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Water Use Analysis Model (WUAM) Demonstration

A.M. Kassem, D.M. Tate and P.A. Dossett

Social Science Series No. 28

Environmental Conservation Service
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Abstract

This is a report on a study intended to demonstrate the application Environment Canada's Water Use Analysis Model (WUAM) on the Saskatchewan portion of the South Saskatchewan River basin. It focuses on the application aspects of the model (data requirements and preparation, scenario development, and model runs) and on the analysis of the results.

The water resources impact of four alternative development scenarios were investigated. The scenarios, all assumed to correspond to the year 2000, covered two levels of future water use in Alberta and two levels of irrigation development in Saskatchewan. Only the irrigat-ed area in Saskatchewan was varied; all other irrigation parameters were assumed to remain constant. The system was also simulated under the extreme condition of Alberta's using 50% of the monthly natural streamflow.

Two primary issues were emphasized in the analysis of WUAM's simulation results: irrigation water use in Saskatchewan and the impacts of developments in Alberta and in Saskatchewan on Lake Diefenbaker's recreational value and instream uses downstream. Irrigation water uses (by irrigation area, node, and basin total) and consumptive uses from Lake Diefenbaker (irrigation, evaporation, and diversion) were analyzed for the various scenarios and their frequencies of occurrence were presented.

The study showed that lake levels required for recreational uses will be satisfied only 21% to 39% of the time, depending on the scenario. Minimum flows required for instream uses below the Gardiner dam will always be satisfied.

This report presents only one application of WUAM and illustrates the advantages of the model in river basin planning studies. It does not cover the complete range of the model's capabilities.

Résumé

Ce rapport décrit une étude dont le but est d'expliquer l'application du modèle d'analyse d'utilisation de l'eau (WUAM) d'Environnement Canada à la partie du bassin hydrographique de la rivière Saskatchewan Sud qui se trouve sur le territoire de la Saskatchewan. Il porte principalement sur les caractéristiques d'application du modèle (besoins en données et préparation de celles-ci, élaboration des scénarios et modélisation) ainsi que sur l'analyse des résultats.

L'incidence sur les ressources en eau de quatre scénarios de développement différents a été examinée. Ces scénatios, qui par hypothèse se réalisent tous en l'an 2000 dépeignent deux niveaux d'utilisation future de l'eau en Alberta et deux niveaux de développement de l'irrigation en Saskatchewan. Seule l'entedue irriguée en Saskatchewan a été modifiée, tous les autres paramètres d'irrigation étant censés demeurer constants. Le comportement du système a également été simulé dans le cadre d'une situation extrême où l'Alberta utiliserait 50 % de l'écoulement mensuel naturel des eaux.

Deux questions principales ont été mises en évidence dans l'analyse des résultats de la simulation du WUAM : l'utilisation de l'eau à des fins d'irrigation en Saskatchewan et l'incidence des aménagements réalisés en Alberta et en Saskatchewan sur la valeur récréative du lac Diefenbaker ainsi que sur l'utilisation *in situ* du cours d'eau en aval. Les prélèvements d'eau destinée à l'irrigation (par noeud et périmètre d'irrigation ainsi que pour l'ensemble du bassin) et la consommation totale (irrigation, évaporation et dérivation) d'eau du lac Diefenbaker ont été analysés pour les divers scénarios, et l'on a présenté les fréquences auxquelles ces formes de consommation ont lieu.

L'étude a révélé que le lac n'atteindra les niveaux qui permettent de le consacrer à des usages récréatifs que de 21 % à 39 % du temps, selon le scénario. Par contre, en aval du barrage Gardiner, le débit sera toujours suffisant pour l'utilisation *in situ* du cours d'eau.

Ce rapport, qui ne présente qu'une seule application du WUAM, expose les avantages qu'offre le modèle en ce qui concerne les études de planification de l'aménagement des bassins hydrographiques. Il ne couvre pas l'intégralité des capacités du modèle.

Preface

A preliminary version of this report was produced in July 1987 and distributed to mem-bers of the board of the South Saskatchewan River Basin (SSRB) Study in Saskatchewan, a federal–provincial water planning study that had been initiated in May 1986. After extensive review, the board chose a different approach to supply-demand balance analyses, largely out of consideration for maintaining consistency with methods used in Alberta, the upstream province. The report was based on study conducted as part of Environment Canada's water use analysis program and was not funded by, or part of the technical work of, the SSRB Study. To avoid producing results conflicting with the SSRB Study, it was decided not to publish the study at that time.

The Water Use Analysis Model (WUAM) presents a relatively new approach to supply-demand balance modelling. Its use of the water demands in a study area as a point of departure contrasts with the more traditional supply side concentration of previous models, including the one used by the SSRB Study. The authors feel that it is valuable that the study report now be published.

Acknowledgments

The authors wish to thank and Tamas Hamory for his valuable assistance in the analysis of data and preparation of the various illustrations. Thanks are also due to Hans Foerstel and to Jim Rogers and Derek Bjonback from the Regina regional office for their constructive reviews and comments on an earlier draft of the report.

Water Use Analysis Model (WUAM) Demonstration

A.M. Kassem, D.M. Tate and P.A. Dossett

1. INTRODUCTION

1.1 The Water Use Analysis Model (WUAM)

The Water Use Analysis Model (WUAM) is a highly flexible, interactive microcomputer simulation model designed primarily to provide projections of multisectoral water uses[1] in a drainage basin context. The model also compares the projected water uses with avail-able supplies and produces, among numerous other details, statistics about the severity and frequency of water shortages, if any.

WUAM depicts a river basin as a dendritic network of nodes (representing tributaries or subbasins) and links (representing the flow path between nodes). Water use projections and water balance calculations are carried out at the node level using monthly time intervals. The model is also able to consider water diversions and interjurisdictional water apportionment, analyze the impacts of water price on water use, model reservoir operations, account for water use priorities, and analyze water rationing and usage cutbacks when available water supplies are approached or exceeded.

WUAM considers water uses individually and then in an integrated manner. Water uses include the withdrawal (or consumptive) uses and nonwithdrawal (or instream) uses. Withdrawal water uses are determined within six main categories: urban-municipal, rural-domestic, industrial, agricultural (irrigation and livestock watering), power generation, and other sectors. All categories of water use can be broken down, when necessary, to provide a fairly fine level of sectoral detail. Two main water use parameters are calculated. The first is water intake, which is the amount of water withdrawn for a particular use, a portion of which is returned to the source. The second is water consumption, which is the difference between water intake and return flow. Nonwithdrawal water uses, such as recreation, waste dilution, etc., are dealt with as constraints on streamflow based on minimum flow requirements.

Water supplies are simulated based on natural streamflow[2] time series data at selected points within the drainage basin. A reservoir simulation subcomponent, which is operated in conjunction with water uses, simulates the regulation effects on water availability. It allows the examination of the operating policies of a particular reservoir in a regional water use context. It also allows the reservoir to act dynamically within a network to alleviate water shortages when possible.

WUAM is flexible enough to be applied to practically any river basin configuration and is well suited to answer a wide range of "what if?" questions relating multisectoral water uses

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[1] Throughout this report, the general term "water use" has been used, even in situations in which a pricing relationship (i.e., water demand) is implied. The term is also used as a generalized reference to various parameters such as intake, gross water use, consumption, etc.

[2] "Natural streamflow" refers to streamflow in its natural state, i.e., without any regulation or water withdrawal/consumption.

to social and economic considerations and to the water balance of a basin.

While it is assumed that the reader has a reasonable knowledge of WUAM, a brief description of the overall model is given in Appendix A. For a detailed description of WUAM, see Kassem (1992).

1.2 Purpose of the Study

This study, which was intended as a demonstration of the utility of WUAM, was conducted on the Saskatchewan portion of the South Saskatchewan River basin. It had two main objectives: to demonstrate the value and output of WUAM and to present preliminary assessments of future water uses in the Saskatchewan portion of the South Saskatchewan River basin and the impacts of these uses, together with Alberta uses, on Lake Diefenbaker.

1.3 Scope of the Study

The study area selected for WUAM demonstration is depicted in Figure 1. The area represents the Saskatchewan portion of the South Saskatchewan River basin from the Alberta-Saskatchewan border to St. Louis. Two dams, the Gardiner and Qu'Appelle, which created Lake Diefenbaker, control the South Saskatchewan River flow and provide the storage necessary for future development in Saskatchewan. Lake Diefenbaker provides water supplies for irrigation, power generation (Coteau Creek hydroelectric power plant and Queen Elizabeth thermal power plant), municipal, industrial, domestic, stock watering, flood control, and recreation uses. Irrigation is by far the dominant water use in the basin.

The increasing water demands in the upstream province, Alberta, have been reduc-ing the quantity of water available to Saskatchewan. A master flow apportionment agreement between Canada and the three prairie provinces (Alberta, Saskatchewan, and Manitoba) requires that Saskatchewan receive a specified minimum flow as well as at least 50% of the annual natural flow in Alberta. The water demands on Lake Dieenbaker have been increasing, in particular, to support expanded irrigation projects.

In this study, only the Saskatchewan portion of the South Saskatchewan River basin was simulated. Water uses in Alberta were accounted for by specifying the corresponding flows at a node just inside Alberta at the Alberta–Saskatchewan border. These flows were obtained from previous investigations carried out by Alberta Environment (1984).

The following issues were addressed in the study:

- Consumptive water use. Water use projections were made for the main water uses in the basin: industrial, urban-municipal, rural-domestic, and agricultural (i.e., irrigation and livestock watering).

- Temporal variation of irrigation water use. The effects of only climatic parameters, represented by precipitation and potential evapotranspiration, on irrigation water use were investigated to illustrate the advantages of WUAM's irrigation submodel.

- Lake Diefenbaker consumptive water use.

- Recreational water uses in Lake Diefenbaker. The study analyzed the impacts of both developments in Alberta and water uses in Saskatchewan on Lake Diefenbaker levels and their effects on the recreational value of the lake. Saskatchewan Water Corporation (1987) specified a required minimum reservoir level of 555.3 m during July and August. In the present study, it was assumed that lake levels above 555.3 m would be required for the months of June through September.

- Instream water uses below the Gardiner dam. River flows above 42.5 $m^3 \cdot s^{-1}$ were assumed as the minimum requirement (Saskatchewan Water Corporation 1987).

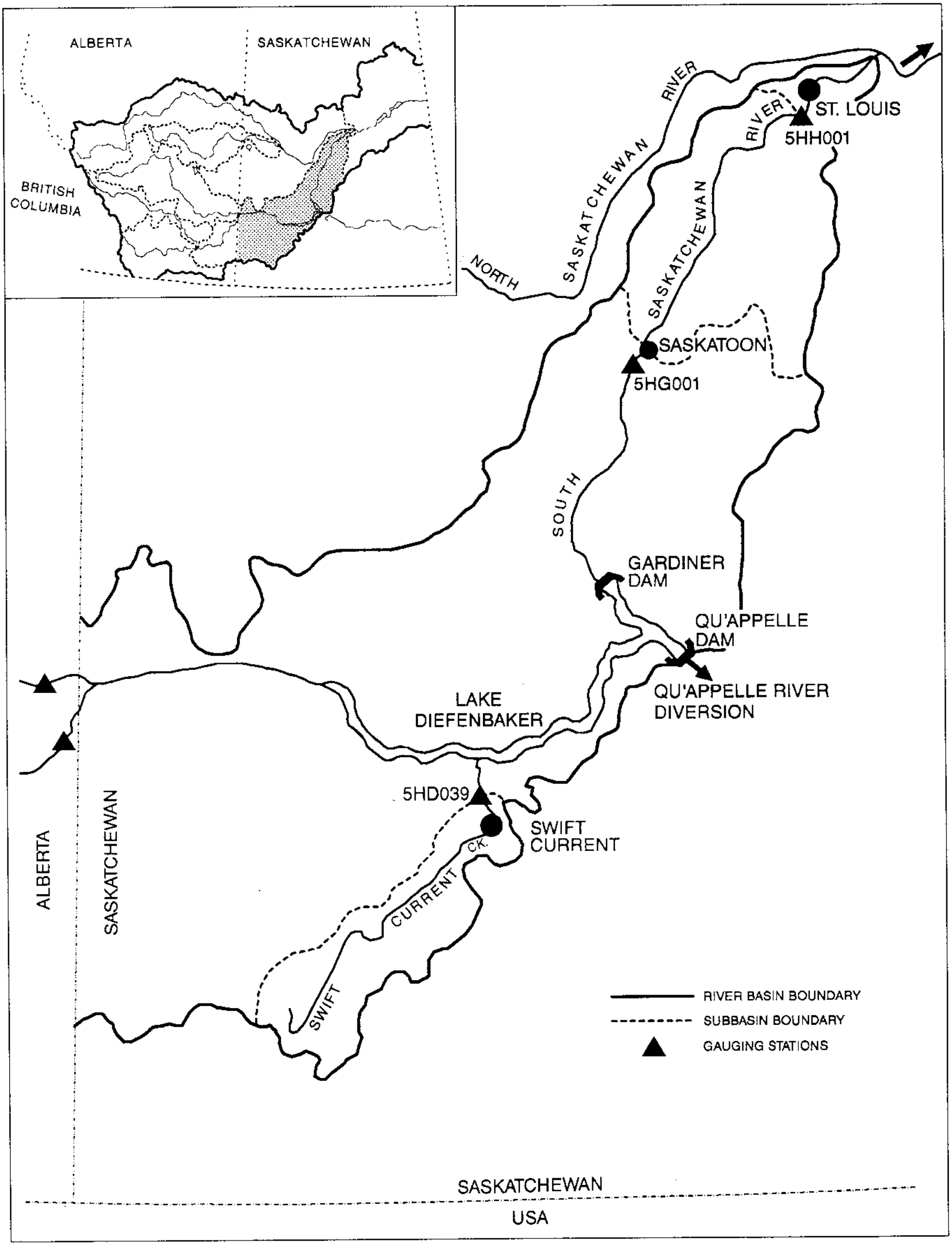

Figure 1. Study area and gauging stations.

Hydro power generation from Lake Diefenbaker was not calculated in the study[3].

The water resources impact of four development scenarios was investigated. The scenarios, all assumed to correspond to the year 2000, covered two levels of future water use in Alberta and two levels of irrigation development in Saskatchewan. In addition, the system was simulated under the extreme condition of Alberta's using 50% of the monthly natural streamflow. Simulations for current conditions were not carried out, primarily because the corresponding flows at the Alberta–Saskatchewan border were not available at the time of the study.

Two historical periods of natural streamflow were used in the water balance simulations. The first covered a 28-year period (1928–1955). This relatively short time span corresponds to the length of record obtained for the Alberta–Saskatchewan boundary flows. The second period covered 56 years (1912–1967) of natural streamflow.

It should be emphasized that many assumptions had to be made to carry out the simulations. In particular, the rule curve and operating constraints data for Lake Diefenbaker were based largely on estimates because of the absence of official data. Data collection was kept to a minimum. The water use and supply data were derived from the model's existing database for the Saskatchewan basin. Every attempt was made, however, to use realistic data that would reasonably reflect water uses and supplies in the basin. Nevertheless, the test results should be viewed as preliminary or experimental rather than as a definitive statement about water uses and supplies in the basin.

2. MODEL SET-UP FOR THE SOUTH SASKATCHEWAN RIVER BASIN

All WUAM applications have three main steps:

- dividing the basin into subbasins
- creating the model's database
- developing and testing the scenario

These steps are described below as they apply to the study area.

2.1 Study Area and WUAM Network

The study area covered the Saskatchewan portion of the South Saskatchewan River basin from the Alberta–Saskatchewan border up to St. Louis (Fig. 1). Five study points (nodes) were selected to demonstrate the application of WUAM. The corresponding WUAM network of nodes and links is presented in Figure 2. The figure also shows the locations of the irrigation areas within the network in terms of supply and return flow nodes. For the sake of simplicity, actual irrigation projects were aggregated to the nine irrigation areas indicated in Figure 2. (See section 2.3.2 for details on this aggregation.)

A dummy node (not matching a real subbasin) was introduced in the network. Named DUMMY01 and located just inside Alberta, it represents the combined flows of the Red Deer and the South Saskatchewan rivers. The primary function of this node is to analyze the water resources impacts of developments in Alberta on Saskatchewan and to simulate interprovincial flow apportionment.

2.2 Data Preparation

WUAM's application to the South Saskatchewan River basin required six primary areas of data:

- industrial water use
- urban-municipal and rural-domestic water use
- agricultural water uses (irrigation and livestock watering)

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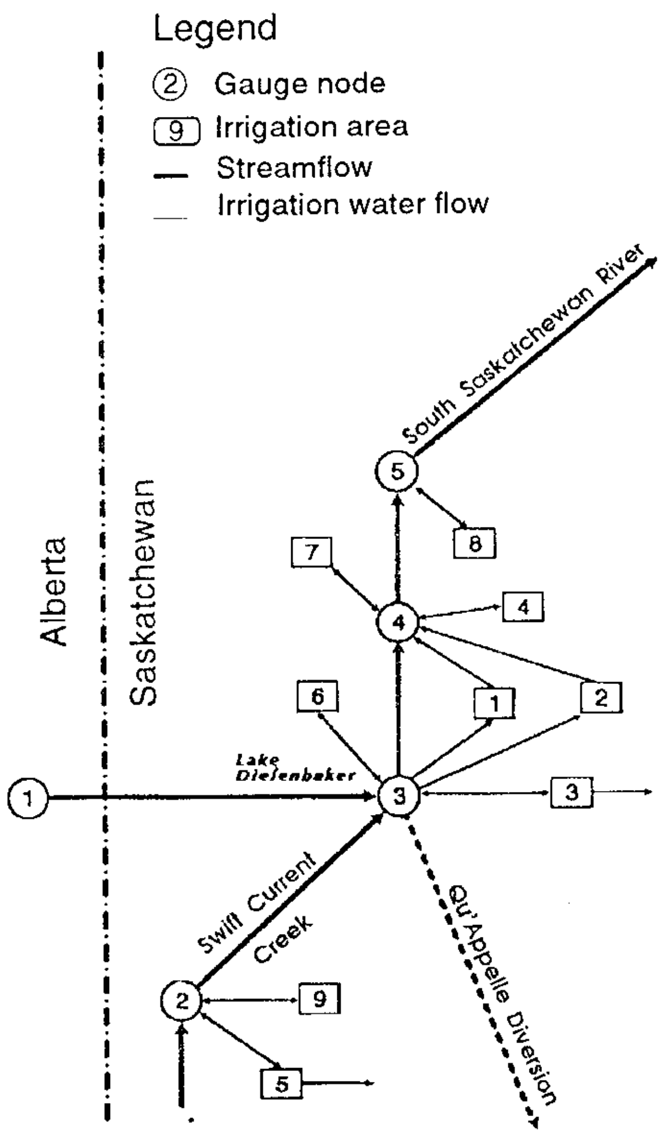
[3] The capability to estimate hydro power generation was later added to WUAM using a separate submodel, the Electric Energy Water Use Submodel (EEWUS). This submodel, which also estimates thermal generation water use, is explained by Acres International Ltd. (1987) and Kassem (1992, Appendix B).



Network nodes

No.	Gauge
1	DUMMY01
2	05HD039
3	DIEFRES
4	05HG001
5	05HH001

Irrigation areas

No.	I.D.	Name
1	SSR-ID	South Saskatchewan River irrigation district
2	SSEWSS	Saskatoon southeast water supply system
3	SSRWUDA	South Saskatchewan River water users' district (A)
4	SSRWUDB	South Saskatchewan River water users' district (B)
5	SCCWUD	Swift Current Creek water users' district
6	SSR-PIA	South Saskatchewan River private irrigation (A)
7	SSR-PIB	South Saskatchewan River private irrigation (B)
8	SSR-PIC	South Saskatchewan River private irrigation (C)
9	SCC-PI	Swift Current Creek private irrigation

Figure 2. WUAM Network

- water supply
- interprovincial flow apportionment
- Lake Diefenbaker reservoir operation

In addition, the model required numerous secondary data, such as water use priority data, economic growth forecasts, and meteoro-logical data (e.g., precipitation and evapo-transpiration, etc.). (For a complete list of WUAM data requirements, see Appendix A, Table A.1.)

2.2.1 Industrial Water Use Data

The industrial water use database consisted of water intake and consumption data for each of 30 industrial sectors. (These sectors correspond in general to those in Statistics Canada's two-digit Standard Industrial Classification [SIC] system.) The data, which were required for each subbasin in the study area, were obtained for 15 industries from Environment Canada's 1981 industrial water use survey (Tate and Scharf 1985) and were estimated for the remaining sectors. (See Table 1 for the base year industrial water use data for the study area.)

