5061	27.36836	4.855598	12.80157	119.1814
125	371.381	37.43595	6.641753	17.51069	163.0228
126	572.0608	57.66488	10.2307	26.97278	251.114

127	193.266	19.4816	3.456357	9.112532	84.83679
128	494.1377	49.81008	8.837128	23.2987	216.9086
129	379.4851	38.25286	6.786686	17.8928	166.5802
130	764.2437	77.03731	13.66769	36.03425	335.4754
131	817.0243	82.35769	14.61161	38.52286	358.6441
132	800.9158	80.73392	14.32353	37.76335	351.5731
133	716.4373	72.21833	12.81272	33.78017	314.4901
134	509.3639	51.34491	9.109431	24.01661	223.5923
135	409.415	41.26986	7.321952	19.304	179.7184
136	340.6744	34.34067	6.0926	16.06287	149.5438
137	223.946	22.57421	4.005036	10.5591	98.3042
138	212.8864	21.45938	3.807247	10.03764	93.44944
139	259.8299	26.19138	4.646781	12.25103	114.0559
140	147.217	14.83977	2.632819	6.941311	64.62293
141	122.5977	12.35809	2.192529	5.780507	53.81595
142	134.2616	13.53384	2.401126	6.330464	58.936
143	90.93922	9.166856	1.626351	4.287803	39.91903
144	93.49794	9.42478	1.672111	4.408447	41.04221
145	94.40384	9.516097	1.688312	4.45116	41.43987
146	76.02808	7.663784	1.359681	3.58474	33.37358
147	86.91441	8.761148	1.554372	4.098032	38.15228
148	90.22925	9.09529	1.613654	4.254328	39.60738
149	65.81193	6.633975	1.176976	3.103046	28.88906
150	42.82199	4.316543	0.765826	2.019066	18.79731
151	22.18648	2.236442	0.396782	1.046097	9.739062
152	34.49944	3.477613	0.616986	1.626656	15.14401
153	20.64838	2.081398	0.369274	0.973575	9.063892
154	28.06005	2.82851	0.501824	1.323037	12.31735
155	0.261908	0.026401	0.004684	0.012349	0.114968
156	44.71323	4.507184	0.799649	2.108238	19.62749
157	55.50352	5.594867	0.992621	2.617003	24.36404
158	55.6729	5.61194	0.995651	2.624989	24.43839
159	29.7853	3.002418	0.532678	1.404383	13.07467
160	19.76798	1.992652	0.353529	0.932064	8.677427
161	25.55865	2.576364	0.457089	1.205096	11.21933
162	41.49259	4.182537	0.742051	1.956384	18.21375
163	30.2165	3.045884	0.54039	1.424714	13.26395
164	23.15152	2.333719	0.41404	1.091599	10.16268
165	38.38938	3.869727	0.686553	1.810067	16.85155
166	35.90408	3.619204	0.642106	1.692885	15.76059
167	18.46493	1.861302	0.330226	0.870625	8.105436
168	86.74825	8.744399	1.5514	4.090198	38.07935
169	129.5503	13.05893	2.316868	6.108322	56.86788

170	169.0263	17.0382	3.022856	7.969627	74.19645
171	94.67097	9.543024	1.69309	4.463756	41.55713
172	102.9895	10.38155	1.841858	4.855978	45.20868
173	106.5486	10.74031	1.905508	5.023789	46.77098
174	135.1018	13.61853	2.416151	6.370077	59.30479
175	187.7827	18.92887	3.358293	8.853991	82.4298
176	246.8948	24.88749	4.41545	11.64114	108.3779
177	251.3312	25.3347	4.494792	11.85032	110.3253
178	217.61	21.93552	3.891723	10.26036	95.52291
179	760.2075	76.63045	13.5955	35.84394	333.7036
180	542.2138	54.65624	9.696916	25.56549	238.0122
181	483.0307	48.69047	8.63849	22.775	212.033
182	528.596	53.28354	9.453376	24.92341	232.0345
183	481.0915	48.49499	8.603809	22.68356	211.1818
184	471.1173	47.48957	8.425432	22.21328	206.8035
185	432.6774	43.61476	7.737976	20.40083	189.9298
186	253.8292	25.58649	4.539465	11.9681	111.4218
187	219.0256	22.07822	3.91704	10.3271	96.14433
188	118.6898	11.96417	2.12264	5.596247	52.10051
189	108.7834	10.96558	1.945475	5.129158	47.75196
190	150.2225	15.14273	2.68657	7.083023	65.94225
191	179.3619	18.08005	3.207698	8.456953	78.73341
192	217.8436	21.95907	3.895901	10.27137	95.62545
193	237.8064	23.97137	4.252915	11.21262	104.3884
194	153.1239	15.43519	2.738457	7.219822	67.21584
195	70.81926	7.138724	1.266527	3.339143	31.08709
196	89.81998	9.054035	1.606335	4.235031	39.42772
197	99.92258	10.0724	1.787009	4.711371	43.8624
198	100.861	10.167	1.803793	4.755619	44.27435
199	107.7793	10.86437	1.927518	5.081816	47.31121
200	106.0005	10.68506	1.895706	4.997944	46.53038
201	73.25533	7.384285	1.310094	3.454004	32.15644
202	40.24135	4.056409	0.719674	1.897388	17.6645
203	34.9179	3.519794	0.624469	1.646386	15.32769
204	24.6477	2.484538	0.440798	1.162144	10.81945
205	12.13419	1.22315	0.217007	0.572129	5.326469
206	27.1727	2.739063	0.485955	1.281198	11.92783
207	19.0303	1.918292	0.340337	0.897282	8.353612
208	29.35832	2.959378	0.525042	1.384251	12.88724
209	28.08133	2.830655	0.502205	1.324041	12.32669
210	2.856296	0.28792	0.051082	0.134675	1.253811
211	23.97359	2.416586	0.428742	1.13036	10.52354
212	5.27525	0.531756	0.094342	0.248729	2.315644

213	10.33085	1.04137	0.184756	0.487102	4.534869
214	7.378481	0.743766	0.131956	0.347897	3.238886
215	23.22364	2.34099	0.41533	1.095	10.19434
216	12.09983	1.219687	0.216393	0.57051	5.311388
217	26.14919	2.635891	0.46765	1.23294	11.47855
218	15.30209	1.542481	0.273662	0.721497	6.717063
219	21.69381	2.18678	0.387971	1.022868	9.522797
220	62.19699	6.269582	1.112327	2.932601	27.30223
221	142.3717	14.35135	2.546166	6.712854	62.49602
222	66.01055	6.653997	1.180528	3.112411	28.97625
223	33.8084	3.407955	0.604627	1.594073	14.84066
224	105.3563	10.62012	1.884185	4.96757	46.24759
225	131.779	13.28359	2.356727	6.213406	57.84621
226	110.6619	11.15494	1.97907	5.217731	48.57656
227	165.5162	16.68437	2.960082	7.804124	72.65564
228	138.9831	14.00978	2.485566	6.553084	61.00858
229	184.0993	18.55758	3.292419	8.680319	80.81292
230	415.6504	41.89839	7.433465	19.598	182.4555
231	794.4852	80.08571	14.20852	37.46014	348.7503
232	492.7853	49.67375	8.81294	23.23493	216.3149
233	344.3843	34.71463	6.158946	16.23779	151.1722
234	494.0682	49.80307	8.835884	23.29542	216.8781
235	495.026	49.89962	8.853014	23.34058	217.2985
236	551.6833	55.61079	9.866269	26.01198	242.169
237	495.7815	49.97577	8.866524	23.3762	217.6301
238	350.3327	35.31424	6.265327	16.51826	153.7834
239	225.0093	22.68139	4.024051	10.60923	98.77094
240	139.4445	14.05629	2.493817	6.574837	61.2111
241	184.5309	18.60109	3.300139	8.700671	81.0024
242	195.5768	19.71454	3.497684	9.221489	85.85116
243	205.8214	20.74721	3.680897	9.704523	90.34816
244	146.8366	14.80142	2.626016	6.923376	64.45595
245	91.03542	9.176554	1.628072	4.292339	39.96126
246	82.27592	8.293578	1.471417	3.879327	36.11615
247	83.20311	8.387041	1.487999	3.923044	36.52316
248	107.9386	10.88043	1.930368	5.089329	47.38116
249	112.7088	11.36127	2.015677	5.314243	49.47508
250	92.17995	9.291925	1.64854	4.346304	40.46367
251	77.01212	7.762977	1.37728	3.631138	33.80554
252	73.04164	7.362745	1.306272	3.443929	32.06264
253	61.952	6.244887	1.107946	2.92105	27.19469
254	67.91689	6.84616	1.214621	3.202296	29.81306
255	90.27659	9.100062	1.614501	4.25656	39.62816

256	83.48672	8.41563	1.493071	3.936416	36.64765
257	69.82724	7.038727	1.248786	3.292369	30.65164
258	36.60151	3.689506	0.654579	1.725769	16.06674
259	38.1377	3.844358	0.682052	1.798201	16.74107
260	29.9705	3.021086	0.53599	1.413115	13.15596
261	7.795406	0.785793	0.139413	0.367555	3.421902
262	2.373738	0.239278	0.042452	0.111922	1.041985
263	22.02682	2.220348	0.393926	1.038569	9.668979
264	21.26319	2.143372	0.380269	1.002564	9.33377
265	21.92136	2.209717	0.39204	1.033597	9.622683
266	13.44917	1.355703	0.240524	0.634131	5.903699
267	30.64708	3.089287	0.54809	1.445016	13.45296
268	20.50901	2.06735	0.366782	0.967004	9.002715
269	13.63723	1.374661	0.243887	0.642998	5.986252
270	7.201207	0.725896	0.128786	0.339538	3.16107
271	21.1726	2.134241	0.378649	0.998292	9.294005
272	104.2984	10.51349	1.865266	4.91769	45.78322
273	137.4561	13.85585	2.458255	6.481082	60.33824
274	156.1503	15.74027	2.792583	7.362521	68.54435
275	179.4972	18.09368	3.210116	8.463329	78.79277
276	118.6082	11.95595	2.121182	5.592403	52.06473
277	46.83833	4.721398	0.837654	2.208437	20.56033
278	89.95427	9.067572	1.608736	4.241363	39.48667
279	231.0436	23.28966	4.131969	10.89375	101.4198
280	376.0705	37.90866	6.72562	17.7318	165.0813
281	561.0513	56.5551	10.03381	26.45368	246.2812
282	542.6206	54.69725	9.704192	25.58467	238.1908
283	298.3412	30.0734	5.335516	14.06685	130.961
284	445.8954	44.94716	7.974365	21.02406	195.732
285	576.398	58.10208	10.30827	27.17729	253.0179
286	492.6904	49.66419	8.811244	23.23046	216.2733
287	552.167	55.65954	9.874919	26.03479	242.3813
288	556.8745	56.13407	9.959108	26.25675	244.4478
289	521.1288	52.53083	9.319834	24.57133	228.7567
290	351.8224	35.46441	6.29197	16.5885	154.4373
291	283.8407	28.61171	5.076189	13.38315	124.5958
292	230.3938	23.22416	4.120348	10.86312	101.1346
293	179.7025	18.11437	3.213787	8.473008	78.88288
294	256.1359	25.81901	4.580718	12.07686	112.4344
295	217.9617	21.97098	3.898013	10.27694	95.67731
296	202.7542	20.43803	3.626044	9.559904	89.00177
297	123.7083	12.47005	2.212391	5.832872	54.30347
298	80.29918	8.094319	1.436065	3.786123	35.24844