2.2.2 Urban-Municipal and Rural-Domestic Water Use Data

The urban-municipal water use (domestic, commercial, and institutional) data were derived for each node from detailed surveys conducted by Environment Canada (Tate and Lacelle 1987). These surveys covered all municipalities with populations over 1000 and include much detailed information. For the purpose of WUAM, however, only urban-municipal population, water intake, and consumption data were of interest. Table 2 gives the urban-municipal and rural-domestic populations for the study area, together with the corresponding water use coefficients. Average coefficients were used for all nodes.

2.2.3 Agricultural Water Uses Data

Agricultural water uses are divided into irrigation and livestock watering. The irrigation data are discussed in section 2.3.2. Data relating to the 1981 livestock populations were obtained from the 1981 Statistics Canada census and published catalogues. Most of the data were obtained by subbasin from special retrieval of data carried out through Statistics Canada. Intake and consumption data for livestock are generally constant from region to region, therefore, national average coefficients were used. Animal populations and the corresponding water use coefficients used in the study are given in Table 3.

2.2.4 Water Supply Data

Only surface water supplies, represented in WUAM by monthly natural streamflow records at each node in the basin, were considered. The natural streamflow data used in this study were derived by the Prairie Provinces Water Board (PPWB). The data covered the period 1912–1967, except for the boundary (node DUMMY01), where the water supply data covered the period 1912–1982. (See Appendix B for the natural streamflow data at the various nodes.)

Although WUAM has the ability to account for groundwater uses, groundwater use data were not available at the time of this analysis. Therefore, all supplies were assumed to come from surface water sources.

2.2.5 Interprovincial Apportionment Data

The minimum flow required to be passed across the Alberta–Saskatchewan border (node DUMMY01) was assumed to be 50% of the natural flows for each month of the simulation period.

2.2.6 Lake Diefenbaker Reservoir Operation Data

Reservoir operation data for Lake Diefenbaker were derived by Acres International Limited (1986) from historical operation reports (Blain and Richards 1982a, 1982b, 1984a, 1984b). These reports also give some insight into the basic criteria that dictate the operating procedure.

Figure 3 depicts the rule curve and operating constraints derived for Lake

Table 1

Base Year Industrial Water Use Data

		05HD039		05HG001		05HH001	
Sector no.	Sector name	Intake (MCM/yr)	Consumption (%)	Intake (MCM/yr)	Consumption (%)	Intake (MCM/yr)	Consumption (%)
1	Agriculture	0.0000	0.0	0.0000	0.0	0.0000	0.0
2	Forestry, etc.	0.0000	75.0	0.0008	75.0	0.0000	0.0
3	Metal mines	0.0000	0.0	0.0000	0.0	0.0000	0.0
4	Mineral fuels	0.0000	0.0	0.0000	0.0	0.0000	0.0
5	Nonmetal mines	0.0000	0.0	4.1767	20.7	0.0000	0.0
6	Food and beverages	0.2266	9.4	0.0000	0.0	1.7823	25.2
7	Tobacco	0.0000	24.2	0.0000	24.2	0.0000	24.2
8	Rubber and plastics	0.0000	0.0	0.0000	0.0	0.0007	3.8
9	Leather	0.0000	0.0	0.0000	0.0	0.0019	0.0
10	Textiles	0.0000	0.0	0.0000	0.0	0.0000	0.0
11	Wood	0.0000	0.0	0.0000	0.0	0.0000	0.0
12	Furniture	0.0131	0.0	0.0558	0.0	0.0000	0.0
13	Paper	0.0000	0.0	0.0000	0.0	0.0005	2.9
14	Printing	0.0014	2.9	0.0180	2.9	0.0001	9.7
15	Primary metals—iron	0.0000	0.0	0.0000	0.0	0.0000	4.4
16	Primary metals—other	0.0000	4.4	0.2738	4.4	0.0016	0.0
17	Metal fabricating	0.0000	0.0	0.0000	0.0	0.0396	3.4
18	Machinery	0.0552	3.4	0.2622	3.4	0.0023	1.0
19	Transportation equipment	0.0000	0.0	0.0000	0.0	0.0000	3.3
20	Electric products	0.0228	3.3	0.1599	3.3	0.0364	78.7
21	Nonmetal minerals	0.0000	0.0	0.0000	0.0	0.0000	0.0
22	Petroleum and coal	0.0000	0.0	0.0000	0.0	0.5736	57.5
23	Chemicals	0.0000	0.0	0.4480	99.4	0.0000	8.6
24	Miscellaneous manufacture	0.0104	8.6	0.0983	8.6	0.0000	0.0
25	Construction	0.0000	0.0	0.0000	0.0	0.0000	0.0
26	Transportation	0.0000	0.0	0.0000	0.0	133.0668	0.4
27	Electric power	0.0000	0.0	0.0000	0.0	0.0000	0.0
28	Other utilities	0.0000	0.0	0.0000	0.0	0.0000	0.0
29	Trade	0.0000	0.0	0.0000	0.0	0.0000	0.0
30	Other	0.0000	0.0	0.0000	0.0	0.0000	0.0

Table 2
Base Year Urban-Municipal and Rural-Domestic Populations and Water Use Coefficients

					Water use coefficients	
	05HD039	05HG001	05HH001	Total population	Intake (L/cap/d)	Consumption (%)
Urban-municipal	16 859	162 272	7 172	186 303	463	20
Rural-domestic	4 659	40 320	23 501	68 480	137	70
Total	21 518	202 592	30 673	254 783		

Table 3
Base Year Livestock Populations and Water Use Coefficients

					Water use coefficients	
	05HD039	05HG001	05HH001	Total population	Intake (L/cap/d)	Consumption(%)
Beef cattle	41 000	350 000	65 000	456 000	20.4	90
Dairy cattle	2 000	13 000	2 000	17 000	54.0	70
Horses	1 000	9 000	2 000	12 000	68.0	70
Hogs	10 000	85 000	45 000	140 000	6.0	70
Sheep	4 000	23 000	3 000	30 000	3.5	95
Poultry	37 000	836 000	283 000	1 156 000	0.3	95

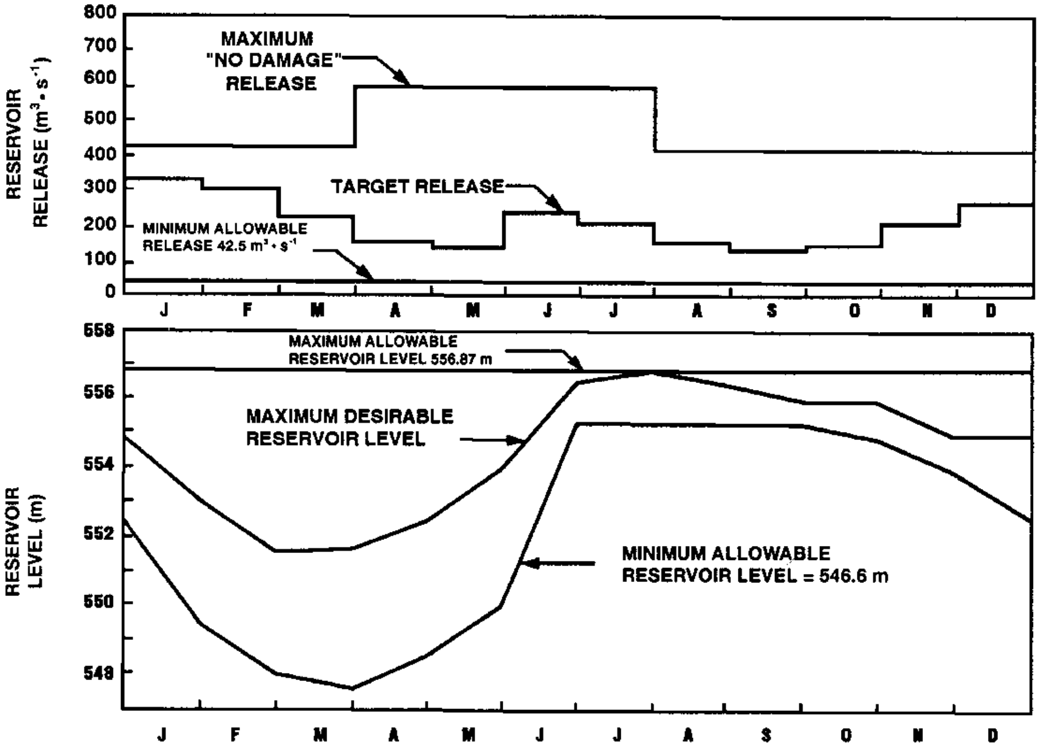


Figure 3. Rule curve and operating constraints for Lake Diefenbaker.

Diefenbaker. The physical and operating constraints are summarized as follows:

- Maximum allowable reservoir level (i.e., full supply level) is 556.87 m.
- Minimum allowable reservoir level (dictated by the level of the riprap) is 545.60 m.
- Minimum monthly riparian flow release (dictated by the minimum flow requirements at Saskatoon) is 42.50 $m^3 \cdot s^{-1}$.
- Reservoir area and storage volume at different levels are as follows:

Level (m)	Area (km^2)	Volume (MCM)
535	180	2 850
540	240	4 000
545	265	5 250
550	328	6 700
555	404	8 550
560	472	10 750

Precipitation and gross evaporation data at Swift Current Creek for 1912–1967 were used to calculate the net evaporation (Fig. 4).

The maximum and minimum monthly desirable reservoir levels were estimated from historical operating practices for the period 1979–1982 (Blain and Richards 1982a, 1982b, 1984a, 1984b). It was assumed that levels greater than 555.3 m should be maintained from June through September for recreation purposes. Levels for the other months were dictated primarily by operating procedures that were designed to accommodate both flood storage and hydroelectric power generation.

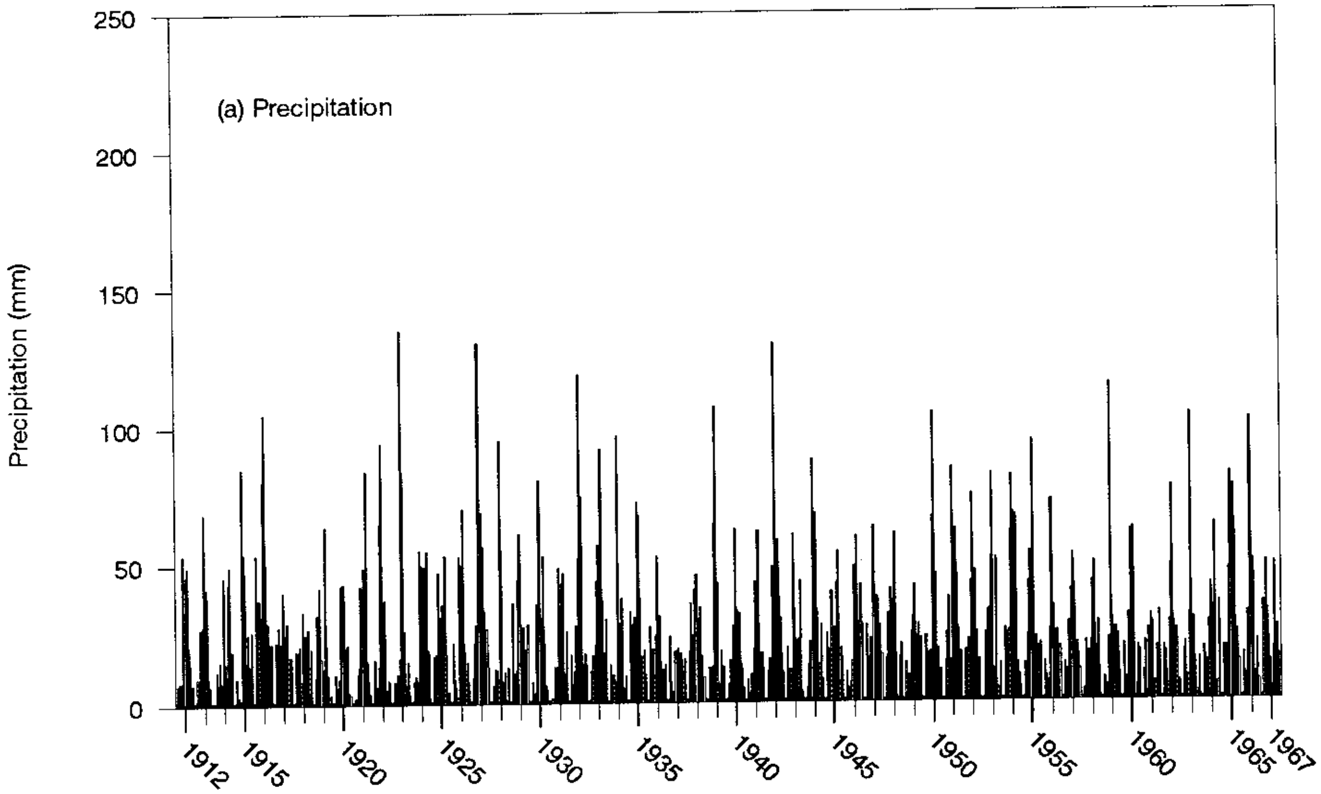
The maximum "no-damage" reservoir releases vary throughout the year. During periods when floods are not expected, the release is set at 425.0 $m^3 \cdot s^{-1}$, which corresponds to the turbine capacity. During periods of high flood, as in 1981 (Blain and Richards 1984a), it appears that the total reservoir release was limited to 600 $m^3 \cdot s^{-1}$, whenever possible, to avoid downstream flood damages.

The selection of target releases is of the utmost importance for the successful use of the reservoir model since they are essentially the driving force for the reservoir. The target releases shown in Figure 3 correspond to the long-term average monthly releases from the reservoir. It must be noted that during dry years these target releases will be too large and the reservoir level will fall toward the minimum desirable reservoir level. During wet years, the opposite will happen, with the reservoir levels moving toward the maximum desirable level. Therefore, it should be expected that the model will produce greater variability in year-to-year reservoir levels than would occur in reality when the target releases are continuously adjusted through prudent operation.

In order to evaluate the performance of the reservoir submodel using the above rule curve and operational constraints for Lake Diefenbaker, the system was simulated for the period from January 1979 to December 1982. Saskatchewan Environment (Blain and Richards 1982a, 1982b, 1984a, 1984b) has measured reservoir levels and releases for this period. For this evaluation, inflows into the reservoir, obtained from Saskatchewan Environment, were adjusted for evaporation. A comparison of the simulated reservoir releases and reservoir levels with the measured values shows a reasonable match with the actual reservoir behaviour (Fig. 5). Generally, however, the WUAM reservoir submodel drew the reservoir lower than observed. This is mainly because the target flows remained the same in all years regardless of the occurrence of low flows, whereas in reality the operators adjust their releases based on anticipated future inflows.

2.3 Application Scenarios

Four development scenarios were tested for the Saskatchewan portion of the South



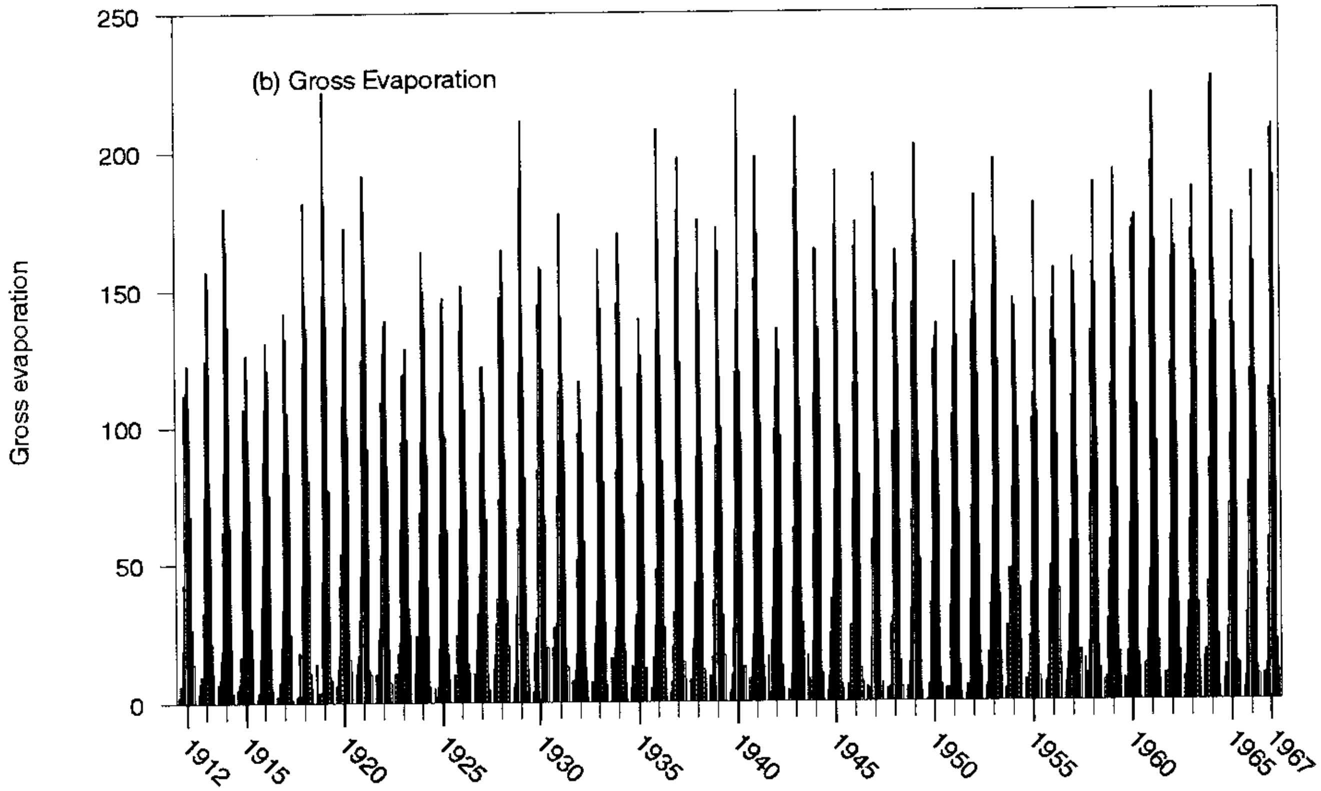
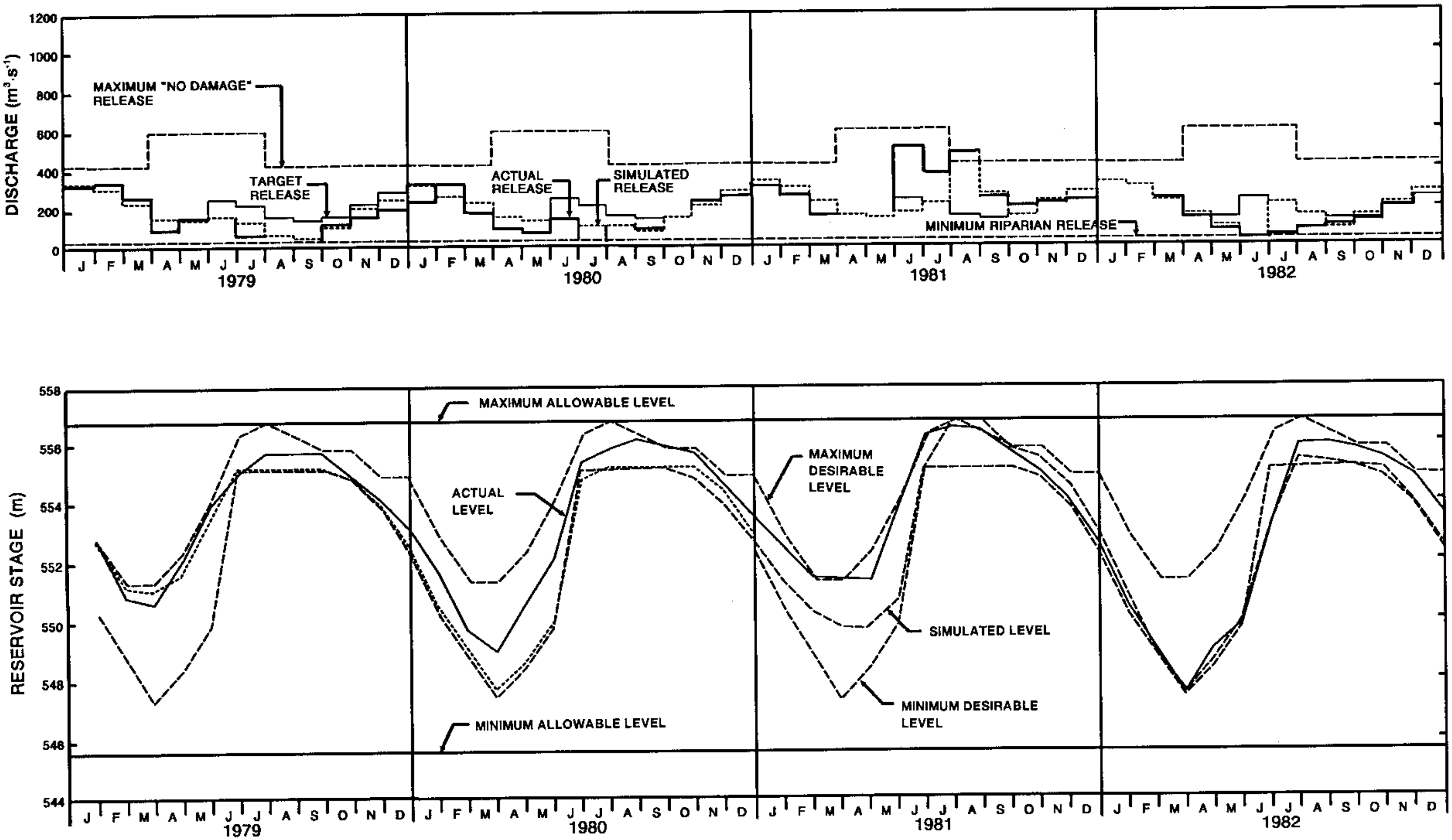


Figure 4. Precipitation and gross evaporation data for Swift Current Creek. (Used for the calculation of net evaporation from Lake Diefenbaker.)