299	85.16842	8.585149	1.523147	4.015709	37.38586
300	73.03605	7.362182	1.306172	3.443665	32.06019
301	71.16766	7.173844	1.272758	3.35557	31.24003
302	53.29465	5.372208	0.953118	2.512854	23.39442
303	41.3245	4.165593	0.739045	1.948459	18.13996
304	36.89469	3.719059	0.659822	1.739592	16.19543
305	44.95758	4.531814	0.804018	2.119759	19.73475
306	27.16368	2.738153	0.485793	1.280773	11.92387
307	68.29969	6.884746	1.221467	3.220344	29.98109
308	78.95042	7.958361	1.411944	3.722529	34.65638
309	16.23484	1.636505	0.290343	0.765476	7.126508
310	34.84744	3.512692	0.623209	1.643064	15.29677
311	4.273603	0.430788	0.076429	0.201501	1.875957
312	17.16254	1.730019	0.306934	0.809217	7.533735
313	33.77002	3.404086	0.603941	1.592264	14.82382
314	53.16594	5.359234	0.950816	2.506785	23.33793
315	30.01669	3.025742	0.536816	1.415293	13.17624
316	1.662848	0.167618	0.029738	0.078404	0.72993
317	11.64104	1.17344	0.208188	0.548877	5.109995
318	19.83173	1.999079	0.354669	0.93507	8.705414
319	16.89917	1.70347	0.302224	0.796799	7.418125
320	19.41495	1.957067	0.347216	0.915419	8.522463
321	8.646922	0.871627	0.154641	0.407704	3.795686
322	8.314242	0.838092	0.148691	0.392018	3.649652
323	24.44508	2.464114	0.437174	1.152591	10.73051
324	79.45593	8.009318	1.420985	3.746364	34.87828
325	37.07117	3.736849	0.662978	1.747913	16.2729
326	58.75312	5.922433	1.050737	2.770222	25.7905
327	64.0643	6.457811	1.145722	3.020645	28.12191
328	105.4512	10.62969	1.885882	4.972044	46.28924
329	25.10769	2.530906	0.449024	1.183833	11.02137
330	35.41251	3.569653	0.633315	1.669707	15.54481
331	134.4258	13.55039	2.404062	6.338204	59.00806
332	190.0341	19.15582	3.398558	8.960147	83.41809
333	250.9075	25.29198	4.487213	11.83034	110.1393
334	665.0314	67.03651	11.89338	31.35637	291.9248
335	505.481	50.9535	9.03999	23.83353	221.8879
336	478.9558	48.27971	8.565615	22.58286	210.2443
337	789.8285	79.6163	14.12524	37.24058	346.7061
338	696.6539	70.22412	12.45891	32.84738	305.8059
339	501.3006	50.53211	8.965229	23.63643	220.0529
340	529.8498	53.40993	9.4758	24.98253	232.5849
341	616.8536	62.18008	11.03177	29.08477	270.7764

342	323.5218	32.61165	5.785842	15.25412	142.0144
343	280.6116	28.28622	5.01844	13.2309	123.1784
344	247.677	24.96634	4.42944	11.67802	108.7212
345	318.4585	32.10126	5.695292	15.01539	139.7918
346	307.9961	31.04663	5.508182	14.52208	135.1991
347	269.694	27.1857	4.823191	12.71613	118.3859
348	333.9499	33.66283	5.972339	15.74581	146.5919
349	223.6832	22.54772	4.000336	10.54671	98.18885
350	172.966	17.43532	3.093313	8.155383	75.92582
351	112.6453	11.35487	2.014541	5.311249	49.44721
352	103.3206	10.41493	1.84778	4.871589	45.35402
353	105.3325	10.61773	1.88376	4.966451	46.23717
354	94.82374	9.558424	1.695822	4.470959	41.62419
355	87.21207	8.791153	1.559695	4.112067	38.28295
356	91.57008	9.230448	1.637633	4.317548	40.19595
357	75.16859	7.577146	1.34431	3.544215	32.99629
358	48.88809	4.928018	0.874311	2.305083	21.4601
359	36.77279	3.706771	0.657642	1.733845	16.14192
360	96.37315	9.714608	1.723531	4.544014	42.30433
361	15.16339	1.5285	0.271181	0.714957	6.65618
362	12.64354	1.274494	0.226116	0.596146	5.550057
363	33.50305	3.377175	0.599166	1.579676	14.70663
364	37.46481	3.776528	0.670018	1.766474	16.4457
365	19.32936	1.948439	0.345685	0.911383	8.484891
366	18.0581	1.820293	0.32295	0.851443	7.926855
367	4.490604	0.452662	0.08031	0.211733	1.971213
368	31.6261	3.187975	0.565599	1.491177	13.88271
369	49.36116	4.975705	0.882772	2.327389	21.66777
370	46.61258	4.698642	0.833616	2.197793	20.46124
371	47.85983	4.824368	0.855922	2.256601	21.00874
372	28.17165	2.839759	0.50382	1.328299	12.36634
373	22.82385	2.30069	0.40818	1.076149	10.01884
374	8.02102	0.808535	0.143447	0.378193	3.520938
375	40.69575	4.102214	0.7278	1.918813	17.86396
376	67.36454	6.790481	1.204743	3.176252	29.5706
377	224.8435	22.66468	4.021087	10.60142	98.69818
378	343.9623	34.6721	6.1514	16.2179	150.987
379	241.4455	24.33819	4.317996	11.38421	105.9858
380	164.7586	16.608	2.946533	7.768404	72.32308
381	198.1523	19.97415	3.543743	9.342921	86.98169
382	127.9549	12.89811	2.288338	6.033101	56.16758
383	73.48533	7.40747	1.314207	3.464849	32.2574
384	175.9283	17.73392	3.14629	8.295054	77.22615

385	195.5689	19.71374	3.497542	9.221115	85.84768
386	602.5809	60.74137	10.77652	28.41181	264.5112
387	612.8802	61.77956	10.96071	28.89743	269.0322
388	722.0623	72.78533	12.91332	34.04539	316.9592
389	712.7134	71.84295	12.74612	33.60458	312.8554
390	869.9074	87.68842	15.55737	41.01632	381.8579
391	396.8913	40.00744	7.097978	18.71351	174.2209
392	326.3821	32.89997	5.836997	15.38898	143.2699
393	388.0005	39.11123	6.938976	18.2943	170.3182
394	346.0413	34.88166	6.18858	16.31592	151.8996
395	336.4939	33.91926	6.017836	15.86576	147.7087
396	263.3708	26.5483	4.710106	12.41799	115.6102
397	204.1578	20.57952	3.651145	9.626082	89.61788
398	284.1838	28.6463	5.082325	13.39933	124.7464
399	276.9511	27.91723	4.952975	13.0583	121.5715
400	295.5526	29.79229	5.285643	13.93536	129.7369
401	207.7863	20.94527	3.716036	9.797166	91.21066
402	140.749	14.18779	2.517147	6.636346	61.78373
403	90.44867	9.117408	1.617578	4.264674	39.7037
404	81.35075	8.20032	1.454872	3.835705	35.71004
405	92.33905	9.307962	1.651386	4.353805	40.5335
406	61.12749	6.161774	1.0932	2.882174	26.83276
407	97.1293	9.790829	1.737054	4.579667	42.63625
408	77.19317	7.781227	1.380518	3.639674	33.88501
409	64.52366	6.504115	1.153937	3.042304	28.32355
410	28.39018	2.861787	0.507728	1.338603	12.46226
411	51.93555	5.235208	0.928812	2.448772	22.79783
412	58.05736	5.852299	1.038294	2.737417	25.48508
413	21.21591	2.138606	0.379424	1.000334	9.313016
414	32.55071	3.281177	0.582135	1.534773	14.28859
415	54.85117	5.529109	0.980955	2.586244	24.07768
416	42.20896	4.254748	0.754862	1.990161	18.52821
417	29.51973	2.975649	0.527929	1.391862	12.9581
418	15.00806	1.512842	0.268403	0.707633	6.587995
419	40.15002	4.047203	0.71804	1.893082	17.62441
420	3.31583	0.334242	0.0593	0.156342	1.455529
421	11.04268	1.113124	0.197487	0.520665	4.847336
422	8.805026	0.887564	0.157469	0.415159	3.865088
423	12.37093	1.247015	0.221241	0.583292	5.430393
424	46.80664	4.718204	0.837087	2.206943	20.54642
425	7.328109	0.738688	0.131055	0.345522	3.216775
426	27.80094	2.802391	0.49719	1.31082	12.20361
427	20.71676	2.088291	0.370497	0.9768	9.093909

428	21.56025	2.173317	0.385582	1.01657	9.464171
429	111.0455	11.19361	1.98593	5.235817	48.74495
430	244.9869	24.69518	4.381331	11.55119	107.5404
431	144.6164	14.57762	2.58631	6.818693	63.48136
432	99.82206	10.06226	1.785211	4.706631	43.81827
433	50.57963	5.098529	0.904563	2.38484	22.20263
434	50.09778	5.049957	0.895946	2.362121	21.99111
435	115.2895	11.62142	2.061831	5.435925	50.60793
436	298.2569	30.0649	5.334007	14.06287	130.924
437	262.6469	26.47534	4.697161	12.38386	115.2925
438	551.524	55.59473	9.863419	26.00447	242.0991
439	817.5989	82.41562	14.62189	38.54996	358.8964
440	691.1363	69.66794	12.36024	32.58722	303.3839
441	537.7063	54.20188	9.616305	25.35296	236.0336
442	830.0303	83.66873	14.84421	39.1361	364.3533
443	449.4468	45.30514	8.037877	21.19151	197.2909
444	414.6726	41.79984	7.415979	19.5519	182.0263
445	329.3828	33.20245	5.890661	15.53047	144.5871
446	241.8838	24.38237	4.325834	11.40487	106.1782
447	210.0578	21.17425	3.75666	9.904268	92.20776
448	133.1642	13.42322	2.3815	6.27872	58.45427
449	244.4857	24.64466	4.372367	11.52755	107.3204
450	306.6904	30.91501	5.484831	14.46051	134.626
451	213.3768	21.50881	3.816017	10.06076	93.66471
452	276.0492	27.82632	4.936846	13.01578	121.1756
453	211.7542	21.34525	3.786998	9.984253	92.95242
454	148.627	14.9819	2.658035	7.007792	65.24186
455	88.95329	8.966671	1.590835	4.194166	39.04728
456	71.46362	7.203677	1.278051	3.369525	31.36995
457	60.66888	6.115546	1.084998	2.860551	26.63145
458	68.0165	6.856201	1.216403	3.206992	29.85679
459	51.48553	5.189845	0.920764	2.427554	22.60029
460	47.56095	4.79424	0.850577	2.242509	20.87754
461	60.05612	6.053778	1.07404	2.831659	26.36247
462	58.42313	5.88917	1.044836	2.754663	25.64564
463	46.92839	4.730476	0.839264	2.212683	20.59986
464	62.27678	6.277625	1.113754	2.936363	27.33725
465	78.3863	7.901497	1.401856	3.69593	34.40875
466	55.48123	5.592619	0.992223	2.615951	24.35425
467	49.42867	4.98251	0.883979	2.330572	21.6974
468	16.77996	1.691454	0.300092	0.791179	7.365795
469	39.45932	3.977579	0.705688	1.860515	17.32121
470	61.90478	6.240126	1.107101	2.918823	27.17396

471	24.40271	2.459843	0.436417	1.150593	10.71191
472	1.830961	0.184565	0.032745	0.08633	0.803726
473	12.81794	1.292074	0.229235	0.604368	5.626612
474	9.154806	0.922823	0.163724	0.431651	4.018629
475	47.69915	4.80817	0.853049	2.249025	20.9382
476	75.6071	7.621348	1.352152	3.56489	33.18878
477	28.32777	2.855496	0.506612	1.33566	12.43487
478	9.154806	0.922823	0.163724	0.431651	4.018629
479	26.91646	2.713234	0.481372	1.269117	11.81535
480	28.01237	2.823704	0.500971	1.320789	12.29642
481	29.84394	3.008329	0.533727	1.407148	13.10041
482	163.2525	16.45618	2.919597	7.697387	71.66193
483	77.20239	7.782156	1.380683	3.640109	33.88906
484	79.1781	7.981312	1.416016	3.733264	34.75632
485	27.64606	2.786779	0.49442	1.303517	12.13562
486	117.5973	11.85405	2.103103	5.544737	51.62096
487	244.2437	24.62026	4.368039	11.51614	107.2142
488	308.7802	31.12567	5.522205	14.55905	135.5433
489	332.9398	33.561	5.954274	15.69818	146.1485
490	433.0945	43.6568	7.745434	20.42049	190.1128
491	533.5863	53.78657	9.542623	25.1587	234.2251
492	444.6649	44.82312	7.952359	20.96604	195.1918
493	582.303	58.69732	10.41387	27.45571	255.61
494	485.7044	48.95998	8.686306	22.90106	213.2067
495	786.6852	79.29945	14.06903	37.09237	345.3264
496	674.3809	67.97895	12.06058	31.7972	296.0288
497	691.7885	69.73367	12.3719	32.61797	303.6701
498	414.7178	41.80439	7.416786	19.55403	182.0461
499	264.9245	26.70492	4.737893	12.49125	116.2923
500	220.4317	22.21996	3.942186	10.3934	96.76153
501	286.271	28.85669	5.119652	13.49774	125.6626
502	289.5706	29.1893	5.178662	13.65331	127.111
503	288.6686	29.09838	5.162531	13.61078	126.7151
504	218.4334	22.01853	3.906449	10.29918	95.88437
505	112.9517	11.38575	2.02002	5.325694	49.58169
506	102.0833	10.29021	1.825652	4.813251	44.8109
507	151.1397	15.23519	2.702973	7.126268	66.34486
508	142.5268	14.36699	2.54894	6.720167	62.5641
509	132.4213	13.34834	2.368215	6.243693	58.12818
510	127.6602	12.86841	2.283067	6.019205	56.03822
511	117.7113	11.86554	2.105142	5.550114	51.67102
512	120.9608	12.1931	2.163256	5.703329	53.09744
513	116.825	11.7762	2.089291	5.508324	51.28195

514	97.05365	9.783203	1.735701	4.5761	42.60304
515	123.3432	12.43324	2.205861	5.815656	54.14319
516	137.7834	13.88884	2.464109	6.496515	60.48193
517	41.43991	4.177227	0.741109	1.9539	18.19062
518	29.40747	2.964332	0.525921	1.386568	12.90882
519	20.79555	2.096233	0.371906	0.980514	9.128494
520	55.70367	5.615042	0.996201	2.62644	24.4519
521	52.39643	5.281665	0.937054	2.470502	23.00014
522	54.23777	5.467277	0.969985	2.557322	23.80842
523	8.375038	0.844221	0.149779	0.394885	3.676339
524	12.15448	1.225196	0.21737	0.573086	5.335376
525	11.12108	1.121027	0.198889	0.524361	4.881752
526	14.7937	1.491235	0.26457	0.697526	6.493901
527	9.531979	0.960843	0.170469	0.449435	4.184194
528	30.09279	3.033414	0.538178	1.418881	13.20965
529	57.49012	5.79512	1.02815	2.710671	25.23609
530	74.73503	7.533441	1.336556	3.523772	32.80597
531	48.82355	4.921512	0.873157	2.302041	21.43177
532	57.95583	5.842065	1.036478	2.73263	25.44051
533	26.76019	2.697481	0.478577	1.261748	11.74675
534	24.78209	2.498085	0.443201	1.168481	10.87844
535	22.36561	2.254499	0.399985	1.054543	9.817694
536	38.66375	3.897383	0.69146	1.823004	16.97199
537	23.98623	2.41786	0.428968	1.130956	10.52909
538	51.15662	5.156691	0.914882	2.412046	22.45591
539	49.249	4.964398	0.880766	2.3221	21.61853
540	218.0469	21.97957	3.899537	10.28096	95.7147
541	235.9594	23.78518	4.219883	11.12553	103.5776
542	560.1634	56.4656	10.01793	26.41182	245.8915
543	574.3562	57.89627	10.27175	27.08102	252.1216
544	634.1576	63.92436	11.34123	29.90066	278.3723
545	601.0541	60.58747	10.74921	28.33983	263.841
546	692.3673	69.79202	12.38225	32.64526	303.9242
547	650.7752	65.59945	11.63842	30.68419	285.6668
548	733.6402	73.95241	13.12037	34.59129	322.0415
549	341.7237	34.44644	6.111365	16.11234	150.0043
550	187.3038	18.8806	3.349729	8.831412	82.21959
551	156.3158	15.75694	2.795541	7.37032	68.61697
552	150.1109	15.13149	2.684574	7.077762	65.89327
553	190.4037	19.19307	3.405167	8.977572	83.58032
554	107.0362	10.78947	1.914229	5.046781	46.98504
555	221.8942	22.36738	3.968341	10.46236	97.40352
556	163.0284	16.43359	2.915589	7.686821	71.56356

557	134.1398	13.52156	2.398947	6.324718	58.88251
558	96.84635	9.762308	1.731994	4.566326	42.51205
559	89.56751	9.028585	1.60182	4.223127	39.3169
560	84.97818	8.565972	1.519744	4.006739	37.30235
561	107.7852	10.86496	1.927623	5.082093	47.31379
562	77.75746	7.838109	1.390609	3.66628	34.13271
563	96.57865	9.735322	1.727206	4.553703	42.39453
564	88.63944	8.935034	1.585222	4.179368	38.90951
565	74.73131	7.533066	1.33649	3.523597	32.80434
566	57.1942	5.765291	1.022857	2.696718	25.10619
567	37.59967	3.790123	0.67243	1.772832	16.5049
568	48.11091	4.849677	0.860412	2.268439	21.11895
569	22.86644	2.304983	0.408942	1.078157	10.03754
570	1.880767	0.189585	0.033636	0.088679	0.825589
571	0.282886	0.028516	0.005059	0.013338	0.124177
572	14.48226	1.459841	0.259	0.682842	6.357188
573	33.38299	3.365073	0.597019	1.574015	14.65393
574	13.69555	1.380539	0.24493	0.645748	6.01185
575	4.936155	0.497574	0.088278	0.232741	2.166794
576	6.666258	0.671972	0.119219	0.314315	2.926246
577	11.73966	1.183381	0.209951	0.553527	5.153285
578	35.43809	3.572231	0.633772	1.670913	15.55604
579	33.66987	3.393991	0.60215	1.587541	14.77986
580	13.74987	1.386015	0.245902	0.648309	6.035697
581	30.98611	3.123462	0.554154	1.461002	13.60178
582	8.384678	0.845192	0.149951	0.395339	3.68057
583	24.65217	2.484989	0.440878	1.162355	10.82141
584	120.8226	12.17916	2.160783	5.69681	53.03674
585	184.1611	18.56381	3.293526	8.683236	80.84008
586	75.87745	7.6486	1.356987	3.577637	33.30746
587	50.64036	5.104651	0.905649	2.387704	22.22929
588	40.8143	4.114164	0.72992	1.924403	17.916
589	25.3204	2.552347	0.452828	1.193862	11.11474
590	61.16909	6.165968	1.093944	2.884135	26.85102
591	158.9591	16.0234	2.842814	7.494954	69.77729
592	382.8508	38.59214	6.84688	18.0515	168.0577
593	255.9242	25.79768	4.576932	12.06688	112.3415
594	476.0545	47.98725	8.513728	22.44607	208.9707
595	404.0659	40.73066	7.226289	19.05179	177.3703
596	202.907	20.45343	3.628775	9.567106	89.06883
597	253.204	25.52347	4.528283	11.93862	111.1474
598	639.8084	64.49397	11.44229	30.1671	280.8527
599	641.0806	64.62222	11.46504	30.22708	281.4112

600	673.3286	67.87288	12.04176	31.74758	295.5669
601	648.5115	65.37127	11.59794	30.57745	284.6731
602	378.167	38.12	6.763115	17.83065	166.0017
603	286.2934	28.85896	5.120054	13.4988	125.6725
604	158.4604	15.97313	2.833896	7.471442	69.5584
605	145.2367	14.64015	2.597403	6.847939	63.75365
606	217.8179	21.95648	3.895441	10.27016	95.61416
607	225.0302	22.6835	4.024426	10.61022	98.78014
608	203.8577	20.54927	3.645779	9.611935	89.48617
609	119.1977	12.01536	2.131723	5.620194	52.32346
610	120.8662	12.18355	2.161563	5.698866	53.05588
611	94.54944	9.530774	1.690916	4.458026	41.50379
612	110.474	11.136	1.975709	5.20887	48.49407
613	112.5805	11.34834	2.013382	5.308193	49.41876
614	78.84252	7.947485	1.410015	3.717441	34.60902
615	95.50377	9.626972	1.707983	4.503023	41.9227
616	54.95081	5.539152	0.982737	2.590942	24.12142
617	91.06958	9.179998	1.628683	4.29395	39.97625
618	40.59952	4.092513	0.726079	1.914276	17.82172
619	57.65576	5.811817	1.031112	2.718481	25.30879
620	64.13324	6.46476	1.146955	3.023896	28.15218
621	52.25722	5.267633	0.934565	2.463939	22.93903
622	33.99889	3.427157	0.608034	1.603055	14.92428
623	10.43876	1.052248	0.186686	0.49219	4.58224
624	10.89533	1.098271	0.194851	0.513717	4.782656
625	10.94547	1.103325	0.195748	0.516081	4.804665
626	5.165761	0.520719	0.092384	0.243567	2.267582
627	16.24975	1.638008	0.290609	0.766179	7.133053
628	18.75019	1.890057	0.335327	0.884075	8.230656
629	20.93415	2.110205	0.374385	0.98705	9.189337
630	7.533527	0.759395	0.134729	0.355207	3.306946
631	9.040731	0.911324	0.161684	0.426272	3.968554
632	12.35409	1.245317	0.22094	0.582498	5.422998
633	21.5238	2.169643	0.38493	1.014852	9.448171
634	57.29403	5.775353	1.024643	2.701425	25.15001
635	47.02617	4.740333	0.841013	2.217294	20.64279
636	72.05589	7.263379	1.288643	3.39745	31.62993
637	88.31764	8.902596	1.579467	4.164195	38.76825
638	38.4868	3.879547	0.688295	1.81466	16.89431
639	21.21296	2.138309	0.379371	1.000195	9.311721
640	36.67114	3.696525	0.655824	1.729052	16.0973
641	157.6979	15.89627	2.82026	7.435491	69.2237
642	172.5426	17.39264	3.085741	8.135419	75.73996

643	320.2189	32.27871	5.726774	15.09839	140.5645
644	539.9701	54.43007	9.65679	25.4597	237.0273
645	535.4529	53.97473	9.576005	25.24671	235.0444
646	349.2897	35.2091	6.246674	16.46908	153.3255
647	113.6008	11.45119	2.03163	5.356302	49.86665
648	620.0125	62.49851	11.08826	29.23372	272.1631
649	700.3247	70.59415	12.52456	33.02046	307.4172
650	926.3761	93.38058	16.56725	43.67883	406.6456
651	918.9411	92.63112	16.43428	43.32826	403.3819
652	741.6807	74.76291	13.26417	34.9704	325.571
653	700.1282	70.57433	12.52105	33.01119	307.331
654	504.4656	50.85115	9.021831	23.78566	221.4422
655	374.0755	37.70757	6.689943	17.63774	164.2056
656	177.5219	17.89456	3.17479	8.370193	77.92568
657	165.914	16.72447	2.967195	7.82288	72.83025
658	207.1509	20.88123	3.704674	9.76721	90.93177
659	191.1024	19.26351	3.417664	9.01052	83.88706
660	94.91646	9.567771	1.69748	4.475331	41.6649
661	92.94838	9.369384	1.662283	4.382535	40.80098
662	84.00481	8.467854	1.502337	3.960844	36.87507
663	84.95148	8.56328	1.519267	4.00548	37.29063
664	98.66112	9.94524	1.764449	4.651892	43.30866
665	95.9146	9.668385	1.715331	4.522393	42.10304
666	72.4535	7.303458	1.295754	3.416197	31.80446
667	85.46017	8.614557	1.528364	4.029465	37.51392
668	78.60927	7.923973	1.405843	3.706444	34.50663
669	76.56014	7.717416	1.369197	3.609826	33.60713
670	52.22343	5.264227	0.933961	2.462346	22.9242
671	9.942556	1.00223	0.177812	0.468794	4.364422
672	39.77465	4.009365	0.711327	1.875383	17.45963
673	24.68198	2.487993	0.441411	1.16376	10.8345
674	20.48264	2.064692	0.36631	0.965761	8.99114
675	21.28153	2.145221	0.380598	1.003429	9.341823
676	32.32032	3.257953	0.578014	1.52391	14.18745
677	34.29835	3.457343	0.61339	1.617174	15.05574
678	17.33203	1.747103	0.309965	0.817209	7.608134
679	5.088078	0.512888	0.090995	0.239904	2.233482
680	22.61777	2.279917	0.404495	1.066433	9.928384
681	12.7247	1.282676	0.227568	0.599972	5.585684
682	9.088214	0.91611	0.162533	0.428511	3.989397
683	10.90646	1.099393	0.19505	0.514242	4.787541
684	14.90359	1.502312	0.266535	0.702707	6.542137
685	31.17259	3.14226	0.557489	1.469794	13.68364