Source: Acres International Limited (1986).

Figure 5. Simulated and observed Lake Diefenbaker reservoir operations.

Saskatchewan River basin, all assumed to correspond to the year 2000:

Scenario 1: Base case — Alberta and Saskatchewan
Scenario 2: Base case — Alberta flows limited to apportionment
Scenario 3: High irrigation — Alberta and Saskatchewan
Scenario 4: High irrigation — Alberta flows limited to apportionment

Scenarios 1 and 2 are identical except for the flows at the Alberta–Saskatchewan border. In scenario 1, the Alberta flows were obtained from Alberta Environment, corresponding to Run 1A (Alberta Environment 1984). In scenario 2, the boundary flows were assumed to be equal to the apportionment flows (i.e., 50% of the monthly natural flows at the border). For these two scenarios, the Qu'Appelle diversion was assumed to be 187.3 MCM annually (i.e., average 5.9 $m^3 \cdot s^{-1}$), distributed throughout the year (Fig. 6).

Similarly, the only difference between scenarios 3 and 4 is the boundary flows at the border. In scenario 3, the Alberta flows correspond to high irrigation in Alberta (Run 4C, Alberta Environment 1984). The boundary flows for scenario 4 were assumed to be equal to apportionment flows (as in scenario 2). The Qu'Appelle diversion for these two scenarios was assumed to be 346.8 MCM (or 11 $m^3 \cdot s^{-1}$), uniformly distributed throughout the year.

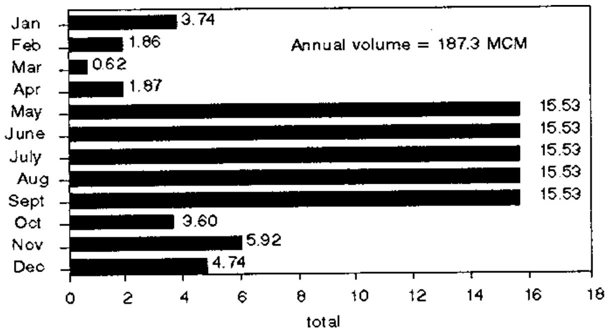


Figure 6. Monthly distribution of the Qu'Appelle diversion for the base case scenarios.

2.3.1 *Growth Assumptions*

In all the application scenarios, assumptions were made about the growth of industry (Fig. 7), population (Fig. 8), and livestock (Fig. 9). Regional industrial growth rates were assumed to apply equally to all sub-basins in the study area. (The annual growth rates for the 30 industrial sectors [Fig. 7] are regional averages for the forecast period and correspond to projec-tions developed by the Economic Council of Canada for the period 1981–1999 [personal com-munications].) The annual population growth rates for the period 1981–2000 (Fig. 8) cor-respond to Statistics Canada's projections. Sub-basin populations were assumed to grow at the provincial rate; base-year per capita urban-municipal water use was assumed to apply for future years.

2.3.2 *Irrigation Development Scenario Data*

Unlike the other water uses, irrigation can vary greatly from year to year in response to physical, climatic, economic, social, and political factors. Physical factors include the area irrigat-ed, crop type/mix, and methods, intensities, and efficiencies of irrigation. Climatic factors are dominated by precipitation and potential evapo-transpiration. The cost component will affect the degree of physical changes, and social and political factors can override other factors.

The irrigation submodel allows the following physical parameters to be varied, either singly or in any combination:

- area irrigated
- crop type/mix
- mix of irrigation methods
- soil type
- delivery efficiency
- irrigation application efficiency
- irrigation level[4] by crop and irrigation type
- irrigation water salinity

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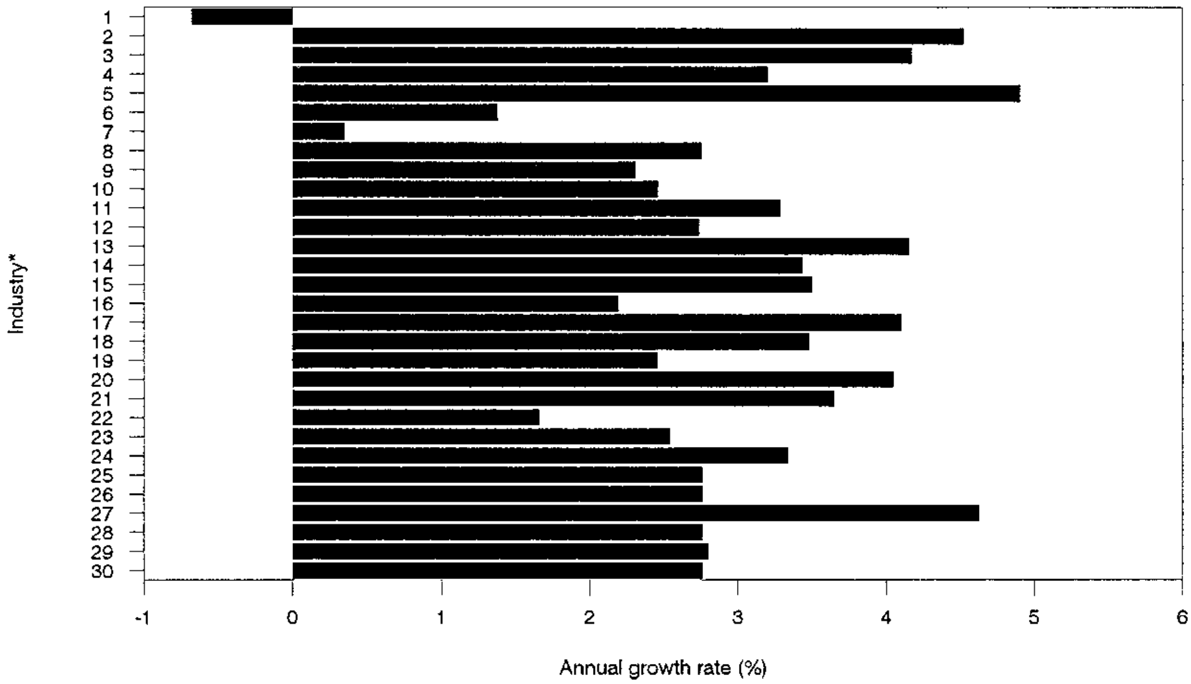
[4] The irrigation level is the fraction of optimal irrigation. Optimal irrigation is the volume of water applied to maintain optimal soil moisture levels that are needed to achieve maximum potential crop yield.



* Numbers correspond to the industrial sectors shown in Table 1.

Figure 7. Industrial growth scenario data.

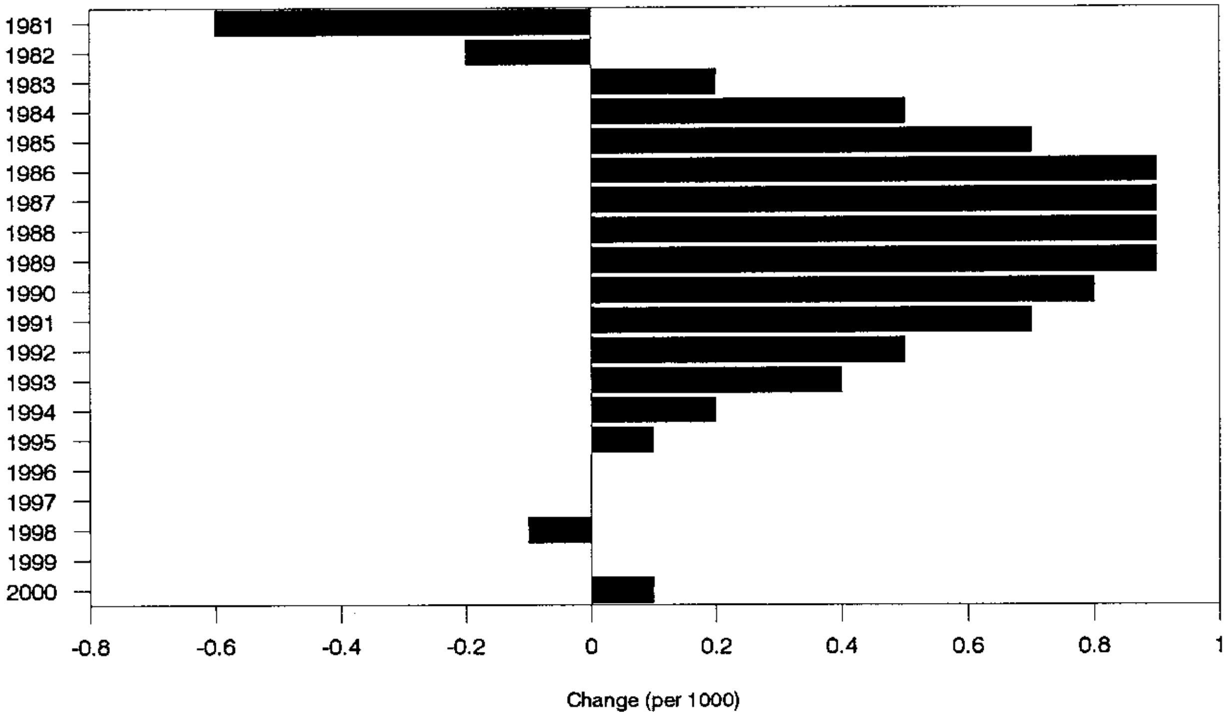


Figure 8. Population growth scenario data.

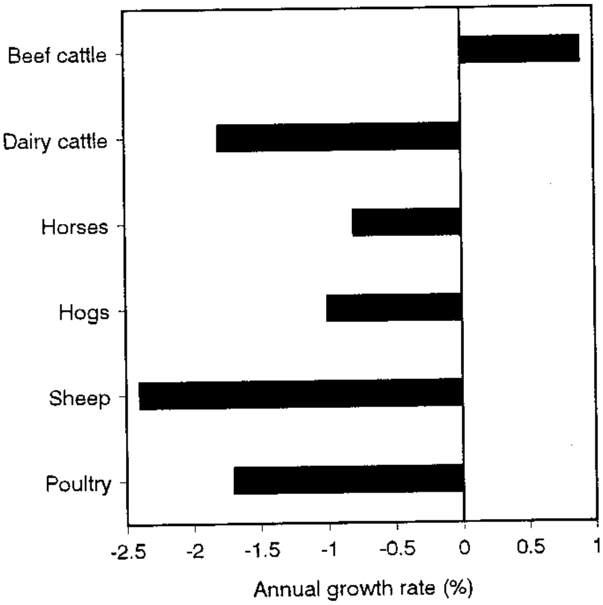


Figure 9. Livestock growth scenario data.

Irrigation water use is highly dependent on climatic variations. Annual variations in precipitation can be very significant and are the dominant factor in evaluating irrigation water use. Potential evapotranspiration can also vary from year to year. The irrigation submodel evaluates irrigation water uses on a year-by-year and month-by-month basis using historical data on precipitation and potential evapotranspiration.

The irrigation submodel is described in Appendix C. The specific assumptions for irrigation development and the parameters used for the estimation of irrigation water requirements are presented below.

Three crops were considered to be representative of the range of crops in the study area: wheat, representing grain; alfalfa, representing forage; and potatoes, representing specialty crops. The parameters for the various crops are presented in Tables 4 and 5. The cropping season used was a five-month period from May through September.

Table 4

Constant Parameters for Crop Data

	Grain	Forage	Specialty
Minimum optimal depletion fraction	0.150	0.150	0.000
Maximum optimal depletion fraction	0.600	0.700	0.250
Depletion equation constant A	1.309	1.309	0.854
Depletion equation constant B	-0.602	-0.602	-0.677
Maximum root depth (m)	1.200	1.500	0.600
Maximum soil salinity for 90% yield (mmho·cm^{-1})	7.400	3.400	2.500
Maximum soil salinity for 0% yield (mmho·cm^{-1})	20.000	15.500	10.000
Depletion fraction for which ET* fraction = 0.95	0.700	0.750	0.600
Depletion fraction for which ET fraction = 0.10	0.930	0.950	0.600
Depletion fraction for which ET fraction = 0.80	0.830	0.900	0.720

*Evapotranspiration

Four soil types were considered to represent the range of soils in the study area: light, medium, medium heavy, and heavy. The soil parameters are given in Table 6.

The irrigation areas and their location within the basin in terms of water supply and return flow are shown in Table 7. The irrigation data are summarized by irrigation area in Tables 8 through 11.

In the study, only the irrigated area was allowed to vary in the scenarios investigated. All other parameters were assumed to remain unchanged. Varying these parameters could significantly change the results of analysis. The breakdown of WUAM irrigation scenario data (irrigated area) by project is given in Table 12. The irrigated areas in the basin for the year 2000 base case and in the high irrigation scenarios were assumed to be 76 300 and 142 600 ha, respectively.

A rather high irrigation level of 60% was assumed to apply for all crops for the future conditions. The present level of irrigation is probably in the 50% range (Pohjakas 1981).

Table 5
Monthly Parameters for Crop Data

	Monthly crop factors			Depletion adjustment factors			Root depth adjustment factors			Soil salinity adjustment factors		
	Grain	Forage	Specialty	Grain	Forage	Specialty	Grain	Forage	Specialty	Grain	Forage	Specialty
Jan.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mar.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Apr.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
May	0.25	0.80	0.29	0.80	1.00	1.00	0.22	1.00	0.31	0.60	1.00	1.00
June	0.82	0.94	0.64	1.00	1.00	0.90	0.64	1.00	0.70	1.00	1.00	1.00
July	1.11	0.95	0.89	1.00	1.00	0.90	0.98	1.00	1.00	1.00	1.00	1.00
Aug.	0.47	0.83	0.92	1.20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sept.	0.25	0.73	0.52	1.00	1.00	1.10	1.00	1.00	1.00	1.00	1.00	1.00
Oct.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nov.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dec.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 6
Parameters for Soil Data

Soil type	Moisture storage capacity (mm/m)	Leaching efficiency (%)	Percolation efficiency (%)
Light	60.0	90.0	40.0
Medium	140.0	70.0	20.0
Medium heavy	170.0	55.0	15.0
Heavy	200.0	40.0	10.0

Table 7
Relation of Irrigation Areas to the Network

Irrigation area		Subbasin nodes					
			Return flow nodes				
No.	I.D.	Water supply nodes	No.	% of return flow	No.	% of return flow	Precipitation station
1	SSR-ID	3	4	100			SWFTSAS*
2	SSEWSS	3	4	100			SWFTSAS
3	SSRWUDA	3	3	100†			SWFTSAS
4	SSRWUDB	4	4	100			SWFTSAS
5	SCCWUD	2	2	20	0‡	80	SWIFT§
6	SSR-PIA	3	3	100			SWFTSAS
7	SSR-PIB	4	4	100			SWFTSAS
8	SSR-PIC	5	5	100			SWFTSAS
9	SCC-PI	2	2	100			SWIFT

*Average of Swift Current and Saskatoon
†Will vary with level of development
‡Return flow outside basin boundaries
§Swift Current

Table 8

Rainfall and Irrigation Application Efficiencies

Irrigation area		Rainfall application efficiency (%)	Irrigation application efficiency (%)			
No.	I.D.		Furrow	Border dike	Wheel roll	Centre pivot
1	SSR-ID	100	55	60	70	80
2	SSEWSS	100	55	60	70	80
3	SSRWUDA	100	55	60	70	80
4	SSRWUDA	100	55	60	70	80
5	SCCWUD	100	55	60	70	80
6	SSR-PIA	100	55	60	70	80
7	SSR-PIB	100	55	60	70	80
8	SSR-PIC	100	55	60	70	80
9	SCC-PI	100	55	60	70	80

Table 9

Crop, Soil, and Irrigation Distribution

Irrigation area		Crop (% of area)			Soils (% of area)				Irrigation (% of area)			
No.	I.D.	Grain	Forage	Specialty	Light	Medium	Medium heavy	Heavy	Furrow	Border dike	Wheel roll	Centre pivot
1	SSR-ID	77.7	17.9	4.4	-	50	50	-	17	17	16	50
2	SSEWSS	65.0	25.0	10.0	-	50	50	-	10	10	40	40
3	SSRWUDA	40.0	55.0	5.0	-	50	50	-	0	20	50	50
4	SSRWUDB	40.0	55.0	5.0	-	50	50	-	0	20	50	50
5	SCCWUD	25.0	65.0	10.0	-	50	50	-	25	25	25	25
6	SSR-PIA	45.0	45.0	10.0	-	50	50	-	10	10	40	40
7	SSR-PIB	45.0	45.0	10.0	-	50	50	-	10	10	40	40
8	SSR-PIC	45.0	45.0	10.0	-	50	50	-	10	10	40	40
9	SCC-PI	25.0	65.0	10.0	-	50	50	-	10	10	40	40

Table 10

Base Case Scenario Irrigation Areas and Operational Parameters

Irrigation area		Irrigated area (ha)	Crop irrigation level (%)			Delivery efficiency (%)	Delivery evaporative losses (%)
No.	I.D.		Grain	Forage	Specialty		
1	SSR-ID	22 000	60	60	60	85	35
2	SSEWSS	8 900	60	60	60	85	35
3	SSRWUDA	15 100	60	60	60	85	15
4	SSRWUDB	1 400	60	60	60	85	15
5	SCCWUD	4 000	60	60	60	85	15
6	SSR-PIA	12 500	60	60	60	85	15
7	SSR-PIB	4 200	60	60	60	85	15
8	SSR-PIC	4 200	60	60	60	85	15
9	SCC-PI	4 000	60	60	60	85	15
	Total	76 300					

Table 11
High Irrigation Scenario Irrigation Areas and Operational Parameters

Irrigation area		Irrigated area (ha)	Crop irrigation level (%)			Delivery efficiency (%)	Delivery evaporative losses (%)
No.	I.D.		Grain	Forage	Specialty		
1	SSR-ID	44 00	60	60	60	85	35
2	SSEWSS	10 500	60	60	60	85	35
3	SSRWUDA	51 700	60	60	60	85	15
4	SSRWUDB	2 400	60	60	60	85	15
5	SCCWUD	4 000	60	60	60	85	15
6	SSR-PIA	15 600	60	60	60	85	15
7	SSR-PIB	5 200	60	60	60	85	15
8	SSR-PIC	5 200	60	60	60	85	15
9	SCC-PI	4 000	60	60	60	85	15
	Total	142 600					

Table 12
WUAM Current and Future Scenario Irrigation Areas by Actual Projects

			Irrigated area (ha)		
No.	I.D.	Actual project	Current	Scenarios 1 & 2	Scenarios 3 & 4
1	SSR-ID	No. 1 (Outlook/East Side)	14 850	20 000	20 000
		No. 2 (Conquest/West Side)	0	2 000	24 000
		Total	14 850	22 000	44 000
2	SSEWSS	Several (served by SSWES)	6 100	8 900	10 500
3	SSRWUDA	Chesterfield Flats	290	300	300
		Miry Creek	650	650	650
		Riverhurst	0	3 200	10 700
		Thundercreek-Mortlach	0	2 000	12 400
		Grainland	1 050	2 650	7 250
			0	800	8 100
			0	2 700	7 500
			770	2 800	4 800
		Total	2 760	15 100	51 700
4	SSRWUDB	French Flats	160	400	600
		Moon Lake	240	1 000	1 800
		Total	400	1 400	2 400
5	SCCWUD	North Waldeck	630	700	700
		Rush Lake	2 400	2 600	2 600
		Herbert	600	700	700
		Total	3 630	4 000	4 000
6	SSR-PIA	Private irrigation	-	12 500	15 600
7	SSR-PIB	Private irrigation	-	4 200	5 200
8	SSR-PIC	Private irrigation	-	4 200	5 200
9	SCC-PI	Private irrigation	-	4 000	4 000
		Grand total	**27 740**	**76 300**	**142 600**

The precipitation data used in the study are depicted in Figure 10. Mean monthly reference potential evapotranspiration data (Hobbs and Krogman 1983), gathered at Vauxhall, Alberta, were used for all irrigation areas. These data are presented in Table 13, together with the corresponding crop factors.