686	21.97467	2.215091	0.392994	1.03611	9.646086
687	42.35383	4.269352	0.757453	1.996992	18.5918
688	128.9319	12.9966	2.30581	6.079167	56.59645
689	191.681	19.32184	3.428011	9.037801	84.14105
690	28.35559	2.858301	0.50711	1.336972	12.44708
691	25.59066	2.57959	0.457662	1.206605	11.23337
692	101.9583	10.2776	1.823415	4.807354	44.756
693	27.44496	2.766508	0.490824	1.294036	12.04735
694	38.70906	3.901951	0.69227	1.82514	16.99188
695	94.4118	9.5169	1.688455	4.451536	41.44337
696	86.88501	8.758184	1.553846	4.096646	38.13938
697	424.5713	42.79764	7.593006	20.01863	186.3715
698	264.6329	26.67553	4.732678	12.4775	116.1643
699	137.0445	13.81436	2.450895	6.461677	60.15758
700	406.7032	40.9965	7.273454	19.17614	178.528
701	382.54	38.5608	6.84132	18.03684	167.9212
702	653.101	65.8339	11.68002	30.79385	286.6877
703	952.0165	95.96518	17.0258	44.88778	417.9008
704	849.3431	85.6155	15.1896	40.0467	372.8309
705	829.2732	83.59241	14.83067	39.1004	364.0209
706	495.0234	49.89935	8.852966	23.34045	217.2974
707	519.4762	52.36424	9.290278	24.49341	228.0312
708	348.6305	35.14266	6.234886	16.438	153.0362
709	366.2139	36.9151	6.549346	17.26706	160.7547
710	347.6613	35.04496	6.217553	16.3923	152.6108
711	357.4961	36.03632	6.393437	16.85601	156.9278
712	335.9316	33.86258	6.007779	15.83924	147.4618
713	194.2477	19.58056	3.473913	9.158819	85.26772
714	187.2834	18.87854	3.349364	8.830449	82.21062
715	163.1617	16.44702	2.917973	7.693106	71.62207
716	159.0533	16.03289	2.844499	7.499397	69.81865
717	174.8393	17.62415	3.126814	8.243707	76.74811
718	130.1383	13.1182	2.327384	6.136046	57.12599
719	116.1751	11.71068	2.077668	5.47768	50.99666
720	108.0343	10.89007	1.932078	5.093839	47.42314
721	84.01784	8.469168	1.50257	3.961459	36.88079
722	24.02028	2.421293	0.429577	1.132561	10.54403
723	56.86054	5.731657	1.01689	2.680986	24.95972
724	96.04618	9.681649	1.717684	4.528598	42.1608
725	63.60669	6.411682	1.137538	2.999068	27.92103
726	37.6555	3.795751	0.673429	1.775465	16.5294
727	44.17233	4.45266	0.789975	2.082734	19.39005
728	26.57466	2.678779	0.47526	1.253001	11.66531

729	51.50316	5.191623	0.921079	2.428385	22.60803
730	85.45976	8.614516	1.528357	4.029446	37.51375
731	87.77784	8.848183	1.569813	4.138743	38.5313
732	27.94822	2.817237	0.499824	1.317764	12.26826
733	11.41049	1.1502	0.204064	0.538007	5.008792
734	8.149579	0.821494	0.145747	0.384254	3.57737
735	32.55295	3.281403	0.582175	1.534878	14.28957
736	56.03398	5.648338	1.002108	2.642014	24.59689
737	34.61435	3.489197	0.619041	1.632074	15.19445
738	8.149579	0.821494	0.145747	0.384254	3.57737
739	23.96095	2.415312	0.428516	1.129764	10.51799
740	200.1124	20.17174	3.578798	9.435342	87.84212
741	200.8284	20.24391	3.591603	9.469103	88.15643
742	218.6169	22.03703	3.909731	10.30783	95.96493
743	262.4736	26.45787	4.694061	12.37568	115.2164
744	203.7514	20.53855	3.643877	9.60692	89.43949
745	103.8595	10.46925	1.857417	4.896999	45.59058
746	49.26915	4.96643	0.881126	2.323051	21.62738
747	207.0346	20.86951	3.702594	9.761725	90.8807
748	298.6645	30.10598	5.341296	14.08209	131.1029
749	343.8702	34.66281	6.149754	16.21355	150.9466
750	542.6083	54.69601	9.703972	25.58409	238.1854
751	1079.461	108.8119	19.30501	50.89682	473.8444
752	777.6532	78.38901	13.9075	36.66651	341.3616
753	248.0338	25.0023	4.43582	11.69484	108.8779
754	831.08	83.77454	14.86298	39.18559	364.8141
755	781.8575	78.81282	13.98269	36.86475	343.2072
756	587.0696	59.17779	10.49911	27.68045	257.7023
757	402.4713	40.56992	7.197771	18.97661	176.6703
758	224.162	22.59599	4.008899	10.56929	98.39903
759	193.8745	19.54294	3.46724	9.141225	85.10391
760	265.1261	26.72524	4.741498	12.50075	116.3808
761	237.4998	23.94046	4.247431	11.19817	104.2538
762	305.5669	30.80176	5.464738	14.40754	134.1328
763	294.5553	29.69177	5.267808	13.88834	129.2991
764	241.83	24.37695	4.324871	11.40233	106.1546
765	250.7331	25.2744	4.484095	11.82212	110.0628
766	192.7145	19.42601	3.446494	9.08653	84.59471
767	148.4146	14.96049	2.654238	6.997781	65.14865
768	123.5166	12.45072	2.208962	5.823832	54.21931
769	123.041	12.40278	2.200458	5.80141	54.01056
770	107.5442	10.84067	1.923314	5.070733	47.20803
771	101.3095	10.21221	1.811813	4.776765	44.47122

772	84.94222	8.562347	1.519101	4.005043	37.28656
773	88.55585	8.926608	1.583727	4.175427	38.87281
774	75.71689	7.632415	1.354116	3.570067	33.23698
775	33.879	3.415072	0.60589	1.597402	14.87166
776	81.31149	8.196362	1.454169	3.833853	35.6928
777	32.76654	3.302934	0.585995	1.544949	14.38333
778	9.87332	0.995251	0.176574	0.465529	4.33403
779	9.88926	0.996857	0.176859	0.466281	4.341028
780	38.57989	3.88893	0.68996	1.81905	16.93518
781	49.53372	4.993099	0.885858	2.335525	21.74351
782	14.18256	1.42963	0.25364	0.66871	6.225629
783	4.698321	0.4736	0.084024	0.221527	2.062393
784	22.64872	2.283036	0.405048	1.067892	9.941968
785	19.39879	1.955437	0.346927	0.914657	8.515369
786	40.71504	4.104158	0.728145	1.919722	17.87243
787	57.51555	5.797683	1.028604	2.71187	25.24725
788	49.94959	5.03502	0.893295	2.355134	21.92607
789	21.64651	2.182012	0.387125	1.020637	9.502034
790	8.39204	0.845935	0.150083	0.395686	3.683802
791	24.67382	2.487171	0.441265	1.163376	10.83091
792	102.1035	10.29224	1.826012	4.8142	44.81974
793	212.5831	21.42881	3.801823	10.02334	93.3163
794	200.3807	20.19878	3.583596	9.447994	87.9599
795	58.24468	5.871181	1.041644	2.746249	25.56731
796	61.43611	6.192884	1.098719	2.896725	26.96823
797	25.34263	2.554588	0.453226	1.19491	11.1245
798	35.74387	3.603054	0.639241	1.685331	15.69027
799	132.7094	13.37738	2.373367	6.257278	58.25465
800	204.4872	20.61273	3.657037	9.641616	89.76251
801	345.3314	34.8101	6.175885	16.28245	151.588
802	225.9979	22.78104	4.041731	10.65585	99.20489
803	140.7446	14.18734	2.517068	6.636137	61.78179
804	584.0928	58.87773	10.44588	27.5401	256.3956
805	822.499	82.90956	14.70952	38.781	361.0473
806	675.0381	68.0452	12.07234	31.82819	296.3173
807	493.0337	49.69879	8.817382	23.24664	216.4239
808	679.0639	68.45101	12.14434	32.01801	298.0845
809	711.5537	71.72605	12.72538	33.5499	312.3463
810	582.0969	58.67654	10.41018	27.44599	255.5195
811	494.3599	49.83247	8.841101	23.30917	217.0061
812	375.3161	37.83262	6.71213	17.69623	164.7502
813	303.8064	30.6243	5.433254	14.32454	133.36
814	367.6868	37.06357	6.575687	17.33651	161.4012

815	346.2056	34.89822	6.191519	16.32367	151.9717
816	236.9014	23.88014	4.236729	11.16995	103.9911
817	214.6477	21.63692	3.838746	10.12068	94.22258
818	158.2658	15.95351	2.830415	7.462265	69.47296
819	126.72	12.77363	2.266252	5.974874	55.62549
820	135.5577	13.66449	2.424306	6.391575	59.50494
821	147.7405	14.89254	2.642182	6.965997	64.85275
822	84.96279	8.56442	1.519469	4.006013	37.29559
823	66.71976	6.725486	1.193212	3.145851	29.28756
824	73.75493	7.434646	1.319029	3.47756	32.37575
825	74.06677	7.46608	1.324605	3.492264	32.51263
826	56.95122	5.740798	1.018512	2.685262	24.99953
827	26.29187	2.650273	0.470202	1.239667	11.54118
828	54.14976	5.458405	0.968411	2.553172	23.76979
829	10.18338	1.026506	0.182119	0.480149	4.470137
830	44.04554	4.439879	0.787708	2.076756	19.3344
831	45.43483	4.579922	0.812554	2.142262	19.94425
832	39.27778	3.959279	0.702441	1.851955	17.24152
833	48.05446	4.843986	0.859403	2.265778	21.09417
834	39.97294	4.029353	0.714873	1.884732	17.54667
835	24.39147	2.458709	0.436215	1.150063	10.70697
836	3.743104	0.377312	0.066941	0.176488	1.643087
837	9.812527	0.989122	0.175487	0.462663	4.307344
838	11.60257	1.169562	0.2075	0.547063	5.093107
839	30.59669	3.084208	0.547189	1.44264	13.43084
840	11.49275	1.158493	0.205536	0.541886	5.044903
841	16.76964	1.690414	0.299907	0.790692	7.361267
842	7.008285	0.706449	0.125336	0.330442	3.076384
843	20.60538	2.077064	0.368505	0.971548	9.045016
844	43.375	4.372288	0.775716	2.04514	19.04006
845	138.3313	13.94408	2.473909	6.522352	60.72246
846	158.5829	15.98547	2.836086	7.477215	69.61215
847	225.3307	22.71379	4.029799	10.62439	98.91201
848	163.932	16.52468	2.93175	7.729429	71.96023
849	162.4725	16.37756	2.905648	7.660613	71.31956
850	130.0297	13.10726	2.325443	6.130929	57.07835
851	206.1059	20.77589	3.685985	9.717937	90.47305
852	186.8916	18.83905	3.342358	8.811979	82.03867
853	238.8509	24.07666	4.271595	11.26187	104.8469
854	305.9457	30.83995	5.471514	14.42541	134.2991
855	879.0349	88.60849	15.7206	41.44668	385.8645
856	780.1424	78.63993	13.95202	36.78388	342.4543
857	533.2887	53.75658	9.537302	25.14468	234.0945

858	802.0409	80.84734	14.34365	37.8164	352.067
859	458.5468	46.22244	8.200622	21.62058	201.2855
860	565.7776	57.03152	10.11833	26.67653	248.3559
861	471.1561	47.49349	8.426126	22.21511	206.8205
862	258.9758	26.10528	4.631507	12.21076	113.681
863	314.7707	31.72952	5.629339	14.8415	138.173
864	199.6654	20.12668	3.570804	9.414267	87.64591
865	154.9198	15.61623	2.770576	7.3045	68.00418
866	281.6469	28.39058	5.036956	13.27971	123.6328
867	308.079	31.05499	5.509665	14.52599	135.2355
868	257.041	25.91025	4.596905	12.11954	112.8317
869	215.998	21.77304	3.862895	10.18435	94.81533
870	143.3715	14.45214	2.564047	6.759998	62.93492
871	108.0253	10.88917	1.931918	5.093417	47.41921
872	77.36534	7.798582	1.383597	3.647792	33.96058
873	74.73783	7.533724	1.336607	3.523904	32.8072
874	71.17153	7.174234	1.272827	3.355753	31.24173
875	86.95228	8.764965	1.555049	4.099818	38.16891
876	73.1044	7.369071	1.307394	3.446888	32.09019
877	72.89358	7.347819	1.303624	3.436947	31.99764
878	49.18692	4.958141	0.879656	2.319174	21.59128
879	29.42348	2.965946	0.526208	1.387323	12.91584
880	72.38576	7.296631	1.294542	3.413004	31.77473
881	65.86999	6.639828	1.178015	3.105784	28.91454
882	48.02261	4.840775	0.858833	2.264276	21.08019
883	59.22604	5.970104	1.059195	2.79252	25.99809
884	49.26955	4.96647	0.881134	2.32307	21.62755
885	67.78272	6.832634	1.212222	3.195969	29.75416
886	53.40046	5.382874	0.95501	2.517843	23.44087
887	50.03017	5.043142	0.894736	2.358933	21.96144
888	34.6575	3.493546	0.619813	1.634108	15.21339
889	33.36965	3.363728	0.596781	1.573386	14.64807
890	45.26268	4.56257	0.809475	2.134145	19.86868
891	63.72796	6.423907	1.139707	3.004787	27.97427
892	26.10729	2.631668	0.466901	1.230964	11.46016
893	29.73982	2.997834	0.531865	1.402239	13.05471
894	22.96318	2.314735	0.410672	1.082719	10.08001
895	39.76243	4.008133	0.711109	1.874807	17.45427
896	207.4063	20.90697	3.709241	9.77925	91.04386
897	187.9153	18.94224	3.360665	8.860244	82.48801
898	254.8627	25.69068	4.557948	12.01683	111.8755
899	226.6201	22.84376	4.05286	10.68519	99.47803
900	145.6832	14.68516	2.605389	6.868993	63.94965

901	56.59743	5.705135	1.012185	2.66858	24.84422
902	105.1273	10.59705	1.88009	4.956775	46.1471
903	172.8217	17.42078	3.090732	8.148579	75.86248
904	121.6291	12.26046	2.175207	5.734836	53.39077
905	228.0664	22.98956	4.078725	10.75338	100.1129
906	367.5035	37.04509	6.572409	17.32787	161.3207
907	796.3965	80.27837	14.2427	37.55026	349.5893
908	429.3564	43.27999	7.678582	20.24424	188.4719
909	545.333	54.97067	9.752701	25.71256	239.3815
910	488.8526	49.27732	8.742608	23.0495	214.5886
911	579.1302	58.37749	10.35713	27.30611	254.2172
912	553.3257	55.77634	9.895641	26.08942	242.89
913	436.8077	44.0311	7.811841	20.59557	191.7428
914	242.2216	24.41642	4.331875	11.4208	106.3265
915	158.7109	15.99838	2.838376	7.483252	69.66835
916	144.2158	14.53724	2.579146	6.799806	63.30553
917	132.1789	13.3239	2.363879	6.232263	58.02176
918	276.0705	27.82846	4.937227	13.01678	121.185
919	163.3384	16.46484	2.921134	7.701442	71.69967
920	110.8781	11.17674	1.982937	5.227925	48.67148
921	129.4083	13.04462	2.31433	6.101629	56.80557
922	130.0456	13.10886	2.325728	6.131678	57.08532
923	86.05003	8.674017	1.538913	4.057277	37.77285
924	96.56923	9.734373	1.727038	4.553259	42.3904
925	90.58938	9.131592	1.620095	4.271308	39.76546
926	101.7367	10.25526	1.819453	4.796907	44.65873
927	114.6094	11.55286	2.049668	5.403858	50.30939
928	82.55638	8.32185	1.476433	3.892551	36.23927
929	71.99416	7.257156	1.287539	3.39454	31.60283
930	54.63347	5.507164	0.977061	2.575979	23.98212
931	72.52001	7.310164	1.296943	3.419334	31.83366
932	83.97089	8.464435	1.50173	3.959245	36.86018
933	45.15149	4.551361	0.807486	2.128902	19.81987
934	53.92184	5.43543	0.964335	2.542426	23.66974
935	36.1431	3.643297	0.646381	1.704154	15.86551
936	17.11644	1.725372	0.306109	0.807044	7.513499
937	8.126816	0.819199	0.145339	0.383181	3.567378
938	2.540654	0.256103	0.045437	0.119792	1.115255
939	30.37653	3.062015	0.543252	1.43226	13.3342
940	14.38531	1.450068	0.257266	0.67827	6.314631
941	11.11618	1.120533	0.198801	0.52413	4.879601
942	33.74795	3.401861	0.603546	1.591223	14.81413
943	39.52688	3.98439	0.706896	1.863701	17.35087

944	13.01964	1.312405	0.232842	0.613879	5.715149
945	20.4692	2.063336	0.36607	0.965127	8.985237
946	34.99113	3.527176	0.625779	1.649839	15.35984
947	23.59799	2.378725	0.422025	1.11265	10.35866
948	73.9528	7.454592	1.322567	3.48689	32.46261
949	54.93643	5.537703	0.98248	2.590264	24.11511
950	156.0777	15.73295	2.791284	7.359097	68.51248
951	22.35576	2.253505	0.399809	1.054079	9.813369
952	38.64671	3.895666	0.691155	1.8222	16.96451
953	23.97566	2.416795	0.428779	1.130457	10.52445
954	33.81587	3.408708	0.604761	1.594425	14.84394
955	120.6563	12.1624	2.15781	5.68897	52.96376
956	75.90193	7.651067	1.357425	3.578792	33.3182
957	222.6795	22.44654	3.982386	10.49938	97.74825
958	704.0181	70.96645	12.59062	33.1946	309.0385
959	251.6421	25.36603	4.500351	11.86498	110.4618
960	492.5681	49.65186	8.809057	23.22469	216.2196
961	512.0916	51.61986	9.158213	24.14522	224.7897
962	636.3264	64.14298	11.38002	30.00292	279.3243
963	756.8382	76.29082	13.53525	35.68508	332.2246
964	821.006	82.75906	14.68282	38.7106	360.3919
965	634.6697	63.97598	11.35039	29.92481	278.597
966	422.8325	42.62237	7.56191	19.93664	185.6082
967	329.0851	33.17244	5.885336	15.51643	144.4564
968	285.2411	28.75288	5.101234	13.44918	125.2105
969	249.0935	25.10913	4.454773	11.74481	109.3431
970	313.4813	31.59954	5.606279	14.78071	137.6069
971	362.6174	36.55256	6.485026	17.09749	159.1759
972	394.465	39.76287	7.054588	18.59911	173.1559
973	245.671	24.76414	4.393565	11.58344	107.8407
974	149.6883	15.08888	2.677016	7.057835	65.70776
975	149.2976	15.0495	2.670029	7.039415	65.53626
976	136.3661	13.74598	2.438763	6.42969	59.85979
977	103.9131	10.47465	1.858375	4.899524	45.61409
978	80.90718	8.155606	1.446939	3.81479	35.51532
979	76.11348	7.672392	1.361209	3.588766	33.41107
980	82.7367	8.340026	1.479658	3.901053	36.31842
981	58.42079	5.888934	1.044794	2.754552	25.64462
982	16.19644	1.632633	0.289656	0.763665	7.10965
983	56.30553	5.675711	1.006965	2.654818	24.71609
984	93.14042	9.388743	1.665717	4.39159	40.88528
985	101.586	10.24008	1.816758	4.789802	44.59259
986	68.13391	6.868036	1.218503	3.212528	29.90832

987	41.25105	4.158189	0.737731	1.944996	18.10772
988	32.00356	3.226023	0.57235	1.508975	14.04841
989	48.73647	4.912734	0.8716	2.297934	21.39355
990	53.44004	5.386864	0.955718	2.519709	23.45824
991	30.33194	3.05752	0.542454	1.430157	13.31462
992	12.38005	1.247934	0.221404	0.583722	5.434395
993	10.78165	1.086812	0.192818	0.508357	4.732755
994	7.700452	0.776221	0.137714	0.363078	3.38022
995	24.28579	2.448057	0.434326	1.14508	10.66058
996	12.62783	1.27291	0.225835	0.595405	5.543159
997	8.381761	0.844898	0.149899	0.395202	3.67929
998	46.87678	4.725274	0.838341	2.21025	20.57721
999	47.1072	4.748501	0.842462	2.221114	20.67836
1000	100.7243	10.15322	1.801348	4.749174	44.21434
1001	152.617	15.3841	2.729393	7.195925	66.99336
1002	167.5425	16.88862	2.99632	7.899665	73.54511
1003	74.41514	7.501196	1.330836	3.508689	32.66556
1004	37.48368	3.778431	0.670356	1.767363	16.45398
1005	42.81956	4.316298	0.765782	2.018951	18.79624
1006	128.7898	12.98227	2.303269	6.072466	56.53407
1007	184.2353	18.57129	3.294852	8.686731	80.87262
1008	131.9101	13.2968	2.359072	6.219588	57.90376
1009	110.5412	11.14278	1.976912	5.212041	48.5236
1010	108.4277	10.92973	1.939113	5.112387	47.59583
1011	907.3668	91.4644	16.22729	42.78253	398.3012
1012	526.5352	53.0758	9.416521	24.82624	231.1299
1013	720.1223	72.58978	12.87862	33.95392	316.1076
1014	563.5484	56.80681	10.07846	26.57142	247.3774
1015	574.9099	57.95207	10.28165	27.10712	252.3646
1016	384.8709	38.79576	6.883007	18.14674	168.9444
1017	420.4706	42.38429	7.51967	19.82528	184.5714
1018	246.2416	24.82165	4.40377	11.61034	108.0912
1019	181.955	18.34143	3.254071	8.579215	79.87165
1020	193.511	19.5063	3.460739	9.124085	84.94434
1021	157.1194	15.83795	2.809914	7.408213	68.96974
1022	141.8774	14.30153	2.537326	6.689549	62.27905
1023	183.3396	18.481	3.278834	8.644501	80.47946
1024	140.6138	14.17415	2.514728	6.629969	61.72437
1025	186.1965	18.76898	3.329926	8.779204	81.73353
1026	129.1415	13.01773	2.309559	6.089051	56.68847
1027	94.29967	9.505597	1.686449	4.446249	41.39414
1028	78.0995	7.872587	1.396726	3.682407	34.28285
1029	121.2251	12.21974	2.167982	5.715789	53.21344

1030	101.6204	10.24354	1.817373	4.791423	44.60768
1031	79.92041	8.056139	1.429292	3.768264	35.08217
1032	28.95309	2.91853	0.517795	1.365144	12.70936
1033	19.25113	1.940553	0.344286	0.907695	8.45055
1034	38.52656	3.883555	0.689006	1.816535	16.91176
1035	39.21964	3.953419	0.701402	1.849214	17.216
1036	72.31858	7.289858	1.293341	3.409836	31.74524
1037	3.38932	0.34165	0.060614	0.159807	1.487789
1038	17.64876	1.77903	0.315629	0.832143	7.747167
1039	3.12009	0.314511	0.055799	0.147113	1.369607
1040	12.44203	1.254182	0.222513	0.586644	5.461603
1041	39.36655	3.968227	0.704029	1.856141	17.28049
1042	43.1283	4.34742	0.771304	2.033508	18.93176
1043	32.41828	3.267828	0.579766	1.528528	14.23045
1044	21.46614	2.163831	0.383899	1.012133	9.422861
1045	17.99745	1.814179	0.321865	0.848583	7.900228
1046	36.84544	3.714094	0.658941	1.73727	16.17381
1047	24.72456	2.492285	0.442172	1.165768	10.85319
1048	11.13268	1.122196	0.199096	0.524908	4.886843
1049	8.5451	0.861363	0.15282	0.402903	3.75099
1050	6.78871	0.684316	0.121409	0.320089	2.979998
1051	19.9598	2.011988	0.35696	0.941109	8.761629
1052	41.27749	4.160855	0.738204	1.946242	18.11933
1053	95.15497	9.591813	1.701745	4.486577	41.76959
1054	175.3881	17.67947	3.136629	8.269585	76.98903
1055	164.1422	16.54586	2.935508	7.739337	72.05247
1056	166.0701	16.7402	2.969987	7.830239	72.89877
1057	247.6036	24.95895	4.428128	11.67456	108.689
1058	98.36444	9.915334	1.759143	4.637904	43.17843
1059	168.1825	16.95313	3.007764	7.929838	73.82602
1060	232.4847	23.43493	4.157741	10.9617	102.0524
1061	97.45302	9.82346	1.742843	4.59493	42.77835
1062	400.7155	40.39293	7.16637	18.89382	175.8996
1063	235.5508	23.744	4.212575	11.10627	103.3983
1064	270.244	27.24114	4.833026	12.74206	118.6273
1065	259.7908	26.18744	4.646083	12.24919	114.0388
1066	380.7745	38.38283	6.809746	17.9536	167.1462
1067	376.798	37.98199	6.738631	17.7661	165.4007
1068	561.657	56.61615	10.04464	26.48224	246.5471
1069	424.9261	42.83341	7.599351	20.03535	186.5272
1070	279.0577	28.12958	4.99065	13.15763	122.4962
1071	267.375	26.95194	4.781717	12.60679	117.368
1072	172.36	17.37423	3.082475	8.126809	75.6598