Table 13
Crop Evapotranspiration Data

Month	ETP_r* (mm)†	Monthly crop factors		
		Grains	Forages	Specialties
May	153.8	0.25	0.80	0.29
June	180.0	0.82	0.94	0.64
July	189.05	1.11	0.95	0.89
Aug.	176.9	0.47	0.83	0.92
Sept.	126.5	0.25	0.73	0.52

*Mean monthly reference potential evapotranspiration
†From Hobbs and Krogman 1983

2.3.3 Simulation Period

The water balance simulation period used in WUAM is governed by the shortest historical periods of precipitation, evaporation, natural streamflows, and boundary flows which are included in the database. The following periods of record were covered in the present simulations:

- precipitation: 71 years (1912–1982)
- evaporation (Lake Diefenbaker): 56 years (1912–1967)
- natural streamflows:
  - 56 years (1912–1967) for all nodes except DUMMY01
  - 71 years (1912–1982) for node DUMMY01
- boundary flows:
  - 28 years (1928–1955) for scenarios 1 and 3
  - 71 years (1912–1982) for scenarios 2 and 4

The results of the overall water balance simulations would, therefore, cover the periods 1928–1955 (28 years) for scenarios 1 and 3 and 1912–1967 (56 years) for scenarios 2 and 4.

The natural streamflow data, together with the boundary flow assumptions at the Alberta–Saskatchewan border, are presented graphically in Appendix B.

3. ANALYSIS OF RESULTS

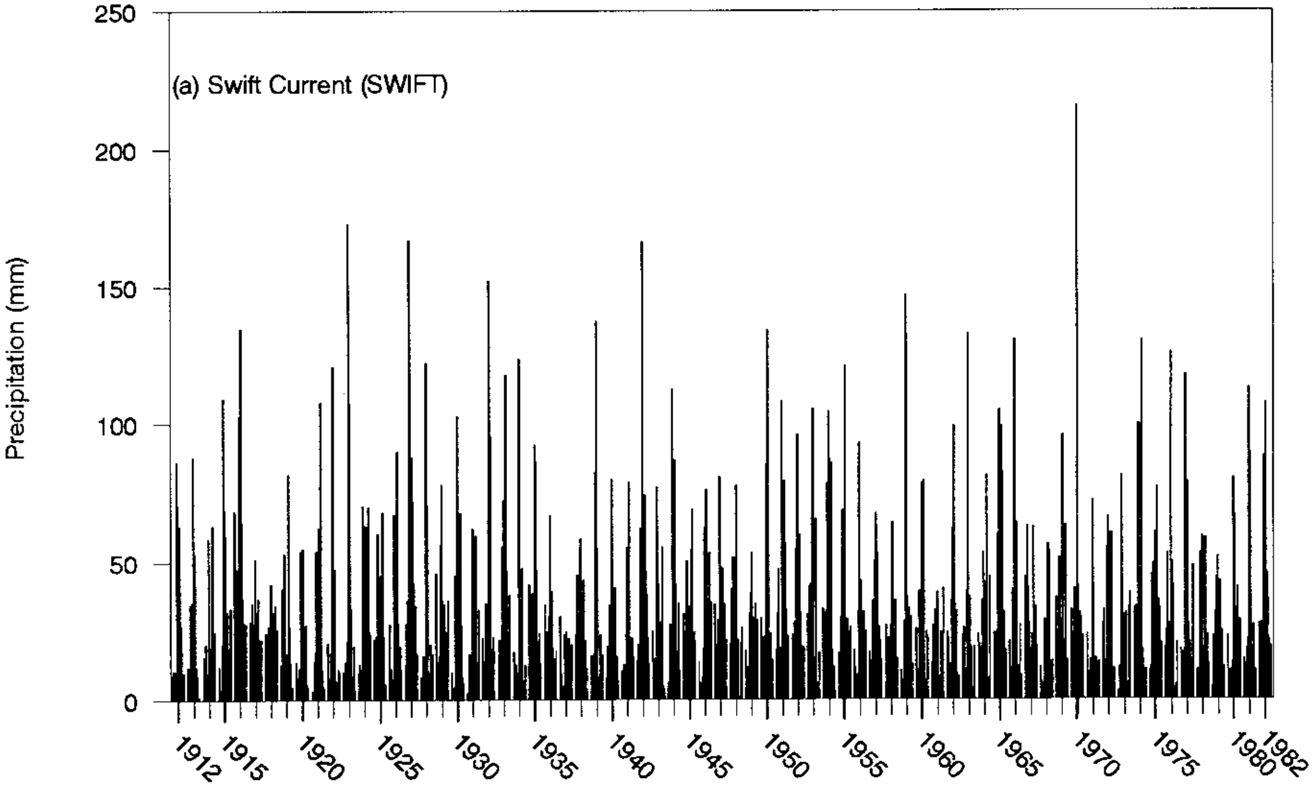
3.1 Withdrawal Water Use

Total basin water intake and consumption volumes were projected for the industrial, urban and rural, livestock, and irrigation sectors (Table 14). For the base case scenarios (1 and 2), the average water intake from the basin is predicted to be 470.15 MCM, of which 283.89 MCM (60%) will be consumed. For the high irrigation scenarios (3 and 4), average intake and consumption will increase to 839.88 and 518.73 MCM, respectively (i.e., about a 79% increase). Of the above total, irrigation accounts for approximately 90% and 94% of intake for the two sets of scenarios. In terms of consumption, this proportion increases to 94% and 97%. Note that these figures exclude the other major consumptive uses, i.e., reservoir evaporation and the Qu'Appelle diversion. They also exclude thermal power water use (at the Queen Elizabeth plant), which consumes a negligible amount of water by returning almost all the water withdrawn for cooling purposes.

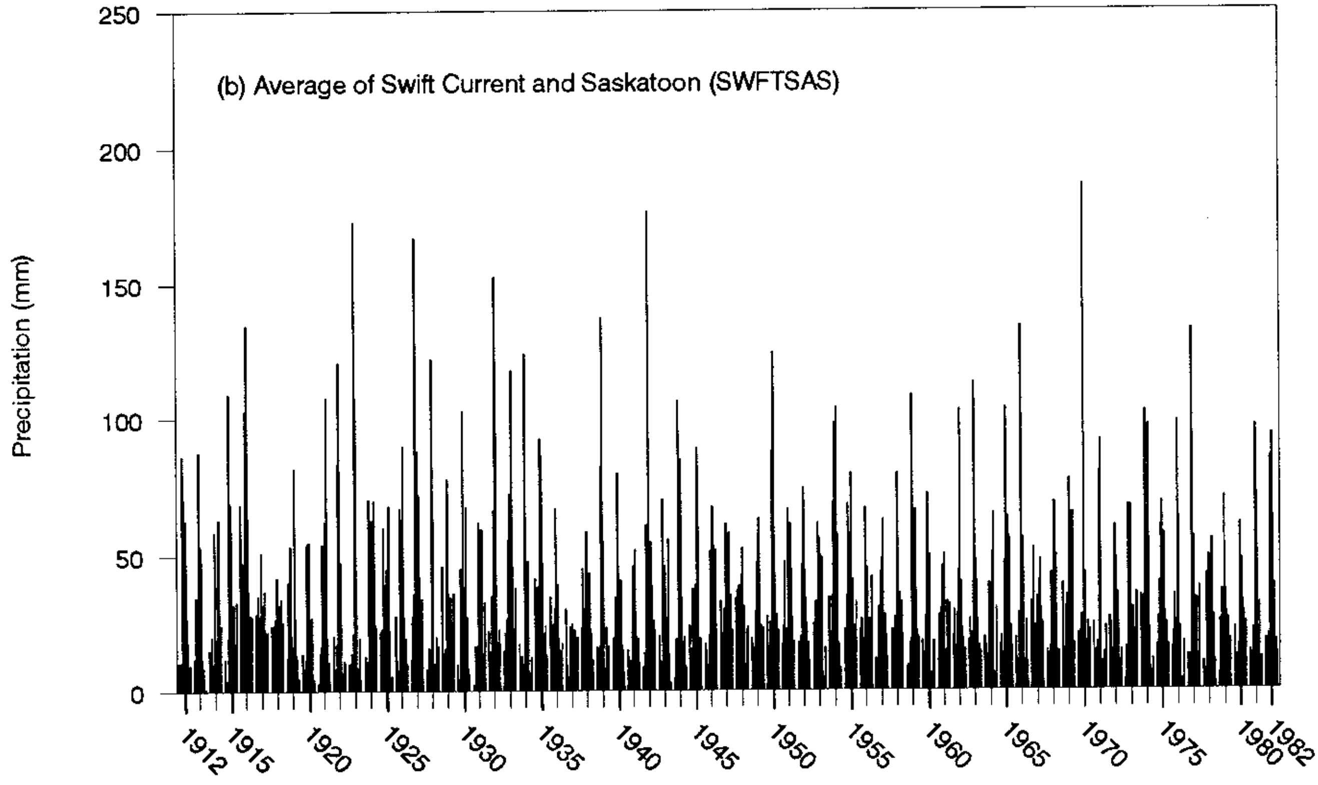
Table 14
Withdrawal Water Use Projection*

Sector	Base case scenarios		High irrigation scenarios	
	Average intake (MCM)	Average consumption (MCM)	Average intake (MCM)	Average consumption (MCM)
Industrial	13.16	3.00	13.16	3.00
Urban and rural	29.01	7.52	29.01	7.52
Livestock	5.71	4.99	5.71	4.99
Average irrigation	422.27	268.38	792.00	503.22
Total	470.15	283.89	839.88	518.73

*Excluding evaporation and diversion.



(a) Swift Current (SWIFT)



(b) Average of Swift Current and Saskatoon (SWFTSAS)

Figure 10. Precipitation data for irrigation water use calculation.

Average water uses are usually considered adequate for water planning purposes. However, average conditions do not always give a complete picture of water uses since they do not account for possible annual variation. This is particularly true in the case of irrigation water use, which may vary significantly from year to year. In the follow-ing section, irrigation water use in the basin and its variations are analyzed, first under average, extreme dry, and wet conditions, and then in terms of a frequency diagram.

Lake Diefenbaker reservoir evaporation losses and diversions are discussed in section 3.2.

3.1.1 Irrigation Water Use

Irrigation is by far the largest water use in the basin and can vary considerably from year to year for a given area and crop, depending primarily on the prevailing climatic conditions. This is demonstrated in Tables 15 and 16 for the base case and high irrigation scenarios, respectively. The tables summarize the simulated irrigation water use under maxi-mum (i.e., dry), minimum (i.e., wet), and average use conditions by irrigation area as well as the basin total. Maximum and mini-mum irrigation water intake for selected dry and wet years, as well as the average intake, are presented by node in Tables 17 and 18. The significant deviation from the average conditions is obvious. Note that the above results reflect only the effect of variation in precipitation on irrigation water use. Other parameters, such as monthly potential evapo-transpiration, were assumed to remain con-stant for the historical period of simulation.

3.1.1.1 Frequency Analysis of Irrigation Water Use

The simulated irrigation water uses for the base case and the high irrigation scenarios are represented in terms of frequency curves in Figures 11 and 12, respectively. These curves are based on the entire irrigated area within the Saskatchewan portion of the South Saskatchewan River basin (i.e., 76 300 ha for the base case and 142 600 ha for the high irrigation scenario) and the 1912–1982 historical precipitation. They indicate the probability of irrigation water use exceeding a

Table 15

Simulated Irrigation Water Use by Irrigation Area for Base Case Scenarios

	Maximum use (dry year)			Minimum use (wet year)			Average use	
Area no.	Intake (MCM)	Consumption (MCM)	Year*	Intake (MCM)	Consumption (MCM)	Year†	Intake (MCM)	Consumption (MCM)
1	151.18	98.85	1937	60.00	39.23	1916	107.11	70.03
2	62.54	41.29	1937	26.19	17.29	1916	45.11	29.78
3	121.60	75.75	1937	58.03	36.33	1916	90.58	56.70
4	11.22	7.02	1937	5.38	3.37	1916	8.40	5.26
5	35.80	20.97	1973	16.20	9.49	1954	27.29	15.98
6	95.50	60.19	1937	44.19	27.85	1916	71.00	44.75
7	32.09	20.22	1937	14.85	9.36	1916	23.86	15.04
8	32.09	20.22	1937	14.85	9.36	1916	23.86	15.04
9	33.42	21.06	1973	14.84	9.35	1954	25.06	15.79
Total	575.44	365.57		254.53	161.63		422.27	268.37

Note: 1912–1982 precipitation.
*Year of historical precipitation record that would result in maximum irrigation water demand.
†Year of historical precipitation record that would result in minimum irrigation water demand.

Table 16

Simulated Irrigation Water Use by Irrigation Area for High Irrigation Scenarios

	Maximum use (dry year)			Minimum use (wet year)			Average use	
Area no.	Intake (MCM)	Consumption (MCM)	Year*	Intake (MCM)	Consumption (MCM)	Year†	Intake (MCM)	Consumption (MCM)
1	302.36	197.70	1937	120.00	73.48	1916	214.21	140.07
2	73.78	48.71	1937	30.90	20.40	1916	53.22	35.14
3	414.29	259.35	1937	198.69	124.38	1916	310.13	194.14
4	19.23	12.04	1937	9.22	5.77	1916	14.40	9.01
5	35.80	20.97	1973	16.20	9.49	1954	27.29	15.98
6	119.19	75.12	1937	55.14	34.75	1916	88.61	55.85
7	39.73	25.04	1937	18.38	11.58	1916	29.54	18.62
8	39.73	25.04	1937	18.38	11.58	1916	29.54	18.62
9	33.42	21.06	1973	14.84	9.35	1954	25.06	15.79
Total	1077.53	685.03		481.75	300.78		792.00	503.22

Note: 1912–1982 precipitation.
*Year of historical precipitation record that would result in maximum irrigation water demand.
†Year of historical precipitation record that would result in minimum irrigation water demand.

Table 17

Simulated Irrigation Water Use under Various Conditions by Node for Base Case Scenario 2

	Irrigation water intake (MCM)		
No.	Maximum (dry year, 1937)	Minimum (wet year, 1916)	Average
1	-	-	-
2	68.37	34.83	51.4
3	430.22	188.41	313.3
4	43.31	20.23	32.1
5	32.10	14.85	23.8
Total	574.00	258.32	420.6

Note: 1912–1967 precipitation.

Table 18

Simulated Irrigation Water Use under Various Conditions by Node for High Irrigation Scenario 4

	Irrigation water intake (MCM)		
No.	Maximum (dry year, 1937)	Minimum (wet year, 1916)	Average
1	-	-	-
2	68.37	34.83	51.4
3	909.62	404.07	662.7
4	59.05	27.60	43.8
5	39.73	18.38	33.1
Total	1076.77	484.88	791.0

Note: 1912–1967 precipitation.

given volume. For example, in the case of the high irrigation scenario, the irrigation use will always be greater than 480 MCM, will exceed 700 MCM about 80% of the time, and will exceed 800 MCM about 50% of the time.

3.2 Lake Diefenbaker

WUAM results regarding Lake Diefenbaker are presented in some detail. These results are, however, experimental and should be interpreted in view of the scenario data and assumptions, in particular, the rule curve and operating constraints, inflows into the reservoir, and water uses, including the Qu'Appelle diversion.

3.2.1 Withdrawal Water Uses

The major withdrawal water uses from Lake Diefenbaker are irrigation, evaporation, and the Qu'Appelle diversion[5]. They account

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[5] Instream uses, such as reservoir releases for hydro power generation, are also consumptive uses of the lake, but are not included in this analysis.

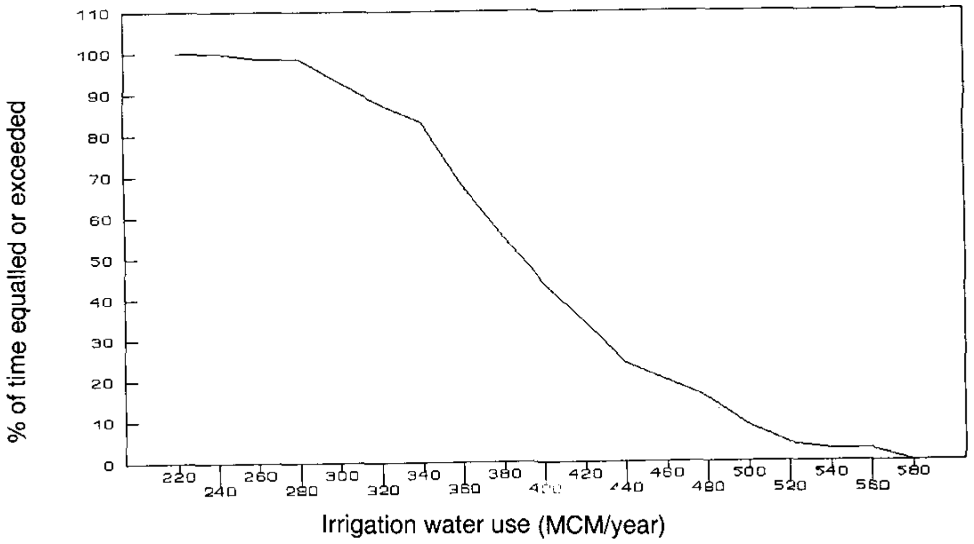

Figure 11. Simulated irrigation water use for base case scenarios (1912–1982 precipitation).

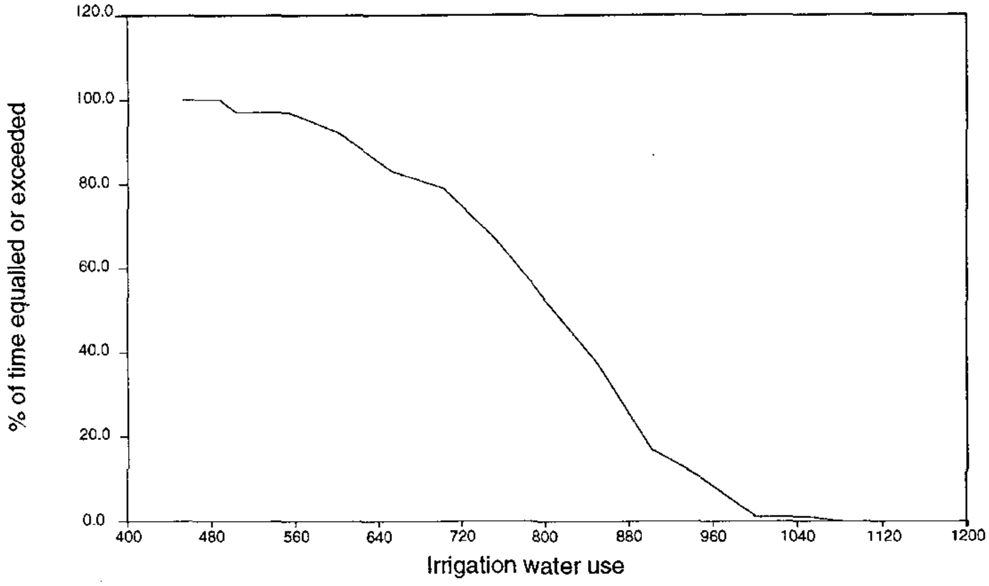

Figure 12. Simulated irrigation water use for high irrigation scenarios (1912–1982 precipitation).

for more than 95% of the total withdrawals from the lake. The predicted mean annual withdrawals from the lake for the year 2000 are presented in Figure 13 for the two sets of water use scenarios. The base case scenarios (1 and 2) assume 58 500 ha are supplied directly from Lake Diefenbaker. For the high irrigation scenarios (3 and 4), this figure is assumed to be 121 800 ha. The results are based on the 1912–1967 simulation period.

For the high irrigation scenarios (3 and 4), the mean annual withdrawal for irrigation purposes only would increase to more than twice (2.1 times) that predicted for the base case scenarios (1 and 2) (i.e., 110% increase).

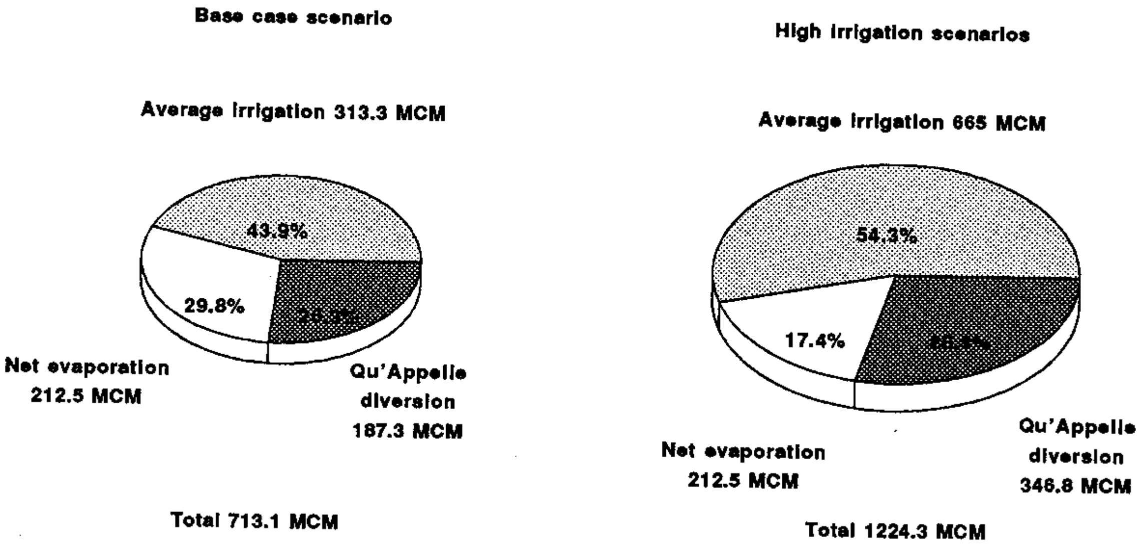

Figure 13. Predicted mean annual major withdrawals from Lake Diefenbaker.

When the Qu'Appelle diversion is taken into account, the share of irrigation of the total increase (i.e., 511.2 MCM or 72%) would drop to only 69%, with diversion contributing the remaining 31%. Note that the increase in irrigation water use in this case is proportion-ate to the increase in the irrigated area since all other parameters were kept the same for the two sets of scenarios. The results would be different if any, or a combination of the other, parameters were changed.

An analysis of consumptive water uses from the lake under extreme wet and dry conditions was also carried out to supplement the results obtained under the average conditions (Fig. 14). Obviously, the worst case is represented by the dry climate. In this case, excluding diversion, the combination of high irrigation water use and large evaporative losses would result in water withdrawals from the lake that are 130% of the average. This contrasts with a little over 50% of the average for the extreme wet year. It can therefore be concluded that the average withdrawals from the lake are closer to the high side rather than the low. This can be best illustrated through a frequency diagram of water withdrawals from Lake Diefenbaker.

3.2.1.1 Frequency Analysis of Water Withdrawals from Lake Diefenbaker

Using WUAM simulation results for the historical period 1912–1967, the combined irrigation water withdrawal and net evaporation from Lake Diefenbaker were analyzed and presented in terms of a frequency curve (Fig. 15). The curve was developed for the high irrigation scenarios considering only the irrigation areas supplied directly from the lake (121 800 ha). It should be noted that irrigation return flows to the lake were ignored in developing this diagram.

3.2.2 Impacts on Lake Diefenbaker Levels and Discharges

Tables 19 through 26 present statistical summaries of lake levels and discharges from the reservoir for the four scenarios simulated. The results are presented on a monthly basis in relation to the rule curve and operating constraints established for the lake (Fig. 3). Reference should be made to Figure 3 when interpreting these results.

Figures 16 through 20 are frequency plots of occurrences of month-end lake levels. The figures indicate the percentages of the time a.

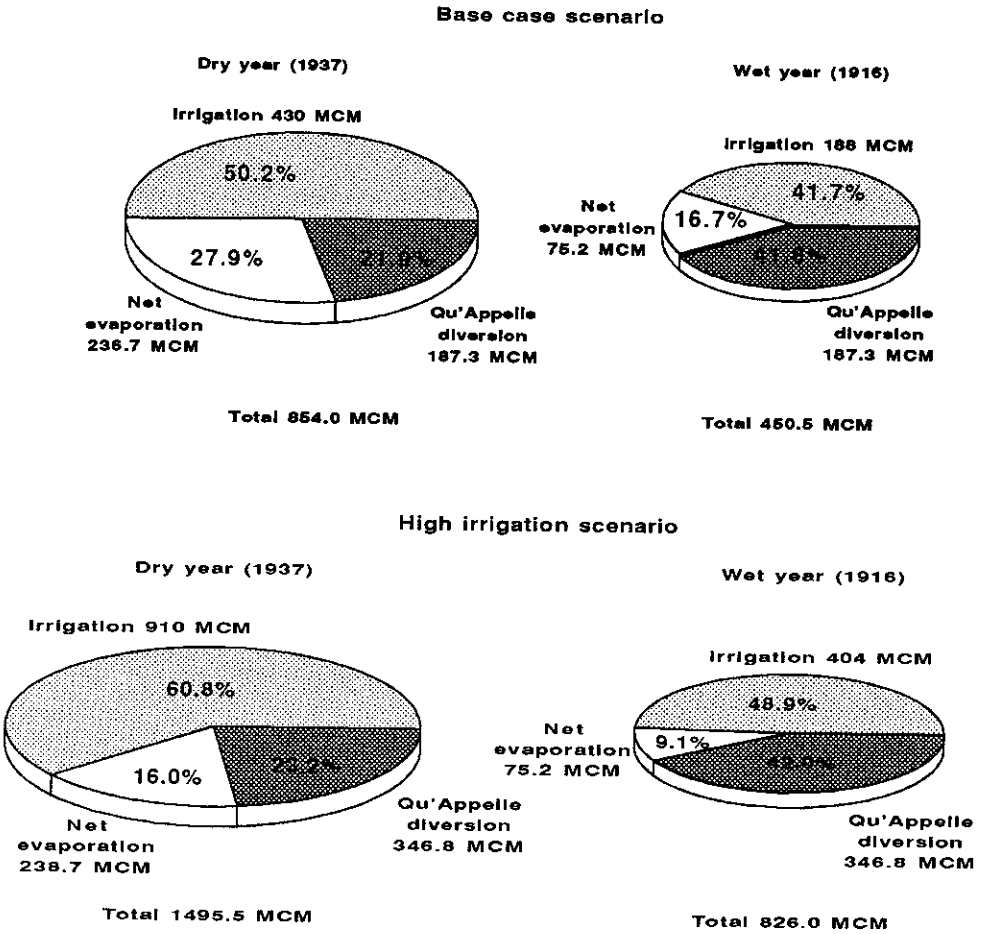

Figure 14. Predicted annual major withdrawals from Lake Diefenbaker under extreme dry and wet conditions.

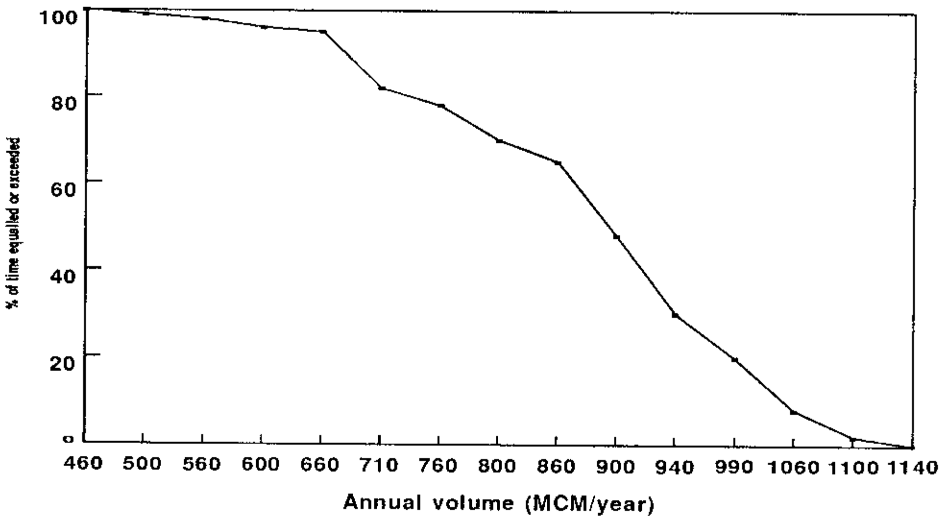

Figure 15. Lake Diefenbaker.

Table 19

Lake Diefenbaker Levels for Base Case Scenario 1*

Month	No. months	Rule curve Upper (m)	Rule curve Lower (m)	Occurrences (%) At minimum supply (545.6 m)	Occurrences (%) Below lower rule curve	Occurrences (%) At lower rule curve	Occurrences (%) Within bounds	Occurrences (%) At upper rule curve	Occurrences (%) Above upper rule curve	Occurrences (%) At maximum supply (556.9 m)
Jan.	28	553.0	550.5	0	21	14	61	4	0	0
Feb.	28	551.5	549.0	0	4	43	50	4	0	0
Mar.	28	551.5	547.5	0	0	11	89	0	0	0
Apr.	28	552.5	548.5	0	32	18	39	7	4	0
May	28	554.0	550.0	0	43	11	32	11	0	4
June	28	556.5	555.3	0	57	14	11	7	4	7
July	28	556.9	555.3	0	61	7	4	0	0	29
Aug.	28	556.5	555.3	0	64	4	7	21	0	4
Sept.	28	556.0	555.3	0	64	7	11	11	0	7
Oct.	28	556.0	555.0	0	61	11	18	7	0	4
Nov.	28	555.0	554.0	0	46	11	25	14	4	0
Dec.	28	555.0	552.5	0	29	21	46	4	0	0
Total	336		Avg.	0	40	14	33	7	1	4

*1928–1955 flows

Table 20

Lake Diefenbaker Discharges for Base Case Scenario 1*

Month	No. months	Rule curve Minimum discharge ($m^3 \cdot s^{-1}$)	Rule curve Maximum discharge ($m^3 \cdot s^{-1}$)	Rule curve Target discharge ($m^3 \cdot s^{-1}$)	Occurrences (%) Below minimum	Occurrences (%) At minimum	Occurrences (%) Below target	Occurrences (%) At target	Occurrences (%) Above target	Occurrences (%) At maximum	Occurrences (%) Above maximum
Jan.	28	42.5	425.0	329.0	0	21	14	61	4	0	0
Feb.	28	42.5	425.0	310.0	0	4	43	50	4	0	0
Mar.	28	42.5	425.0	231.0	0	0	11	89	0	0	0
Apr.	28	42.5	600.0	160.0	0	32	18	39	7	4	0
May	28	42.5	600.0	150.0	0	43	11	32	11	0	4
June	28	42.5	600.0	252.0	0	57	14	11	7	4	7
July	28	42.5	600.0	221.0	0	61	7	4	21	0	7
Aug.	28	42.5	425.0	159.0	0	64	4	7	21	0	4
Sept.	28	42.5	425.0	146.0	0	64	7	11	11	0	7
Oct.	28	42.5	425.0	160.0	0	61	11	18	7	0	4
Nov.	28	42.5	425.0	226.0	0	46	11	25	14	4	0
Dec.	28	42.5	425.0	285.0	0	29	21	46	4	0	0
Total	336			Avg.	0	40	14	33	9	1	3

*1928–1955 flows

Table 21
Lake Diefenbaker Levels for Base Case Scenario 2*

		Rule curve		Occurrences (%)						
Month	No. months	Upper (m)	Lower (m)	At minimum supply (545.6 m)	Below lower rule curve	At lower rule curve	Within bounds	At upper rule curve	Above upper rule curve	At maximum supply (556.9 m)
Jan.	56	553.0	550.5	0	7	79	14	0	0	0
Feb.	56	551.5	549.0	0	2	91	7	0	0	0
Mar.	56	551.5	547.5	0	0	70	30	0	0	0
Apr.	56	552.5	548.5	0	55	34	11	0	0	0
May	56	554.0	550.0	0	50	25	23	2	0	0
June	56	556.5	555.3	0	91	7	0	2	0	0
July	56	556.9	555.3	0	73	5	16	0	0	0
Aug.	56	556.5	555.3	0	66	11	14	9	0	0
Sept.	56	556.0	555.3	0	70	9	12	7	0	0
Oct.	56	556.0	555.0	0	61	18	16	5	0	0
Nov.	56	555.0	554.0	0	48	36	7	9	0	0
Dec.	56	555.0	552.5	0	25	61	14	0	0	0
Total	672		Avg.	0	46	37	14	3	0	0

*1912–1967 flows

Table 22
Lake Diefenbaker Discharges for Base Case Scenario 2*

		Rule curve			Occurrences (%)						
Month	No. months	Minimum discharge $(\mathrm{m}^{3}\cdot\mathrm{s}^{-1})$	Maximum discharge $(\mathrm{m}^{3}\cdot\mathrm{s}^{-1})$	Target discharge $(\mathrm{m}^{3}\cdot\mathrm{s}^{-1})$	Below minimum	At minimum	Below target	At target	Above target	At maximum	Above maximum
Jan.	56	42.5	425.0	329.0	0	7	79	14	0	0	0
Feb.	56	42.5	425.0	310.0	0	2	91	7	0	0	0
Mar.	56	42.5	425.0	231.0	0	0	70	30	0	0	0
Apr.	56	42.5	600.0	160.0	0	55	34	11	0	0	0
May	56	42.5	600.0	150.0	0	50	23	25	2	0	0
June	56	42.5	600.0	252.0	0	91	7	0	2	0	0
July	56	42.5	600.0	221.0	0	73	5	16	5	0	0
Aug.	56	42.5	425.0	159.0	0	66	11	14	9	0	0
Sept.	56	42.5	425.0	146.0	0	70	9	12	7	2	0
Oct.	56	42.5	425.0	160.0	0	61	18	16	5	0	0
Nov.	56	42.5	425.0	226.0	0	48	36	7	9	0	0
Dec.	56	42.5	425.0	285.0	0	25	61	14	0	0	0
Total	672			Avg.	0	46	37	14	3	0	0

*1912–1967 flows

Table 23
Lake Diefenbaker Levels for High Irrigation Scenario 3*

Month	No. months	Rule curve Upper (m)	Rule curve Lower (m)	Occurrences (%) At minimum supply (545.6 m)	Below lower rule curve	At lower rule curve	Within bounds	At upper rule curve	Above upper rule curve	At maximum supply (556.9 m)
Jan.	28	553.0	550.5	0	29	50	21	0	0	0
Feb.	28	551.5	549.0	0	21	61	18	0	0	0
Mar.	28	551.5	547.5	0	7	64	29	0	0	0
Apr.	28	552.5	548.5	0	54	25	18	4	0	0
May	28	554.0	550.0	0	57	14	21	7	0	0
June	28	556.5	555.3	0	79	7	4	7	4	0
July	28	556.9	555.3	0	75	7	7	0	0	11
Aug.	28	556.5	555.3	0	79	4	11	4	4	0
Sept.	28	556.0	555.3	0	79	0	14	0	7	0
Oct.	28	556.0	555.0	0	79	11	4	7	0	0
Nov.	28	555.0	554.0	0	68	14	11	7	0	0
Dec.	28	555.0	552.5	0	39	39	21	0	0	0
Total	336		Avg.	0	55	25	15	3	1	1

*1928–1955 flows

Table 24
Lake Diefenbaker Discharges for High Irrigation Scenario 3*

Month	No. months	Rule curve Minimum discharge (m^3·s^{-1})	Rule curve Maximum discharge (m^3·s^{-1})	Rule curve Target discharge (m^3·s^{-1})	Occurrences (%) Below minimum	At minimum	Below target	At target	Above target	At maximum	Above maximum
Jan.	28	42.5	425.0	329.0	0	29	50	21	0	0	0
Feb.	28	42.5	425.0	310.0	0	21	61	18	0	0	0
Mar.	28	42.5	425.0	231.0	0	7	64	29	0	0	0
Apr.	28	42.5	600.0	160.0	0	54	25	18	4	0	0
May	28	42.5	600.0	150.0	0	57	14	21	7	0	0
June	28	42.5	600.0	252.0	0	79	7	4	7	4	0
July	28	42.5	600.0	221.0	0	75	7	7	7	0	4
Aug.	28	42.5	425.0	159.0	0	79	4	11	4	4	0
Sept.	28	42.5	425.0	146.0	0	79	0	14	0	7	0
Oct.	28	42.5	425.0	160.0	0	79	11	4	7	0	0
Nov.	28	42.5	425.0	226.0	0	68	14	11	7	0	0
Dec.	28	42.5	425.0	285.0	0	39	39	21	0	0	0
Total	336			Avg.	0	55	25	15	4	1	0

*1928–1955 flows

Table 25
Lake Diefenbaker Levels for High Irrigation Scenario 4*

		Rule curve		Occurrences (%)						
Month	No. months	Upper (m)	Lower (m)	At minimum supply (545.6 m)	Below lower rule curve	At lower rule curve	Within bounds	At upper rule curve	Above upper rule curve	At maximum supply (556.9 m)
Jan.	56	553.0	550.5	0	14	75	11	0	0	0
Feb.	56	551.5	549.0	0	9	84	7	0	0	0
Mar.	56	551.5	547.5	0	2	79	20	0	0	0
Apr.	56	552.5	548.5	0	61	30	9	0	0	0
May	56	554.0	550.0	0	57	23	18	2	0	0
June	56	556.5	555.3	0	95	4	0	2	0	0
July	56	556.9	555.3	0	75	7	14	0	0	4
Aug.	56	556.5	555.3	0	71	9	14	5	0	0
Sept.	56	556.0	555.3	0	75	14	2	7	0	0
Oct.	56	556.0	555.0	0	68	20	9	4	2	0
Nov.	56	555.0	554.0	0	57	30	4	9	0	0
Dec.	56	555.0	552.5	0	39	52	9	0	0	0
Total	672		Avg.	0	52	36	10	2	0	0

*1912–1967 flows

Table 26
Lake Diefenbaker Discharges for High Irrigation Scenario 4*

		Rule curve			Occurrences (%)						
Month	No. months	Minimum discharge ($m^3 \cdot s^{-1}$)	Maximum discharge ($m^3 \cdot s^{-1}$)	Target discharge ($m^3 \cdot s^{-1}$)	Below minimum	At minimum	Below target	At target	Above target	At maximum	Above maximum
Jan.	56	42.5	425.0	329.0	0	14	75	11	0	0	0
Feb.	56	42.5	425.0	310.0	0	9	84	7	0	0	0
Mar.	56	42.5	425.0	231.0	0	2	79	20	0	0	0
Apr.	56	42.5	600.0	160.0	0	61	30	9	0	0	0
May	56	42.5	600.0	150.0	0	57	23	18	2	0	0
June	56	42.5	600.0	252.0	0	95	4	0	2	0	0
July	56	42.5	600.0	221.0	0	75	7	14	4	0	0
Aug.	56	42.5	425.0	159.0	0	71	9	14	5	0	0
Sept.	56	42.5	425.0	146.0	0	75	14	2	7	2	0
Oct.	56	42.5	425.0	160.0	0	68	20	9	4	0	0
Nov.	56	42.5	425.0	226.0	0	57	30	4	9	0	0
Dec.	56	42.5	425.0	285.0	0	39	52	9	0	0	0
Total	672			Avg.	0	52	36	10	3	0	0

*1912–1967 flows

given level is equalled or exceeded, comparing the four scenarios. Figure 16 is based on the entire period of record, while Figures 17 through 20 are for the months of June to September.

Figures 21 through 25 are similar frequency plots of occurrences of mean monthly discharges, comparing the reservoir releases for the four scenarios. Figure 21 is based on the entire monthly record, whereas Figures 22 through 25 deal with the months of June to September.

The reservoir's mean month-end levels corresponding to the simulated scenarios are compared in Figure 26. Figures 27 through 30 present plots of the mean, maximum, and minimum month–end levels for each of the scenarios simulated.

In discussing the results of analysis for Lake Diefenbaker, two issues are addressed:

- impacts on recreational uses (levels below 555.3 m; assumed to apply for the months of June through September)
- instream uses below the Gardiner dam (periods below 42.5 $m^3 \cdot s^{-1}$)

3.2.2.1 Impacts on Recreational Uses

Table 27 presents a summary of simulation results with respect to the lake levels required for recreational uses. The table shows that, on average, the recreation level would be satisfied somewhere between only21% and 39% of the time, depending on the scenario. These results contradict an earlier study on Lake Diefenbaker (Saskatchewan Water Corporation 1987), which found recreational lake levels were satisfied most of the time. The findings of the present study are, however, generally similar to the findings of the Canada–Saskatchewan South Saskatchewan River Basin Study (Environment Canada–SaskWater 1991).