1073	136.2003	13.72926	2.435797	6.421872	59.787
1074	177.1073	17.85277	3.167376	8.350647	77.74371
1075	203.6121	20.52451	3.641386	9.600353	89.37835
1076	256.1136	25.81677	4.58032	12.07581	112.4246
1077	208.8175	21.04922	3.734478	9.845787	91.66331
1078	190.6425	19.21715	3.409439	8.988835	83.68518
1079	136.2968	13.73899	2.437523	6.426422	59.82936
1080	111.5077	11.2402	1.994197	5.257613	48.94786
1081	110.2788	11.11632	1.972218	5.199667	48.40839
1082	101.3411	10.21539	1.812377	4.778253	44.48507
1083	92.17809	9.291738	1.648507	4.346216	40.46285
1084	84.40526	8.508221	1.509498	3.979726	37.05086
1085	81.1657	8.181666	1.451562	3.826979	35.62881
1086	23.9763	2.41686	0.428791	1.130488	10.52473
1087	22.67049	2.285231	0.405438	1.068918	9.951524
1088	37.49478	3.779549	0.670554	1.767887	16.45885
1089	33.85555	3.412708	0.605471	1.596296	14.86136
1090	2.126107	0.214316	0.038023	0.100246	0.933284
1091	11.52883	1.162129	0.206181	0.543587	5.06074
1092	0.24178	0.024372	0.004324	0.0114	0.106133
1093	16.51636	1.664883	0.295378	0.77875	7.250087
1094	1.98173	0.199762	0.035441	0.093439	0.869908
1095	15.22134	1.534342	0.272218	0.717689	6.681619
1096	1.238555	0.124849	0.02215	0.058398	0.543681
1097	8.670707	0.874025	0.155066	0.408826	3.806127
1098	6.192777	0.624244	0.110751	0.291991	2.718405
1099	11.13754	1.122687	0.199183	0.525138	4.888979
1100	10.15542	1.023687	0.181619	0.47883	4.457861
1101	6.44057	0.649222	0.115183	0.303674	2.827178
1102	17.73654	1.787879	0.317199	0.836282	7.7857
1103	18.20767	1.835369	0.325625	0.858495	7.992507
1104	90.19184	9.09152	1.612985	4.252564	39.59096
1105	136.9793	13.80779	2.449729	6.458603	60.12896
1106	108.0343	10.89008	1.932079	5.09384	47.42315
1107	86.03363	8.672363	1.53862	4.056504	37.76565
1108	77.36408	7.798455	1.383574	3.647732	33.96003
1109	18.7012	1.885119	0.334451	0.881766	8.209153
1110	133.6007	13.46722	2.389307	6.299302	58.64589
1111	207.4351	20.90987	3.709756	9.780607	91.0565
1112	239.2553	24.11741	4.278826	11.28094	105.0244
1113	88.8983	8.961128	1.589852	4.191573	39.02314
1114	87.19857	8.789791	1.559454	4.11143	38.27702
1115	93.38315	9.41321	1.670058	4.403035	40.99183

1116	199.3892	20.09884	3.565865	9.401244	87.52467
1117	379.594	38.26384	6.788635	17.89794	166.628
1118	265.4521	26.7581	4.747328	12.51612	116.5239
1119	240.285	24.22122	4.297242	11.32949	105.4764
1120	250.7281	25.2739	4.484005	11.82188	110.0606
1121	182.4802	18.39438	3.263465	8.603982	80.10223
1122	146.034	14.72053	2.611664	6.885536	64.10367
1123	142.2385	14.33793	2.543784	6.706575	62.43756
1124	117.0361	11.79748	2.093066	5.518277	51.37462
1125	197.1022	19.8683	3.524963	9.293408	86.52073
1126	241.0802	24.30137	4.311462	11.36698	105.8255
1127	226.5779	22.83951	4.052105	10.6832	99.45952
1128	223.4231	22.5215	3.995684	10.53444	98.07466
1129	213.6169	21.53302	3.820311	10.07208	93.7701
1130	118.1948	11.91427	2.113787	5.572907	51.88322
1131	92.63431	9.337725	1.656666	4.367727	40.66311
1132	90.51811	9.124408	1.61882	4.267948	39.73418
1133	74.64471	7.524337	1.334941	3.519514	32.76633
1134	71.89638	7.2473	1.28579	3.389929	31.55991
1135	81.50416	8.215783	1.457615	3.842938	35.77738
1136	57.06366	5.752132	1.020523	2.690564	25.04888
1137	69.44388	7.000083	1.24193	3.274293	30.48335
1138	45.57444	4.593995	0.81505	2.148844	20.00553
1139	25.21629	2.541853	0.450967	1.188953	11.06904
1140	33.78376	3.405471	0.604187	1.592911	14.82985
1141	2.725723	0.274758	0.048747	0.128518	1.196494
1142	0.990762	0.099871	0.017719	0.046715	0.434909
1143	2.478854	0.249873	0.044332	0.116878	1.088127
1144	14.09567	1.420872	0.252086	0.664614	6.187488
1145	5.941224	0.598887	0.106252	0.28013	2.607982
1146	13.95705	1.406899	0.249607	0.658078	6.126641
1147	3.806157	0.383668	0.068069	0.179461	1.670765
1148	20.06291	2.022382	0.358804	0.94597	8.806893
1149	29.43327	2.966933	0.526383	1.387785	12.92014
1150	37.77432	3.807727	0.675553	1.781067	16.58156
1151	19.31545	1.947036	0.345436	0.910727	8.478783
1152	45.935	4.63034	0.821499	2.165845	20.1638
1153	18.01335	1.815782	0.32215	0.849333	7.90721
1154	6.798476	0.6853	0.121584	0.32055	2.984285
1155	19.98851	2.014882	0.357473	0.942462	8.774232
1156	130.004	13.10467	2.324983	6.129716	57.06706
1157	102.285	10.31053	1.829259	4.822759	44.89942
1158	174.9747	17.6378	3.129236	8.250094	76.80757

1159	129.9763	13.10187	2.324487	6.128408	57.05488
1160	33.09311	3.335852	0.591835	1.560347	14.52668
1161	44.06717	4.442059	0.788094	2.077776	19.34389
1162	107.6364	10.84996	1.924962	5.075077	47.24848
1163	123.9387	12.49327	2.216512	5.843737	54.40462
1164	260.0874	26.21733	4.651386	12.26317	114.169
1165	97.5932	9.837591	1.745351	4.60154	42.83989
1166	556.8513	56.13174	9.958694	26.25566	244.4376
1167	536.8109	54.11162	9.600291	25.31074	235.6406
1168	464.1726	46.78953	8.301233	21.88583	203.755
1169	546.5862	55.09699	9.775112	25.77165	239.9316
1170	592.8683	59.76232	10.60282	27.95386	260.2478
1171	452.6231	45.62532	8.094683	21.34127	198.6852
1172	475.8245	47.96407	8.509614	22.43522	208.8697
1173	502.4097	50.64391	8.985062	23.68872	220.5397
1174	281.8841	28.41448	5.041196	13.29089	123.7369
1175	272.0936	27.42759	4.866105	12.82927	119.4393
1176	205.9817	20.76337	3.683764	9.71208	90.41852
1177	171.0493	17.24212	3.059035	8.065011	75.08447
1178	250.9695	25.29823	4.488323	11.83327	110.1666
1179	206.4822	20.81382	3.692714	9.735677	90.63821
1180	248.013	25.00021	4.435448	11.69386	108.8687
1181	125.962	12.69722	2.252697	5.939135	55.29277
1182	75.8084	7.64164	1.355753	3.574382	33.27715
1183	76.66271	7.727755	1.371031	3.614663	33.65216
1184	69.66995	7.022871	1.245973	3.284952	30.58259
1185	60.72496	6.121198	1.086001	2.863194	26.65606
1186	50.31412	5.071764	0.899814	2.372321	22.08608
1187	75.5466	7.615249	1.35107	3.562038	33.16222
1188	83.4037	8.407261	1.491586	3.932502	36.61121
1189	88.24527	8.895301	1.578173	4.160783	38.73648
1190	38.74259	3.905332	0.69287	1.826721	17.0066
1191	66.86187	6.739812	1.195753	3.152551	29.34994
1192	31.89485	3.215065	0.570406	1.503849	14.00069
1193	19.92317	2.008296	0.356305	0.939382	8.745551
1194	3.609422	0.363837	0.064551	0.170185	1.584406
1195	22.86147	2.304482	0.408853	1.077923	10.03536
1196	9.126384	0.919958	0.163216	0.430311	4.006152
1197	39.92651	4.024673	0.714043	1.882543	17.52629
1198	43.36989	4.371773	0.775624	2.0449	19.03782
1199	59.9495	6.04303	1.072133	2.826631	26.31566
1200	41.94301	4.22794	0.750106	1.977622	18.41147
1201	11.44054	1.153229	0.204602	0.539424	5.021981

1202	8.171039	0.823657	0.14613	0.385266	3.586791
1203	9.805787	0.988443	0.175366	0.462345	4.304386
1204	13.39953	1.3507	0.239636	0.631791	5.88191
1205	29.01747	2.92502	0.518947	1.36818	12.73762
1206	32.97871	3.324321	0.589789	1.554953	14.47646
1207	24.02404	2.421672	0.429644	1.132739	10.54569
1208	74.897	7.549768	1.339453	3.531409	32.87707
1209	104.9618	10.58036	1.87713	4.94897	46.07442
1210	55.04899	5.549049	0.984493	2.595571	24.16452
1211	39.0694	3.938274	0.698715	1.84213	17.15005
1212	39.77437	4.009337	0.711322	1.87537	17.45951
1213	66.65299	6.718756	1.192018	3.142703	29.25825
1214	34.80257	3.50817	0.622407	1.640949	15.27707
1215	73.29018	7.387798	1.310717	3.455647	32.17174
1216	80.27979	8.092365	1.435719	3.785209	35.23992
1217	297.5253	29.99115	5.320924	14.02838	130.6029
1218	161.5515	16.28472	2.889177	7.617189	70.91529
1219	123.2141	12.42023	2.203553	5.809569	54.08653
1220	472.9802	47.67736	8.458747	22.30111	207.6212
1221	586.0927	59.07933	10.48164	27.63439	257.2735
1222	468.2134	47.19686	8.373499	22.07636	205.5288
1223	417.6819	42.10318	7.469796	19.69379	183.3472
1224	415.3855	41.8717	7.428728	19.58551	182.3392
1225	337.8038	34.05131	6.041262	15.92752	148.2837
1226	239.0938	24.10113	4.275938	11.27332	104.9535
1227	195.6726	19.7242	3.499397	9.226005	85.89321
1228	154.4229	15.56614	2.761689	7.281072	67.78607
1229	154.8964	15.61387	2.770158	7.303399	67.99393
1230	245.1973	24.71638	4.385093	11.5611	107.6328
1231	270.6634	27.28342	4.840528	12.76184	118.8115
1232	299.2166	30.16163	5.35117	14.10812	131.3453
1233	180.4396	18.18867	3.22697	8.507763	79.20645
1234	140.6195	14.17473	2.51483	6.630237	61.72686
1235	92.14035	9.287933	1.647832	4.344437	40.44628
1236	86.72777	8.742334	1.551034	4.089233	38.07036
1237	63.57623	6.408612	1.136993	2.997633	27.90767
1238	80.19303	8.083619	1.434167	3.781118	35.20184
1239	78.12786	7.875446	1.397234	3.683745	34.29531
1240	104.7048	10.55445	1.872534	4.936853	45.96162
1241	93.87753	9.463044	1.6789	4.426345	41.20884
1242	50.68459	5.109109	0.90644	2.389789	22.2487
1243	52.63772	5.305989	0.94137	2.48188	23.10606
1244	60.01943	6.050079	1.073384	2.829928	26.34636

1245	48.05106	4.843644	0.859342	2.265617	21.09268
1246	44.08612	4.44397	0.788433	2.07867	19.35221
1247	28.88804	2.911973	0.516632	1.362077	12.68081
1248	18.4134	1.856108	0.329304	0.868196	8.082816
1249	49.9515	5.035212	0.893329	2.355223	21.9269
1250	48.50501	4.889403	0.867461	2.287021	21.29195
1251	44.80581	4.516516	0.801304	2.112603	19.66813
1252	30.68866	3.093478	0.548834	1.446977	13.47121
1253	27.30162	2.752059	0.48826	1.287277	11.98443
1254	43.77523	4.412631	0.782873	2.064011	19.21574
1255	25.37983	2.558338	0.453891	1.196664	11.14083
1256	27.40315	2.762293	0.490076	1.292064	12.02899
1257	12.6854	1.278714	0.226865	0.598119	5.568432
1258	7.563531	0.762419	0.135266	0.356622	3.320117
1259	32.10164	3.23591	0.574104	1.513599	14.09146
1260	70.73639	7.130371	1.265045	3.335235	31.05072
1261	35.18015	3.546231	0.62916	1.658752	15.44282
1262	94.48048	9.523823	1.689683	4.454774	41.47351
1263	92.75994	9.350389	1.658913	4.37365	40.71826
1264	95.07438	9.583689	1.700304	4.482777	41.73421
1265	94.34212	9.509876	1.687208	4.448251	41.41278
1266	68.2968	6.884455	1.221416	3.220208	29.97982
1267	136.1335	13.72253	2.434603	6.418724	59.7577
1268	131.5708	13.2626	2.353003	6.20359	57.75482
1269	348.6993	35.14959	6.236116	16.44124	153.0664
1270	359.9752	36.28623	6.437774	16.97291	158.0161
1271	442.5512	44.61005	7.914557	20.86638	194.264
1272	560.9033	56.54018	10.03116	26.44671	246.2163
1273	290.0929	29.24195	5.188002	13.67794	127.3403
1274	662.6968	66.80117	11.85163	31.24629	290.8999
1275	657.5339	66.28074	11.75929	31.00286	288.6336
1276	655.3353	66.05912	11.71998	30.8992	287.6685
1277	679.7308	68.51824	12.15626	32.04945	298.3773
1278	504.13	50.81733	9.01583	23.76984	221.2949
1279	515.1445	51.9276	9.212811	24.28917	226.1298
1280	247.8709	24.98588	4.432907	11.68716	108.8063
1281	180.9833	18.24349	3.236695	8.533402	79.44514
1282	258.366	26.04381	4.620601	12.18201	113.4133
1283	146.272	14.74451	2.615919	6.896755	64.20812
1284	95.29449	9.605877	1.704241	4.493155	41.83084
1285	115.9223	11.6852	2.073147	5.465761	50.8857
1286	84.33938	8.501579	1.50832	3.976619	37.02194
1287	85.28982	8.597386	1.525318	4.021433	37.43915

1288	82.33602	8.299637	1.472492	3.88216	36.14253
1289	70.9898	7.155915	1.269577	3.347184	31.16196
1290	55.97613	5.642507	1.001074	2.639286	24.5715
1291	74.40494	7.500168	1.330653	3.508208	32.66108
1292	97.4124	9.819366	1.742117	4.593015	42.76052
1293	63.6308	6.414113	1.137969	3.000205	27.93162
1294	36.43037	3.672255	0.651518	1.7177	15.99162
1295	52.05698	5.247448	0.930984	2.454497	22.85113
1296	48.7961	4.918745	0.872666	2.300746	21.41972
1297	28.78256	2.90134	0.514745	1.357104	12.6345
1298	1.210065	0.121977	0.021641	0.057055	0.531175
1299	0.269376	0.027154	0.004817	0.012701	0.118246
1300	19.44834	1.960432	0.347813	0.916993	8.537118
1301	32.98609	3.325065	0.589921	1.555301	14.4797
1302	48.38302	4.877106	0.865279	2.28127	21.2384
1303	20.65147	2.08171	0.36933	0.973721	9.065249
1304	5.62369	0.566879	0.100574	0.265158	2.468597
1305	15.07257	1.519345	0.269557	0.710675	6.616312
1306	36.76018	3.7055	0.657417	1.73325	16.13639
1307	45.30006	4.566337	0.810143	2.135907	19.88509
1308	10.83808	1.0925	0.193827	0.511018	4.757523
1309	8.343018	0.840993	0.149206	0.393375	3.662283
1310	6.609062	0.666207	0.118196	0.311619	2.901139
1311	19.43161	1.958745	0.347514	0.916204	8.529772
1312	77.8319	7.845612	1.391941	3.66979	34.16539
1313	91.60763	9.234234	1.638305	4.319319	40.21244
1314	75.29616	7.590005	1.346592	3.55023	33.05229
1315	18.60984	1.87591	0.332817	0.877458	8.169048
1316	63.85349	6.436561	1.141952	3.010706	28.02938
1317	131.4945	13.25491	2.351638	6.199991	57.72131
1318	70.629	7.119546	1.263125	3.330172	31.00358
1319	237.2383	23.9141	4.242754	11.18583	104.139
1320	286.1298	28.84246	5.117126	13.49108	125.6006
1321	378.0082	38.10399	6.760275	17.82317	165.932
1322	721.0167	72.67994	12.89462	33.99609	316.5003
1323	941.6016	94.91534	16.83954	44.39671	413.3291
1324	534.2413	53.8526	9.554337	25.18959	234.5126
1325	480.9256	48.47827	8.600843	22.67574	211.109
1326	698.2232	70.3823	12.48698	32.92137	306.4947
1327	454.7578	45.84051	8.13286	21.44193	199.6222
1328	376.3184	37.93366	6.730054	17.74349	165.1902
1329	318.2677	32.08203	5.69188	15.00639	139.708
1330	178.8306	18.02648	3.198195	8.4319	78.50017

1331	200.9489	20.25605	3.593757	9.474782	88.20929
1332	124.9034	12.59052	2.233765	5.889222	54.82808
1333	140.641	14.1769	2.515215	6.631254	61.73632
1334	259.5887	26.16707	4.642468	12.23966	113.9501
1335	244.1176	24.60755	4.365784	11.5102	107.1588
1336	233.0774	23.49468	4.168342	10.98965	102.3126
1337	155.5349	15.67823	2.781577	7.333504	68.27421
1338	120.4545	12.14206	2.154201	5.679456	52.87518
1339	102.3669	10.31879	1.830723	4.826621	44.93537
1340	100.6161	10.14231	1.799412	4.74407	44.16683
1341	104.9691	10.5811	1.87726	4.949314	46.07763
1342	66.54806	6.708178	1.190141	3.137755	29.21219
1343	80.28841	8.093233	1.435873	3.785615	35.24371
1344	74.28599	7.488178	1.328526	3.5026	32.60886
1345	39.29544	3.96106	0.702757	1.852788	17.24928
1346	37.50022	3.780097	0.670651	1.768143	16.46124
1347	19.40537	1.9561	0.347044	0.914967	8.518256
1348	41.43914	4.177148	0.741095	1.953864	18.19028
1349	7.368702	0.74278	0.131781	0.347436	3.234594
1350	22.43463	2.261456	0.40122	1.057798	9.847993
1351	24.90718	2.510694	0.445438	1.174379	10.93335
1352	44.07862	4.443214	0.788299	2.078316	19.34892
1353	69.51221	7.006971	1.243152	3.277515	30.51335
1354	69.94624	7.050722	1.250914	3.29798	30.70387
1355	46.14359	4.651367	0.825229	2.17568	20.25537
1356	24.5944	2.479165	0.439845	1.159631	10.79605
1357	20.93384	2.110174	0.37438	0.987035	9.189201
1358	20.16667	2.032841	0.360659	0.950863	8.852439
1359	9.34095	0.941587	0.167053	0.440428	4.100339
1360	12.76434	1.286671	0.228277	0.601841	5.603082
1361	8.095147	0.816007	0.144773	0.381688	3.553477
1362	7.783696	0.784612	0.139203	0.367003	3.416761
1363	22.8852	2.306874	0.409277	1.079042	10.04577
1364	101.4604	10.22741	1.814511	4.783877	44.53743
1365	134.4374	13.55156	2.40427	6.338752	59.01317
1366	24.28544	2.448021	0.434319	1.145064	10.66043
1367	21.91739	2.209317	0.391969	1.033409	9.62094
1368	37.88889	3.819277	0.677603	1.786469	16.63185
1369	106.4737	10.73277	1.904169	5.020258	46.73812
1370	75.46852	7.607379	1.349674	3.558356	33.12795
1371	48.26201	4.864907	0.863115	2.275564	21.18528
1372	74.41358	7.501039	1.330808	3.508616	32.66487
1373	287.5173	28.98232	5.141941	13.5565	126.2097

1374	399.054	40.22544	7.136655	18.81548	175.1703
1375	530.5142	53.4769	9.487682	25.01386	232.8766
1376	378.3507	38.13852	6.7664	17.83932	166.0823
1377	418.5905	42.19477	7.486046	19.73663	183.7461
1378	806.0593	81.2524	14.41551	38.00586	353.8309
1379	629.0557	63.41009	11.24999	29.66011	276.1327
1380	534.5895	53.8877	9.560565	25.20601	234.6655
1381	348.9884	35.17873	6.241285	16.45487	153.1933
1382	222.8686	22.4656	3.985767	10.5083	97.83124
1383	290.6047	29.29354	5.197156	13.70207	127.565
1384	147.1026	14.82824	2.630773	6.935918	64.57272
1385	174.0976	17.54939	3.113551	8.208739	76.42256
1386	209.2728	21.09512	3.742621	9.867255	91.86319
1387	244.7226	24.66853	4.376602	11.53872	107.4244
1388	312.5528	31.50596	5.589675	14.73693	137.1994
1389	233.8447	23.57202	4.182063	11.02583	102.6494
1390	154.84	15.60819	2.769149	7.30074	67.96918
1391	87.7725	8.847645	1.569718	4.138492	38.52895
1392	84.88887	8.556969	1.518147	4.002528	37.26314
1393	97.70407	9.848767	1.747333	4.606767	42.88855
1394	91.35786	9.209057	1.633838	4.307542	40.1028
1395	87.70851	8.841194	1.568573	4.135474	38.50086
1396	69.42383	6.998062	1.241571	3.273348	30.47455
1397	62.38703	6.288738	1.115726	2.941561	27.38565
1398	46.50738	4.688037	0.831735	2.192832	20.41506
1399	55.48546	5.593046	0.992298	2.616151	24.35611
1400	38.3331	3.864053	0.685547	1.807413	16.82684
1401	27.48232	2.770274	0.491492	1.295797	12.06375
1402	52.91085	5.33352	0.946254	2.494757	23.22595
1403	17.95409	1.809808	0.32109	0.846539	7.881196
1404	50.17127	5.057365	0.89726	2.365586	22.02337
1405	43.62189	4.397175	0.780131	2.056781	19.14843
1406	2.667759	0.268915	0.04771	0.125785	1.17105
1407	32.00012	3.225677	0.572288	1.508812	14.0469
1408	29.64129	2.987902	0.530103	1.397593	13.01145
1409	11.67231	1.176592	0.208747	0.550352	5.123721
1410	12.34129	1.244027	0.220711	0.581895	5.417381
1411	34.44024	3.471645	0.615927	1.623864	15.11802
1412	24.44032	2.463633	0.437089	1.152366	10.72842
1413	14.84847	1.496756	0.265549	0.700109	6.517943
1414	8.336574	0.840344	0.149091	0.393071	3.659455
1415	24.51074	2.470732	0.438349	1.155687	10.75933
1416	129.1564	13.01923	2.309825	6.089752	56.695