Table 27

Frequency of Lake Diefenbaker Lake Levels (% occurrence) Required for Recreational Uses*

Scenario	June	July	August	September	Average
1	43	39	36	36	39
2	39	27	34	30	25
3	21	25	21	21	22
4	5	25	29	25	21

*555.3 m

3.2.2.2 Impacts on Instream Uses Below the Gardiner Dam

The operational rules of the reservoir (Fig. 3) dictate that a minimum flow of 42.5 $m^3 \cdot s^{-1}$ be released whenever possible (i.e., as long as the reservoir level is above the allowable minimum). The simulations show that this requirement will always be met (see Figs. 21 through 25) for all scenarios.

4. SUMMARY AND CONCLUDING REMARKS

This report demonstrated the value of WUAM in river basin planning studies. The uniqueness of WUAM, in that it allows detailed analysis of water use and at the same time considers water supplies, on-stream and off-stream storage, water diversions, etc., makes it particularly suitable for studies involving river basin planning. The report illustrated the data requirements, model capabilities, and the type of information that can be obtained from the model and presented a preliminary assessment of future water uses and supplies in the Saskatchewan portion of the South Saskatchewan River basin. The study was based on four development scenarios, encompassing two levels of future water use in Alberta and two levels of irrigation development in Saskatchewan, all assumed to correspond to the year 2000. Special emphasis in the analyses was given to irrigation water uses in Saskatchewan and the impacts of both these uses and water uses in Alberta on Lake Diefenbaker. The scenarios are summarized in Table 28.

Text resumes on p. 38

Table 28. Scenario Summary

	Irrigated area (ha)			Simulation period (years)	
Scenario number	Total	Supplied directly from Lake Diefenbaker	Water use in Alberta	Irrigation	Water balance
1	76 300	58 500	Base case	71 (1912–1982)	28 (1928–1955)
2	76 300	58 500	50% of natural flows	71 (1912–1982)	56 (1912–1967)
3	142 600	121 800	High irrigation	71 (1912–1982)	28 (1928–1955)
4	142 600	121 800	50% of natural flows	71 (1912–1982)	56 (1912–1967)

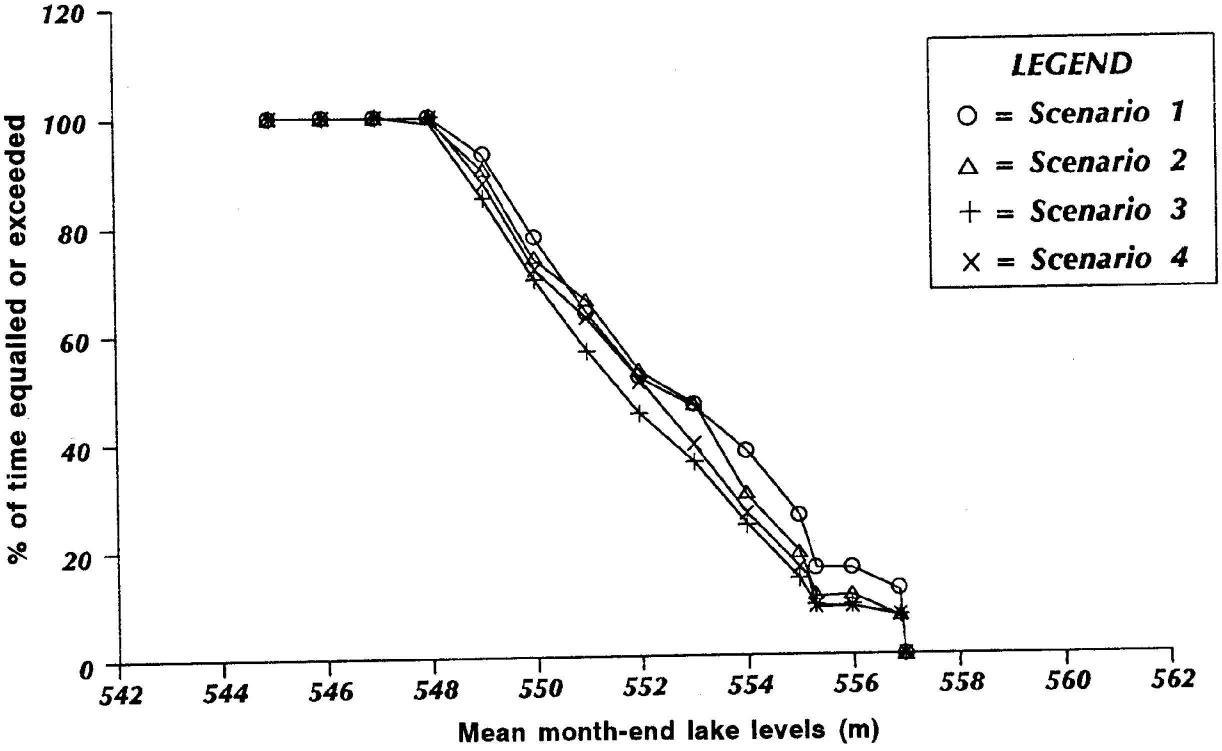

Figure 16. Lake Diefenbaker mean month-end levels.

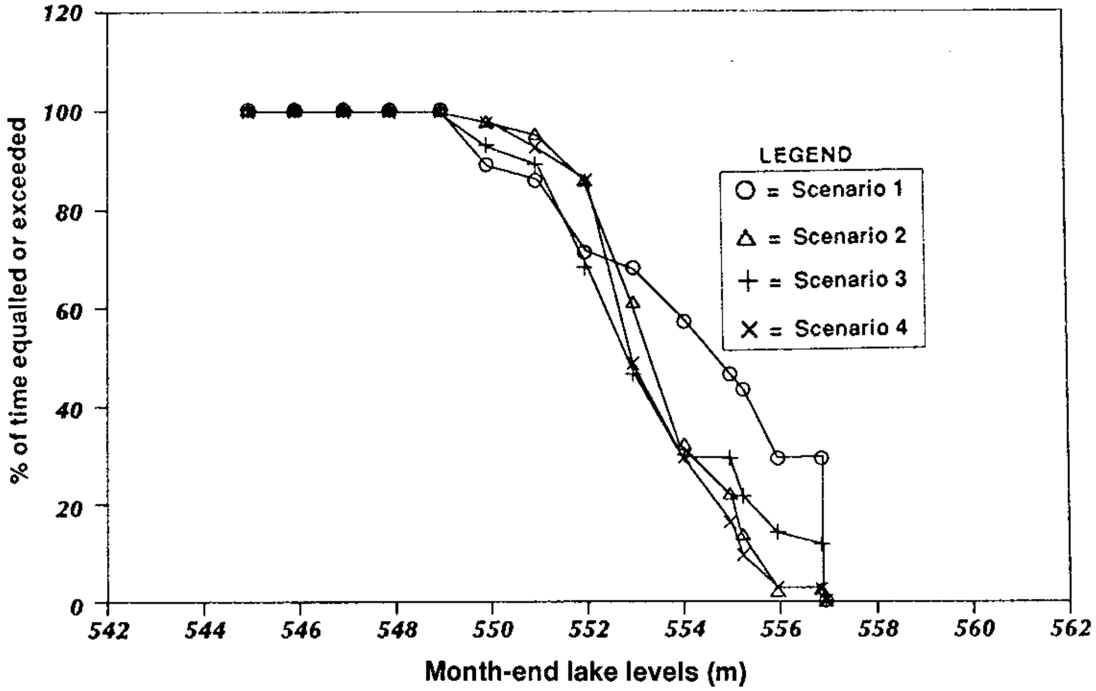

Figure 17. Lake Diefenbaker June 30 levels.

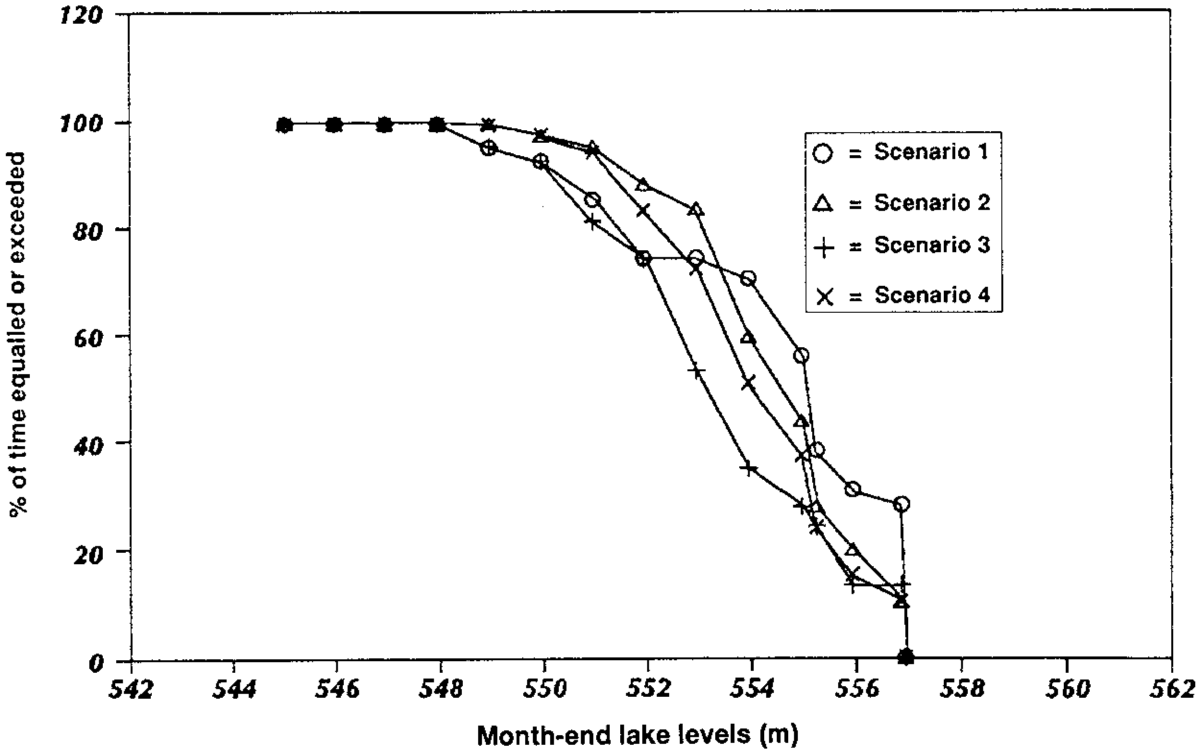

Figure 18. Lake Diefenbaker July 31 levels.

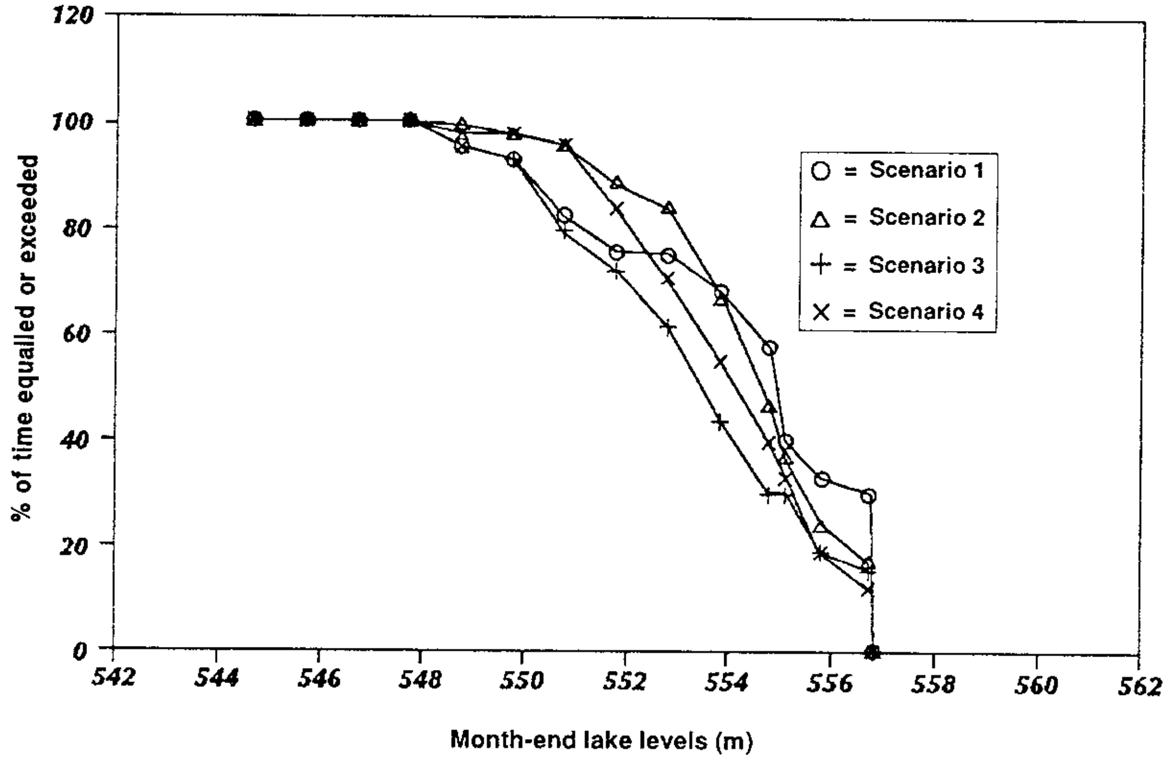

Figure 19. Lake Diefenbaker August 31 levels.

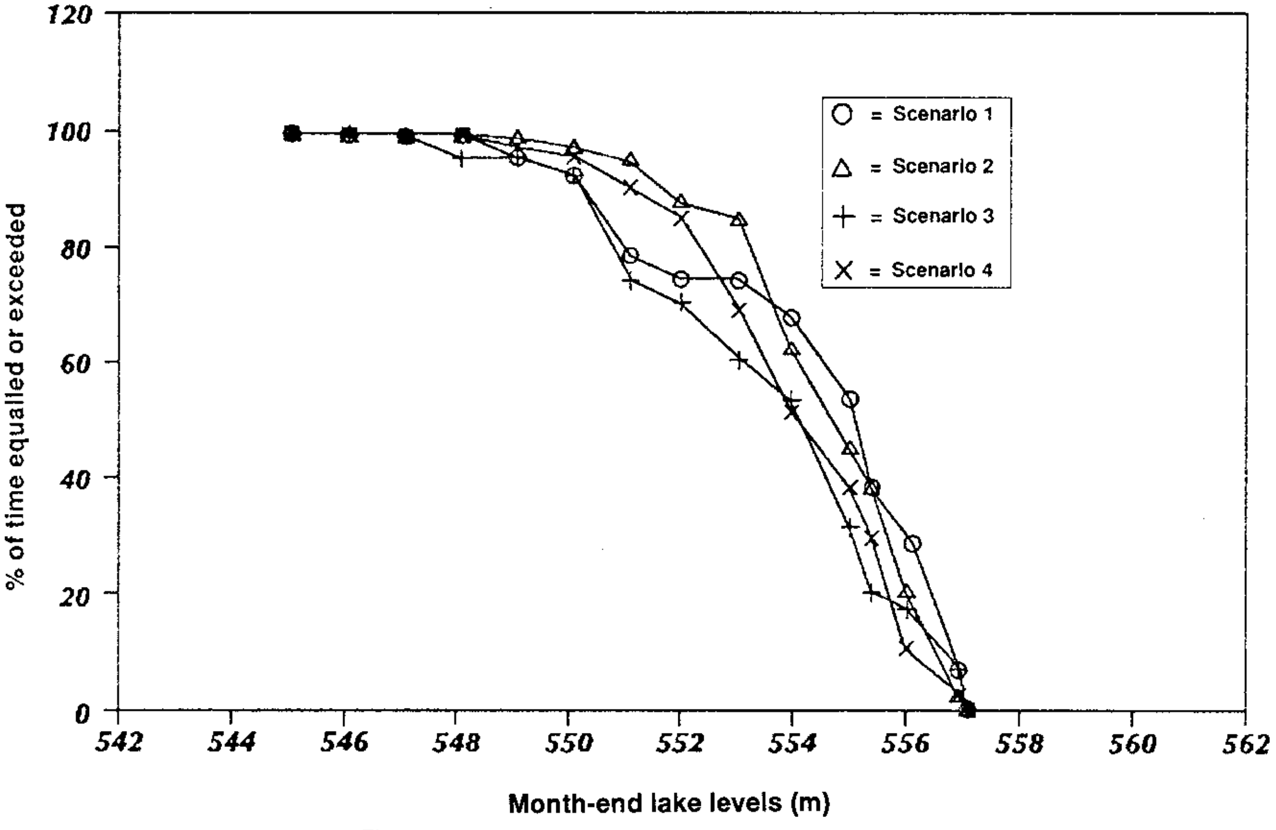

Figure 20. Lake Diefenbaker September 30 levels.

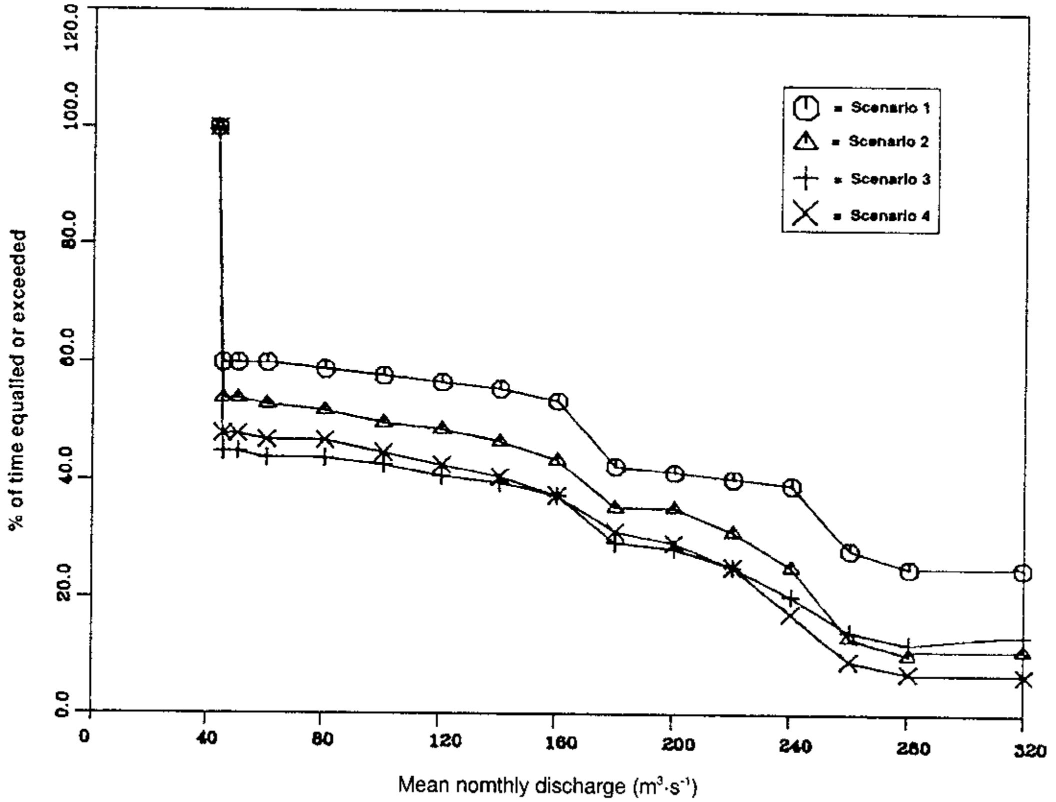

Figure 21. Lake Diefenbaker mean monthly discharges.

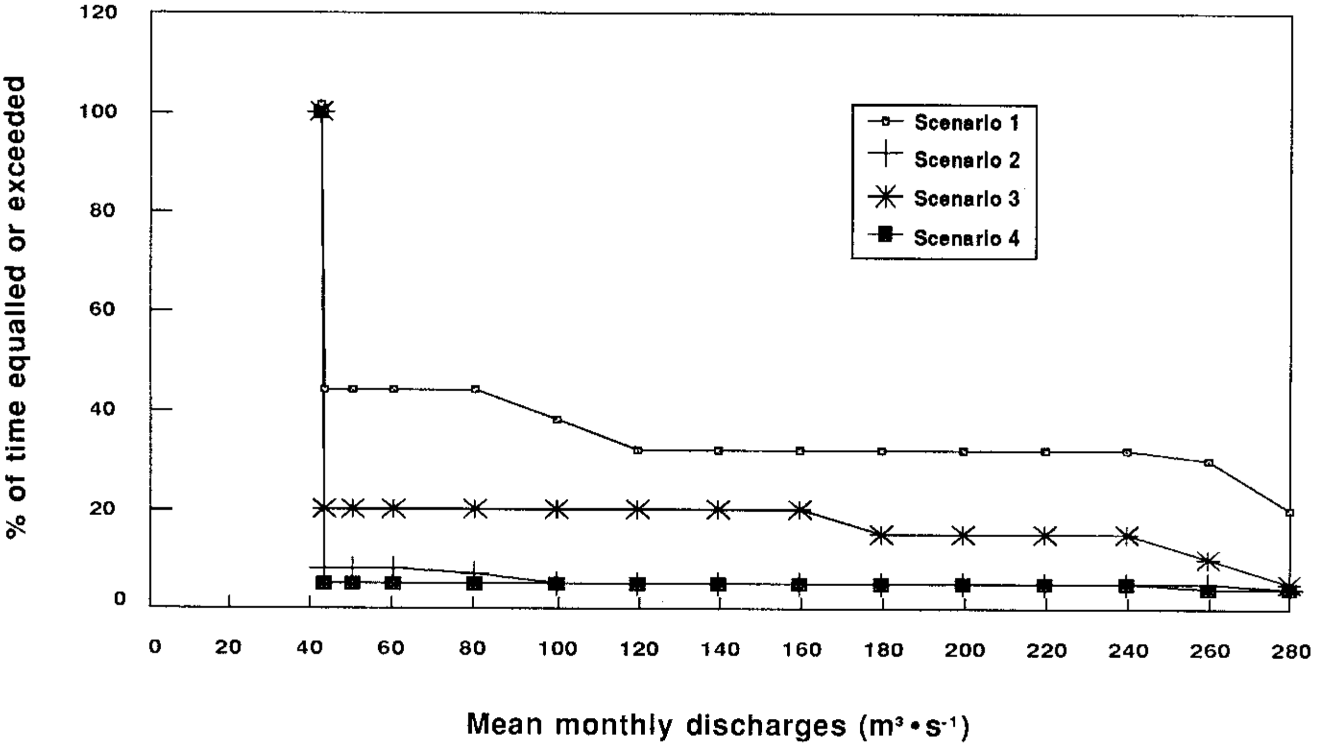

Figure 22. Lake Diefenbaker June mean monthly discharges.

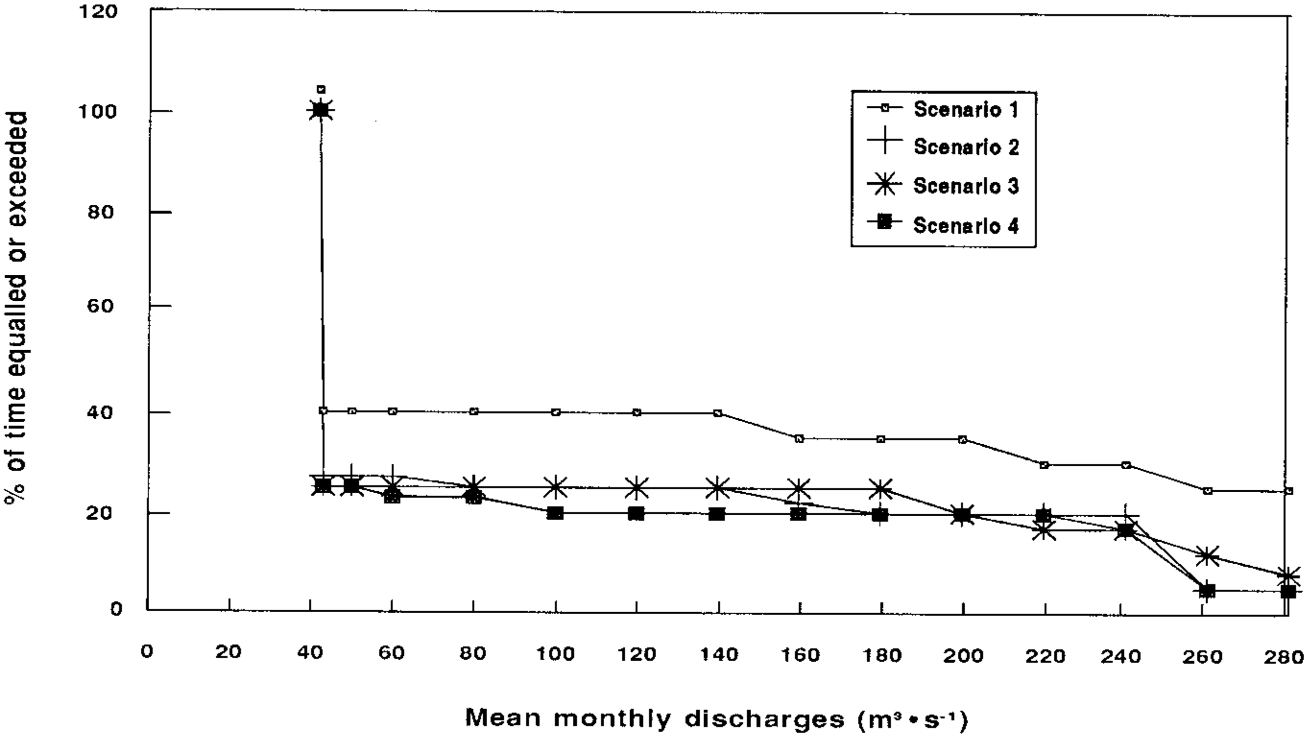

Figure 23. Lake Diefenbaker July mean monthly discharges.

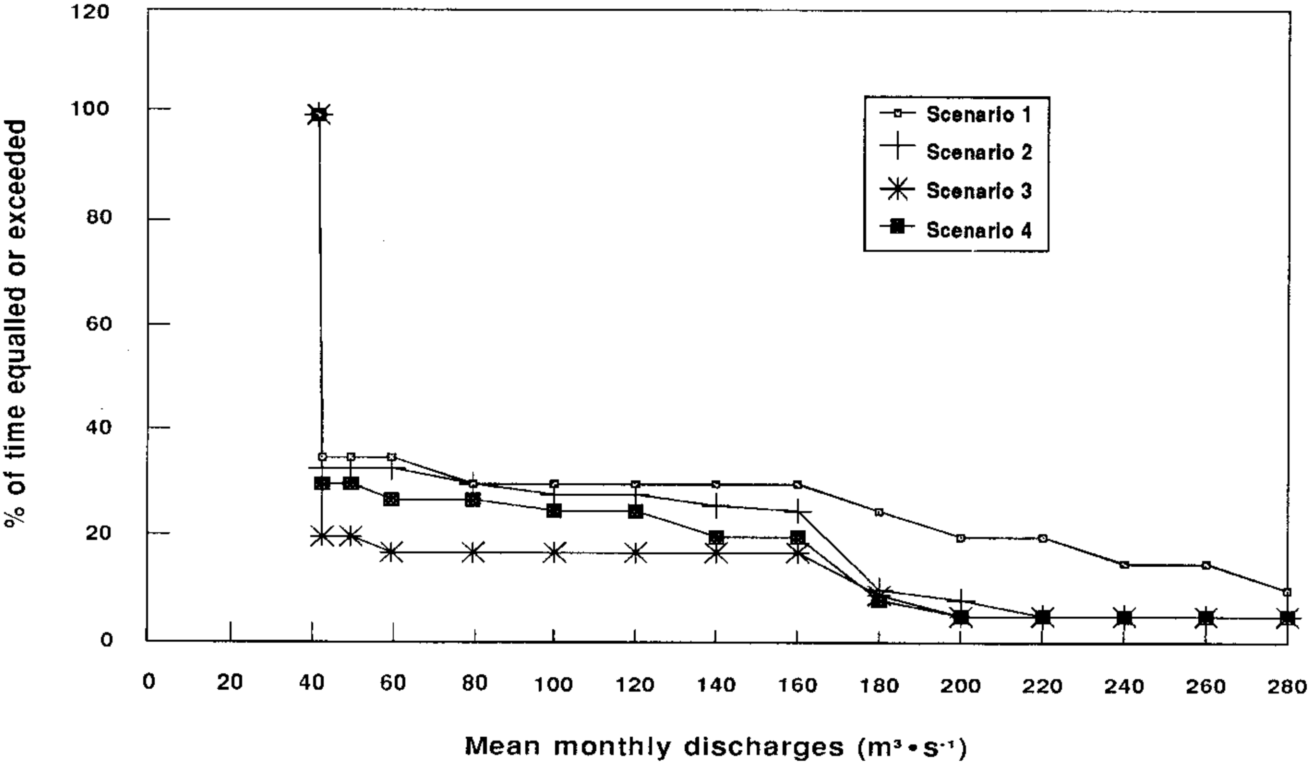

Figure 24. Lake Diefenbaker August mean monthly discharges.

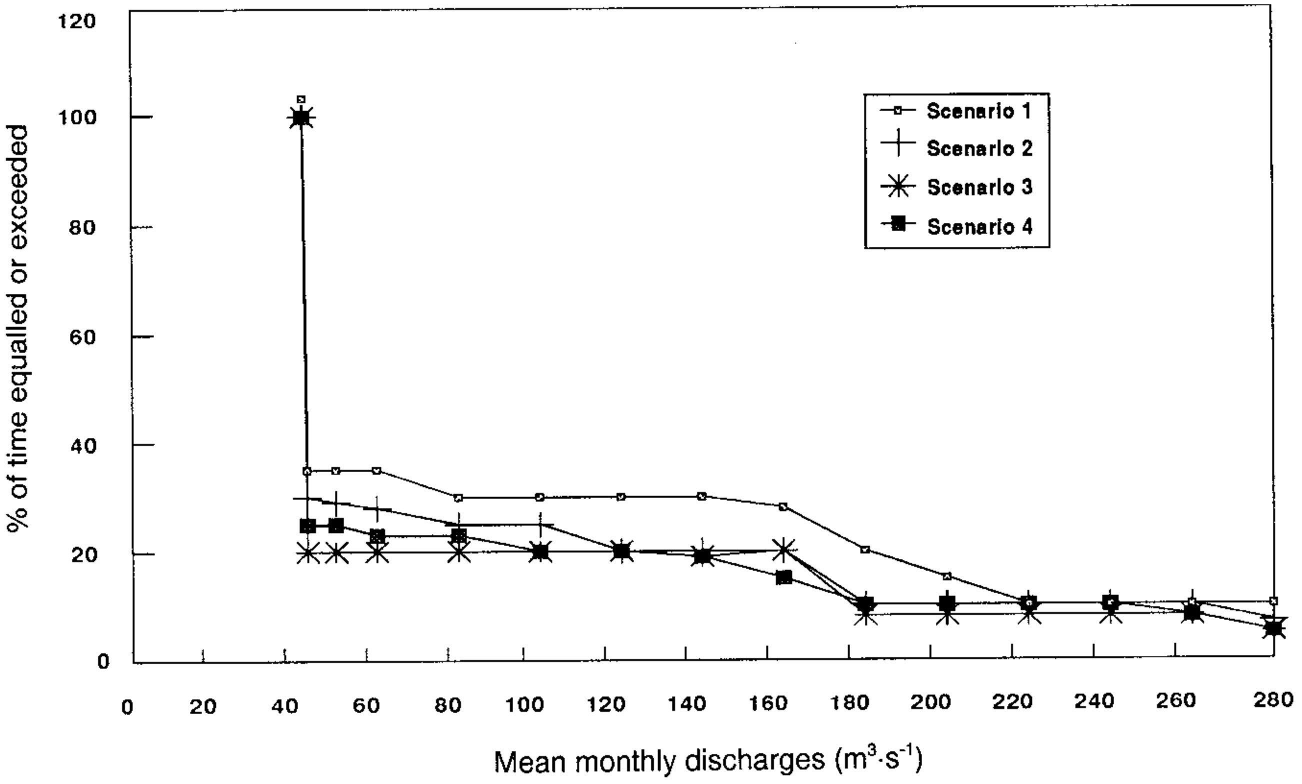

Figure 25. Lake Diefenbaker September mean monthly discharges.

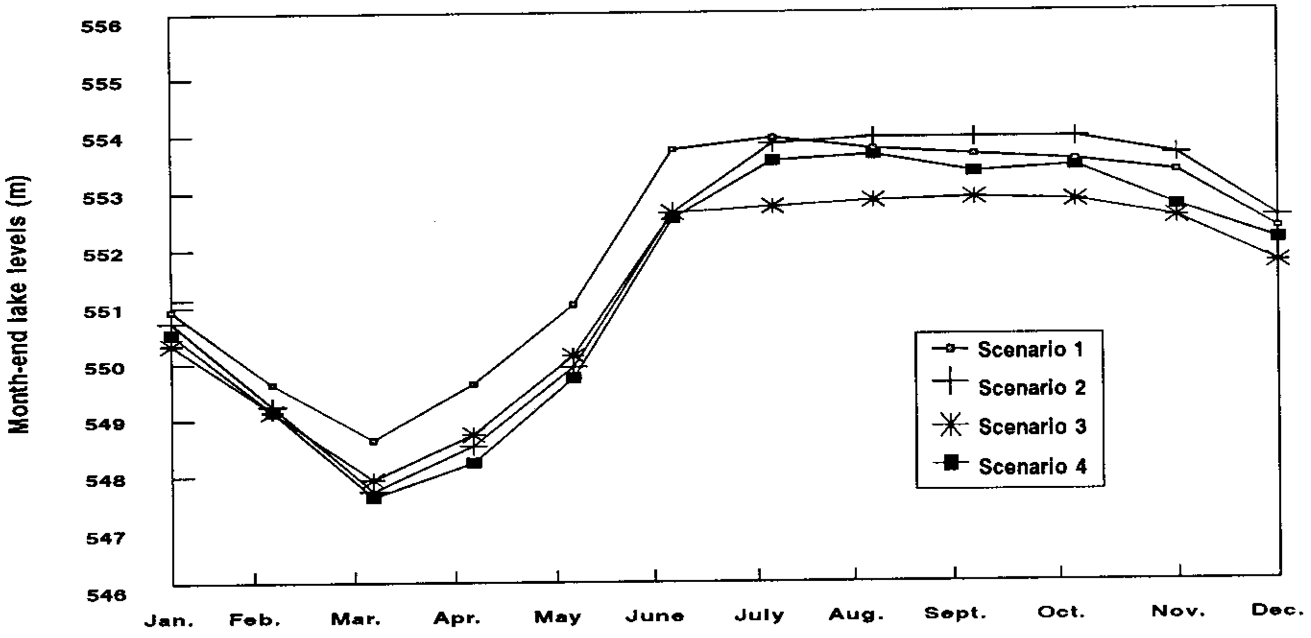

Figure 26. Lake Diefenbaker mean month–end levels.

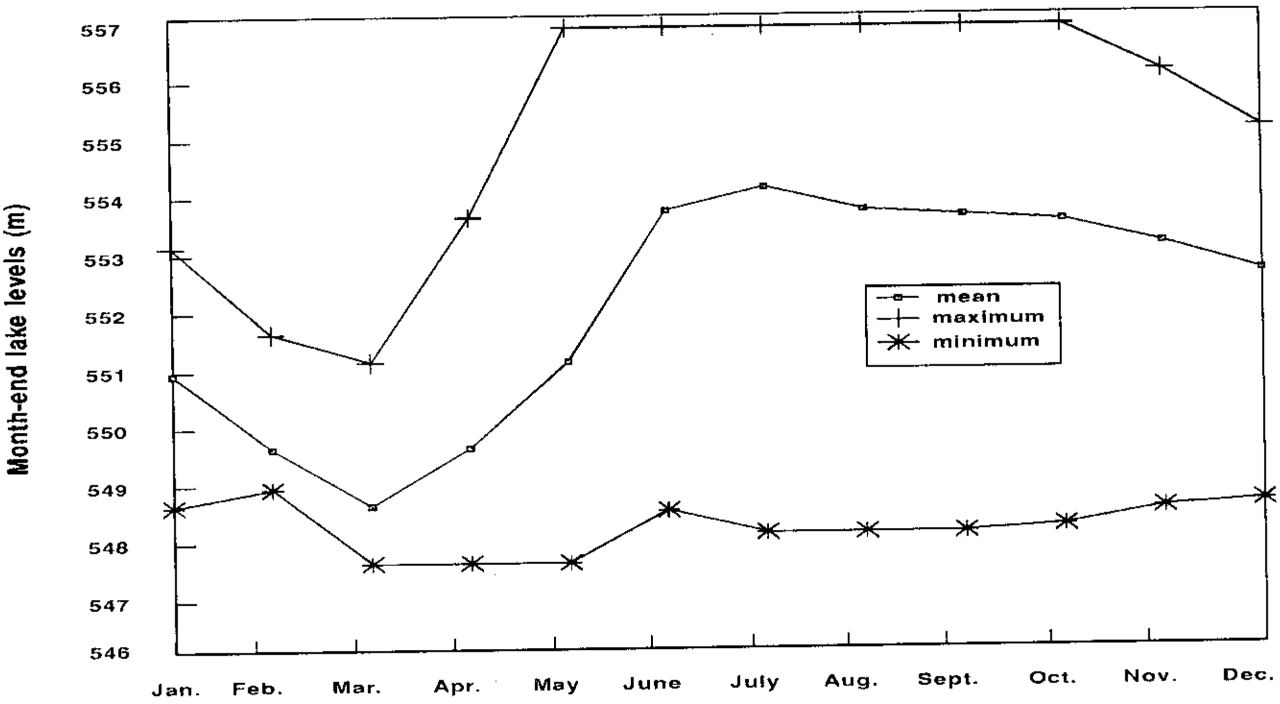

Figure 27. Lake Diefenbaker month-end levels for scenario 1.

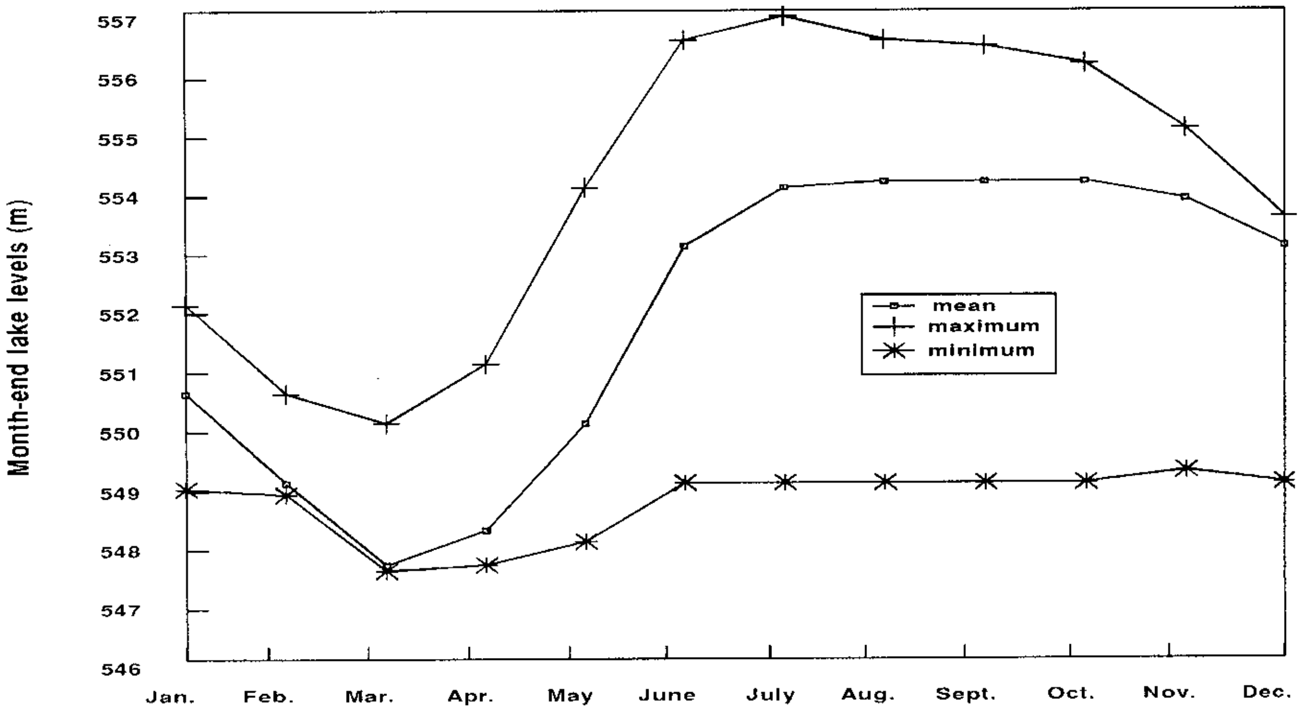

Figure 28. Lake Diefenbaker month-end levels for scenario 2.