1417	205.9129	20.75644	3.682533	9.708836	90.38832
1418	165.6089	16.69371	2.96174	7.808496	72.69633
1419	89.96621	9.068775	1.60895	4.241926	39.49191
1420	64.91036	6.543095	1.160853	3.060537	28.4933
1421	66.69099	6.722586	1.192697	3.144494	29.27493
1422	41.28448	4.161559	0.738329	1.946572	18.1224
1423	208.4805	21.01526	3.728453	9.829901	91.51542
1424	239.6772	24.15994	4.286371	11.30083	105.2096
1425	188.9212	19.04364	3.378654	8.907673	82.92956
1426	242.2957	24.4239	4.333202	11.42429	106.3591
1427	125.7102	12.67185	2.248194	5.927264	55.18225
1428	238.2268	24.01374	4.260433	11.23244	104.573
1429	377.2747	38.03005	6.747156	17.78858	165.6099
1430	396.6138	39.97947	7.093016	18.70042	174.0991
1431	436.891	44.03949	7.81333	20.5995	191.7793
1432	488.1252	49.204	8.7296	23.0152	214.2693
1433	325.0521	32.76591	5.813212	15.32628	142.6861
1434	221.0562	22.28291	3.953355	10.42285	97.03569
1435	168.7122	17.00653	3.017237	7.954813	74.05854
1436	157.5513	15.88149	2.817638	7.428578	69.15934
1437	192.8007	19.4347	3.448036	9.090595	84.63255
1438	288.7972	29.11134	5.16483	13.61685	126.7715
1439	208.9282	21.06038	3.736458	9.851006	91.7119
1440	189.7533	19.12751	3.393536	8.946907	83.29483
1441	140.6631	14.17912	2.51561	6.632295	61.74602
1442	108.1309	10.89981	1.933805	5.098393	47.46554
1443	112.8277	11.37325	2.017803	5.319847	49.52726
1444	99.02756	9.982178	1.771003	4.66917	43.46952
1445	110.5799	11.14668	1.977604	5.213866	48.54059
1446	86.72047	8.741598	1.550903	4.088888	38.06715
1447	45.86521	4.623306	0.82025	2.162554	20.13317
1448	31.34486	3.159625	0.560569	1.477917	13.75926
1449	20.84144	2.100859	0.372727	0.982678	9.148637
1450	17.00672	1.714312	0.304147	0.80187	7.465336
1451	56.19182	5.664248	1.004931	2.649456	24.66618
1452	51.04853	5.145795	0.912949	2.406949	22.40846
1453	10.39488	1.047824	0.185901	0.490121	4.562975
1454	1.333742	0.134444	0.023853	0.062886	0.585464
1455	0.296908	0.029929	0.00531	0.013999	0.130332
1456	21.69813	2.187216	0.388048	1.023071	9.524696
1457	18.24733	1.839367	0.326334	0.860365	8.009917
1458	2.14527	0.216247	0.038366	0.10115	0.941696
1459	17.46118	1.760122	0.312275	0.823298	7.664827

1460	27.59122	2.781251	0.49344	1.300932	12.11155
1461	9.386247	0.946153	0.167863	0.442563	4.120223
1462	21.82582	2.200087	0.390332	1.029092	9.580745
1463	29.64184	2.987957	0.530113	1.397619	13.0117
1464	32.79384	3.305686	0.586483	1.546237	14.39531
1465	11.35177	1.144281	0.203014	0.535238	4.983017
1466	25.10937	2.531075	0.449054	1.183912	11.02211
1467	19.71023	1.986831	0.352497	0.929342	8.652079
1468	48.49822	4.888718	0.867339	2.286701	21.28896
1469	44.92092	4.528119	0.803363	2.118031	19.71866
1470	66.97636	6.751352	1.197801	3.157949	29.4002
1471	54.71757	5.515642	0.978566	2.579945	24.01904
1472	32.63239	3.289411	0.583596	1.538624	14.32444
1473	20.2445	2.040686	0.362051	0.954532	8.886603
1474	64.71163	6.523063	1.157299	3.051167	28.40607
1475	73.07852	7.366462	1.306932	3.445667	32.07883
1476	128.3348	12.9364	2.295131	6.051011	56.33433
1477	201.2843	20.28986	3.599755	9.490596	88.35652
1478	294.1564	29.65155	5.260673	13.86953	129.124
1479	898.1493	90.53526	16.06245	42.34793	394.2551
1480	280.2594	28.25071	5.012141	13.21429	123.0237
1481	318.1953	32.07473	5.690584	15.00297	139.6762
1482	471.4174	47.51983	8.430799	22.22743	206.9352
1483	521.049	52.52279	9.318408	24.56757	228.7217
1484	384.0368	38.71168	6.868089	18.10741	168.5783
1485	344.4872	34.725	6.160787	16.24264	151.2174
1486	248.5238	25.0517	4.444584	11.71795	109.093
1487	129.1108	13.01463	2.309009	6.0876	56.67496
1488	126.6944	12.77105	2.265794	5.973666	55.61425
1489	116.1199	11.70512	2.076681	5.475077	50.97243
1490	200.1583	20.17636	3.579619	9.437506	87.86226
1491	201.5026	20.31187	3.60366	9.500892	88.45238
1492	184.0446	18.55207	3.291443	8.677743	80.78894
1493	98.0462	9.883255	1.753452	4.622899	43.03874
1494	74.75301	7.535254	1.336878	3.52462	32.81387
1495	75.59542	7.620171	1.351944	3.56434	33.18366
1496	67.99154	6.853685	1.215956	3.205815	29.84583
1497	62.42378	6.292443	1.116383	2.943294	27.40178
1498	49.61365	5.001156	0.887287	2.339294	21.7786
1499	46.75221	4.712717	0.836114	2.204376	20.52253
1500	66.64415	6.717865	1.19186	3.142286	29.25437
1501	54.97484	5.541575	0.983167	2.592075	24.13197
1502	36.55946	3.685268	0.653827	1.723786	16.04828

1503	17.65169	1.779326	0.315682	0.832281	7.748455
1504	33.21662	3.348303	0.594044	1.566171	14.5809
1505	8.401198	0.846858	0.150246	0.396118	3.687822
1506	1.072524	0.108113	0.019181	0.05057	0.470799
1507	7.012794	0.706904	0.125416	0.330655	3.078363
1508	23.29705	2.34839	0.416643	1.098461	10.22656
1509	37.62012	3.792184	0.672796	1.773796	16.51387
1510	33.44381	3.371203	0.598107	1.576883	14.68062
1511	20.00967	2.017015	0.357852	0.94346	8.783521
1512	1.325735	0.133637	0.023709	0.062509	0.58195
1513	9.281019	0.935545	0.165981	0.437602	4.074032
1514	7.117569	0.717465	0.12729	0.335595	3.124355
1515	7.954846	0.801865	0.142264	0.375073	3.49189
1516	14.88707	1.500647	0.266239	0.701929	6.534886
1517	6.893908	0.69492	0.12329	0.325049	3.026176
1518	17.38458	1.752401	0.310905	0.819686	7.631201
1519	32.30065	3.255971	0.577663	1.522982	14.17882
1520	20.28278	2.044545	0.362736	0.956337	8.903405
1521	53.17644	5.360293	0.951004	2.50728	23.34254
1522	20.68172	2.084759	0.369871	0.975148	9.078529
1523	18.66506	1.881476	0.333805	0.880062	8.193288
1524	32.26656	3.252534	0.577053	1.521375	14.16385
1525	121.4634	12.24375	2.172243	5.727024	53.31803
1526	162.081	16.33809	2.898646	7.642153	71.1477
1527	233.6576	23.55315	4.178717	11.017	102.5672
1528	266.8351	26.89752	4.772063	12.58133	117.131
1529	234.2801	23.61591	4.18985	11.04635	102.8405
1530	503.3833	50.74205	9.002474	23.73463	220.9671
1531	522.516	52.67067	9.344643	24.63674	229.3656
1532	466.408	47.01486	8.34121	21.99123	204.7362
1533	314.3115	31.68324	5.621127	14.81985	137.9714
1534	642.5589	64.77123	11.49148	30.29679	282.0601
1535	614.5899	61.9519	10.99129	28.97804	269.7827
1536	545.3658	54.97397	9.753287	25.71411	239.3959
1537	537.8075	54.21208	9.618115	25.35774	236.0781
1538	343.7658	34.65229	6.147886	16.20863	150.9008
1539	222.3969	22.41805	3.977331	10.48606	97.62418
1540	136.9141	13.80122	2.448563	6.455528	60.10034
1541	140.0245	14.11475	2.504189	6.602184	61.46569
1542	255.4102	25.74586	4.567739	12.04264	112.1158
1543	208.9711	21.0647	3.737225	9.853029	91.73074
1544	153.5526	15.47841	2.746125	7.240037	67.40404
1545	132.5325	13.35954	2.370203	6.248936	58.17698

1546	132.4961	13.35587	2.369552	6.247218	58.16099
1547	107.9311	10.87968	1.930234	5.088976	47.37787
1548	82.65615	8.331907	1.478217	3.897255	36.28306
1549	94.18216	9.493752	1.684348	4.440708	41.34256
1550	91.67966	9.241494	1.639593	4.322715	40.24405
1551	62.3606	6.286074	1.115253	2.940315	27.37405
1552	59.38041	5.985665	1.061956	2.799799	26.06585
1553	61.57018	6.206398	1.101117	2.903047	27.02708
1554	33.52839	3.37973	0.59962	1.580871	14.71775
1555	48.72744	4.911824	0.871438	2.297509	21.38958
1556	66.78713	6.732277	1.194417	3.149027	29.31713
1557	53.48528	5.391424	0.956527	2.521842	23.4781
1558	58.13695	5.860322	1.039718	2.741169	25.52002
1559	0.921618	0.092901	0.016482	0.043454	0.404557
1560	0.236081	0.023797	0.004222	0.011131	0.103631

Appendix B: Performance Indices

Historical Period- Environmental Index Values

	Baseline	S1	S2	S3	S4	S5
rel	0.630137	0.644889	0.668599	0.686776	0.997629	0.995522
res	0.130342	0.141691	0.174881	0.186712	0.888889	0.647059
vul	0.715945	0.695103	0.570468	0.56343	0.543252	0.291471
SI	0.285742	0.303152	0.36895	0.382543	0.739886	0.769929

Historical Period- Irrigation Index Values

	Baseline	S1	S2	S3	S4	S5
rel	0.505945	0.570106	0.516832	0.579643	0.049709	0.316273
res	0.231283	0.269231	0.244536	0.279874	0.012908	0.111324
vul	0.206556	0.165158	0.180437	0.145075	0.894536	0.560003
SI	0.452815	0.504152	0.469632	0.517627	0.04075	0.249288

Historical Period- Municipal Index Values

	Baseline	S1	S2	S3	S4	S5
rel	0.369073	0.376712	0.112487	0.118282	0.50079	0.486565
res	0.103132	0.099324	0.060552	0.064834	0.043272	0.07491
vul	0.01593	0.015955	0.015155	0.014899	0.745084	0.321523
SI	0.334588	0.332679	0.188596	0.196216	0.176774	0.291344

Paleo Reconstructed Period- Environmental Index Values

	Baseline	S1	S2	S3	S4	S5
rel	0.571795	0.584615	0.610256	0.619872	0.995513	0.995513
res	0.118263	0.135802	0.194079	0.197302	0.571429	0.571429
vul	0.835353	0.808785	0.648484	0.622684	0.090091	0.075579
SI	0.223296	0.247609	0.346587	0.358684	0.802914	0.80716

Paleo Reconstructed Period- Irrigation Index Values

	Baseline	S1	S2	S3	S4	S5
rel	0.386185	0.430141	0.381476	0.425432	0.029231	0.218069
res	0.173913	0.212121	0.164975	0.193989	0.011094	0.069721
vul	0.223381	0.179605	0.205829	0.167782	0.927104	0.591505
SI	0.373633	0.421444	0.368355	0.409526	0.028699	0.183815

Paleo Reconstructed Period- Municipal Index Values

	Baseline	S1	S2	S3	S4	S5
rel	0.184615	0.184615	0.05	0.053205	0.414103	0.264103
res	0.076258	0.076258	0.037787	0.037915	0.099562	0.117596
vul	0.031542	0.03094	0.042471	0.039713	0.716298	0.271073
SI	0.238897	0.238947	0.121849	0.124658	0.226998	0.282889