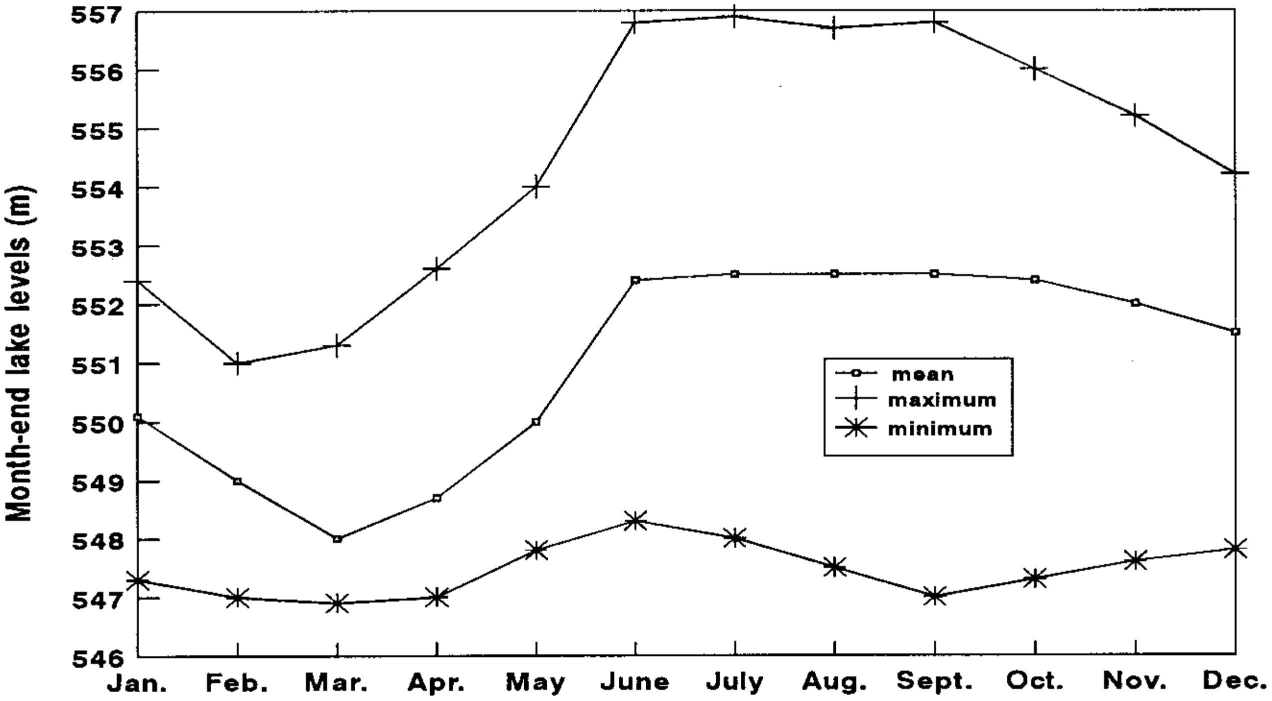

Figure 29. Lake Diefenbaker month–end levels for scenario 3.

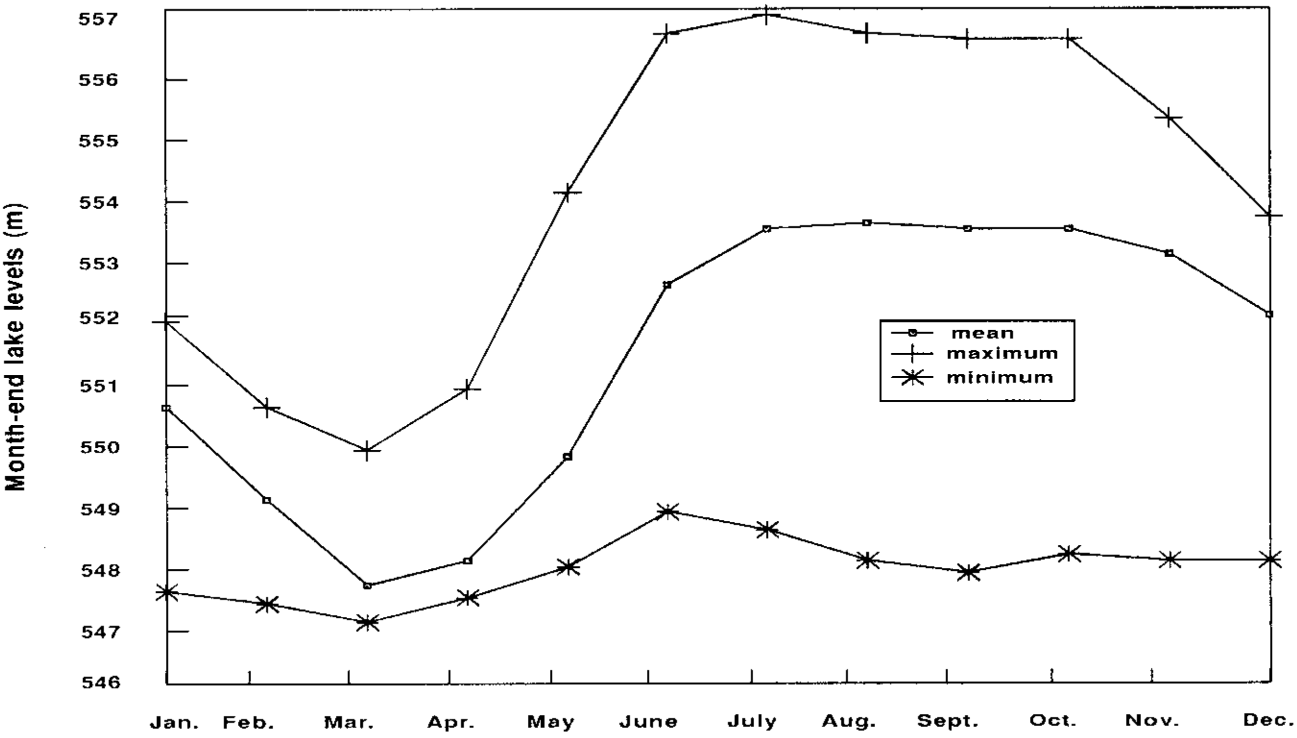

Figure 30. Lake Diefenbaker month–end levels for scenario 4.

The rule curve and operating constraints data for Lake Diefenbaker used in the analysis were derived from a number of sources because of the lack of official data. The same sets of growth rates for the municipal, industrial, and livestock categories were applied for all scenarios. Simulations for present conditions were not carried out because of lack of the corresponding streamflow data at the boundary node.

The simulations covered four nodes within the South Saskatchewan River basin already contained in WUAM's current database and the boundary node at the Alberta–Saskatchewan border. With most of the data already in place, the effort required to carry out the simulations was minimal, involving mainly the selection of scenarios and the actual computer runs.

The following results of WUAM simulations were presented:

(1) Withdrawal water uses (intake and consumption) by sector: industrial, urban-municipal, rural-domestic, livestock watering, and average irrigation.

(2) Irrigation water use by irrigation area, node, and basin total under average, dry, and wet conditions, as well as in terms of a frequency diagram.

(3) Lake Diefenbaker

  (a) consumptive water uses (irrigation, evaporation, and Qu'Appelle diversion) for the average, extreme dry, and extreme wet years, as well as in terms of a frequency diagram

  (b) statistical summaries of lake levels and discharges

  (c) frequency diagrams of lake levels and discharges for selected months

  (d) month-end lake levels: mean, maximum, and minimum.

The main observations from the study are as follows:

(1) Irrigation is by far the dominant water use in the basin for the two sets of scenarios simulated (not counting the Qu'Appelle diversion and evaporation from Lake Diefenbaker), accounting for 90% and 94% of total intake (94% and 97% of consumption).

(2) The average irrigation water use in the basin for the two sets of scenarios is 420 MCM and 790 MCM (approximately 5.5 $dam^3 \cdot ha^{-1}$), out of which 313 MCM (75%) and 665 MCM (85%), respectively, are taken directly from Lake Diefenbaker.

(3) The use of average irrigation, as is customary in many river basin planning studies, is not appropriate. The analysis shows that (a) considering only the variations in precipitation, irrigation water use could vary between 3.4 and 7.6 $dam^3 \cdot ha^{-1}$ (to maintain the same irrigation level of 60%); and (b) the average irrigation water use of 5.5 $dam^3 \cdot ha^{-1}$ will be exceeded about 60% of the time. Systems analyzed according to the average conditions could result in misleading conclusions. This problem does not appear in WUAM, which utilizes a historical period of climatic record and produces information on system reliability and risk of failure.

(4) The average combined irrigation and evaporation water uses from the lake are estimated to be 525 MCM and 880 MCM for the base case and high irrigation scenarios, respectively. The actual range, however, is 263–670 MCM for the base case and 480–1150 MCM for the high scenarios. The average use will be exceeded about 60% of the time.

(5) The lake levels required for recreational uses (i.e., 555.3 m) will be satisfied between 21% and 39% of the time, depending on the scenario.

(6) The simulations also show that the minimum flows required for instream uses below the Gardiner dam (i.e., 42.5 $m^3 \cdot s^{-1}$) will always be satisfied.

The results of the simulations concerning Lake Diefenbaker were mostly dictated by the assumptions undertaken, in particular, the reservoir operation rules and constraints, and should be viewed accordingly. It is interesting, however, to note that, despite differences in the development scenarios, the overall conclusions of the present study regarding Lake Diefenbaker were similar to those obtained by the Canada–Saskatchewan South Saskatchewan River Basin Study (Environment Canada–SaskWater 1991), with both showing lake levels that are considerably below the levels required for recreational use.

This report presented only one application of WUAM in river basin planning, and the analyses were by no means a complete coverage of the model's capabilities. For instance, the full capabilities of the model with regard to water use analysis were not utilized, except for the irrigation component, and then only partially. The irrigation submodel has considerable flexibility, which allows the variations of practically all parameters affecting irrigation water use, either singly or in combination, such as changes in cropping pattern, improvements in irrigation efficiencies, impacts of changes in irrigation levels, impacts of changing climate, etc.

The model has also been applied to several other river basins in Canada:

- Saint-François River basin, Québec (Paquin 1990)
- Yamaska River basin, Québec (Harris 1990)
- Similkameen River basin, British Columbia (McNeill 1991)
- L'Assomption River basin, Québec (Doneys and Dubois 1991a)
- Saint-Maurice River basin, Québec (Doneys and Dubois 1991b)

Other potential applications of WUAM include the following:

(1) Water supply constraints to economic development. The ability to project water use from a multisectoral viewpoint makes WUAM suitable for investigations of water availability/constraints for practically any kind of economic development.

(2) Water conservation studies. Considerable emphasis is now being placed on water demand management as a new direction for managing water resources by the various levels of government. WUAM provides an excellent tool for studying the impacts of various water conservation measures on the future demands on water such as water pricing, metering, and recycling, as well as other measures.

(3) Climatic change impact. A major area for the potential application of WUAM is climatic change impacts on future water use and supply–use balance. Significant research is being carried out worldwide on the theory of global warming and its probable impacts on precipitation, evapo-ration, evapotranspiration, etc. WUAM is uniquely suited for combining the results of such studies and translating them into impacts on water use and water balance.

(4) Interjurisdictional basin studies. WUAM's ability to consider flow apportionment at interjurisdictional boundaries makes it suitable for international and inter-provincial river basin studies. It can be used to quantify the impacts of develop-ments or growth in various sectors on international and interprovincial water apportionment agreements.

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APPENDIX A

Overview of the Water Use Analysis Model (WUAM)

A.1 OVERVIEW

A conceptual overview of the Water Use Analysis Model (WUAM) is presented in Figure A-1. Basically, the model has three principal components: water use, water supply, and water balance. Table A-1 provides a brief description of each component and lists the primary data requirements.

Water use projection is the primary focus and major component of the model. Water uses include withdrawal (or consumptive) water uses and nonwithdrawal (or instream) water uses. Withdrawal water uses are determined within five main categories: urban-municipal, industrial, irrigation, livestock, and power generation. An additional category of water use, termed *special development*, is also included in the model. It was originally intended to simulate water uses in major energy projects, however, it can also be used to account for water uses that are not covered within the five main categories. Nonwithdrawal water uses, such as recreation, waste dilution, etc., are dealt with as constraints on streamflow based on minimum flow requirements.

The second major section of the model concerns water supplies, which are simulated based on time series of natural streamflow[1] data at selected points within the drainage basin. Only ad hoc procedures are used for groundwater supplies. A reservoir simulation subcomponent, which is operated in conjunction with water uses, simulates the regulation effects on water availability and allows the examination of the operating policies of a particular reservoir in a regional water use context. It also allows the reservoir to act dynamically within a network to alleviate water shortages when possible.

The third component of the model is an algorithm that compares the projected water uses against available supplies. This comparison is performed over an extended period of (historical) hydrologic record. The model produces, among numerous other details, statistics about the severity and frequency of water shortages, if any.

WUAM also allows the consideration of several water management issues, including

- the impacts of water pricing on water demands
- water diversions and off-stream storage
- interjurisdictional flow apportionments
- analysis of water rationing and consumptive use cutback when available supplies are exceeded

A.2 CONCEPT

All calculations in the model are carried out at the river basin or subbasin level using monthly time intervals. For the purpose of the model, a basin can refer to any area being studied. A basin can, in turn, be further sub-divided into a number of subbasins. The only constraint on the delineation of subbasins is that a streamflow measurement point must be located at or near the subbasin outlet. For this reason, the subbasin is generally defined as the drainage area above a certain hydrologic gauge. Using operational research terminol-ogy, the basin is called the *network* and the subbasins or gauges are *nodes* in the network.

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[1] "Natural streamflow" refers to streamflow in its natural state, i.e., without any regulation or water withdrawal/consumption.

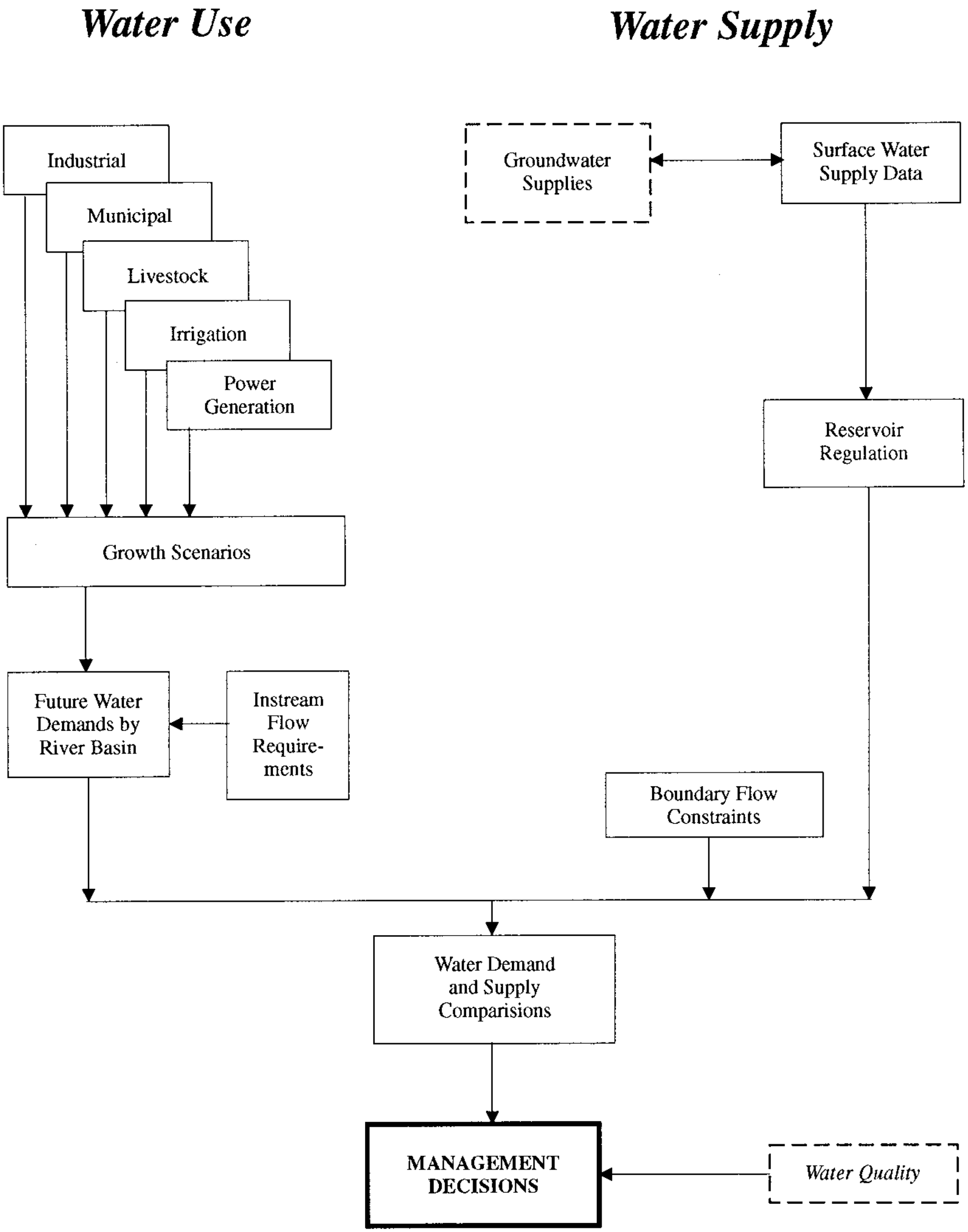

Figure A-1. Conceptual overview of the Water Use Analysis Model (WUAM).

Table A-1. Principal Components of the Water Use Analysis Model

Component	Purpose/description	Major data set
WATER USE		
Urban-municipal	- projection of urban-municipal water uses by subbasin - uses population and water price as major variables - can be disaggregated, e.g., residential, commercial, public, etc.	- base year population by river basin - water use rates by use category - population growth scenario data - future water use rates - pricing data
Rural-domestic	- projection of rural-domestic water uses by subbasin	- rural-domestic population by river basin - rural-domestic water use rates - rural-domestic population growth scenarios
Industrial	- projection of industrial water uses by subbasin and two, three-, and four-digit Standard Industrial Classification Code - takes into account production level, water use practices, industry distribution, and water prices - employs input-output techniques for growth and technological change analysis	- base year water use data by industrial sector and subbasin - economic growth scenarios - water demand curves by industrial sector - input-output tables at provincial level
Thermal energy	- calculates monthly water use for each thermal power plant simulated	- monthly energy generations for a range of hydrologic conditions at each plant - water intake and consumption coefficients for each plant OR plant characteristics; fuel type, cooling type, condenser type
Hydroelectric	- estimates hydroelectric energy generation from simulated flows at the plants	- gross operating head and efficiency at each plant
Irrigation	- simulates irrigation water use by irrigation district/area - uses historical climatic data (precipitation and evapotranspiration) - calculates irrigation diversions and return flows - irrigation areas tied to WUAM network based on their spatial distribution	- irrigated area - location within network of supply nodes and return flow nodes - historical precipitation data - historical evapotranspiration data - crop data/parameters - soil data/parameters - operating parameters
Livestock	- projection of livestock water use by animal type and subbasin	- animal population by type and subbasin - water use coefficients by animal type - animal population growth scenarios
Evaporation	- from reservoirs - based on reservoir surface area and historical evaporation rates	- calculated by reservoir simulation submodel

Table A-1. (Cont'd)

Component	Purpose/description	Majoe data set
Instream	- compares simulated flows against minimum flows required for instream water uses - calculates the frequency of violations of instream flow requirements and the severity of the problem	- minimum monthly flows required to satisfy instream water uses
WATER SUPPLY		
Surface water	- natural streamflow conditions	- historical, monthly natural streamflow records at each node
Groundwater	- adjusts water use data to remove activities supplied from groundwater - assumes same proportion (of groundwater to total uses) applies in future years - does not account for interconnection between surface water and groundwater sources	- groundwater usage data by use type
Reservoir simulation	- traces reservoir levels and releases - calculates evaporative loss based on surface area	- reservoir rule curves and operating constraints - stage-storage-surface area
OTHER FEATURES		
Off-stream storage	- adjusts intake requirements due to off-stream storage	- monthly storage volume (%)
Water pricing	- allows the investigation of the impacts of water price changes on water demands in the urban-municipal and industrial sectors	- water demand curves (quantity of water uses versus price) - price elasticity
Diversions	- incorporates effects of inter- or intra-basin water transfers	- diversion monthly flows provided by user
Interjurisdictional apportionment	- examines effects of administrative arrangements about flow sharing between jurisdictions	- minimum monthly flows provided by user
Use priorities, rationing, and cutbacks	- enables analysis of recommended water rationing in the event of water shortages	- use priorities based on provincial practices

To illustrate the operation of the model, reference is made to Figure A-2, which shows the Saskatchewan River basin in western Canada. The first step in applying WUAM is the selection of study points. These are the points where water use projections and water balance results will be obtained. Key points should be represented, such as interjuris-dictional boundaries, reservoirs (current or future), and locations where water diversions or significant water use developments exist or are proposed.

From the point of view of the model, the basin (Fig. A-2) is translated into a network (Fig. A-3). The network is represented by

- nodes, representing the subbasins
- links, denoting the flow path between nodes
- irrigation areas

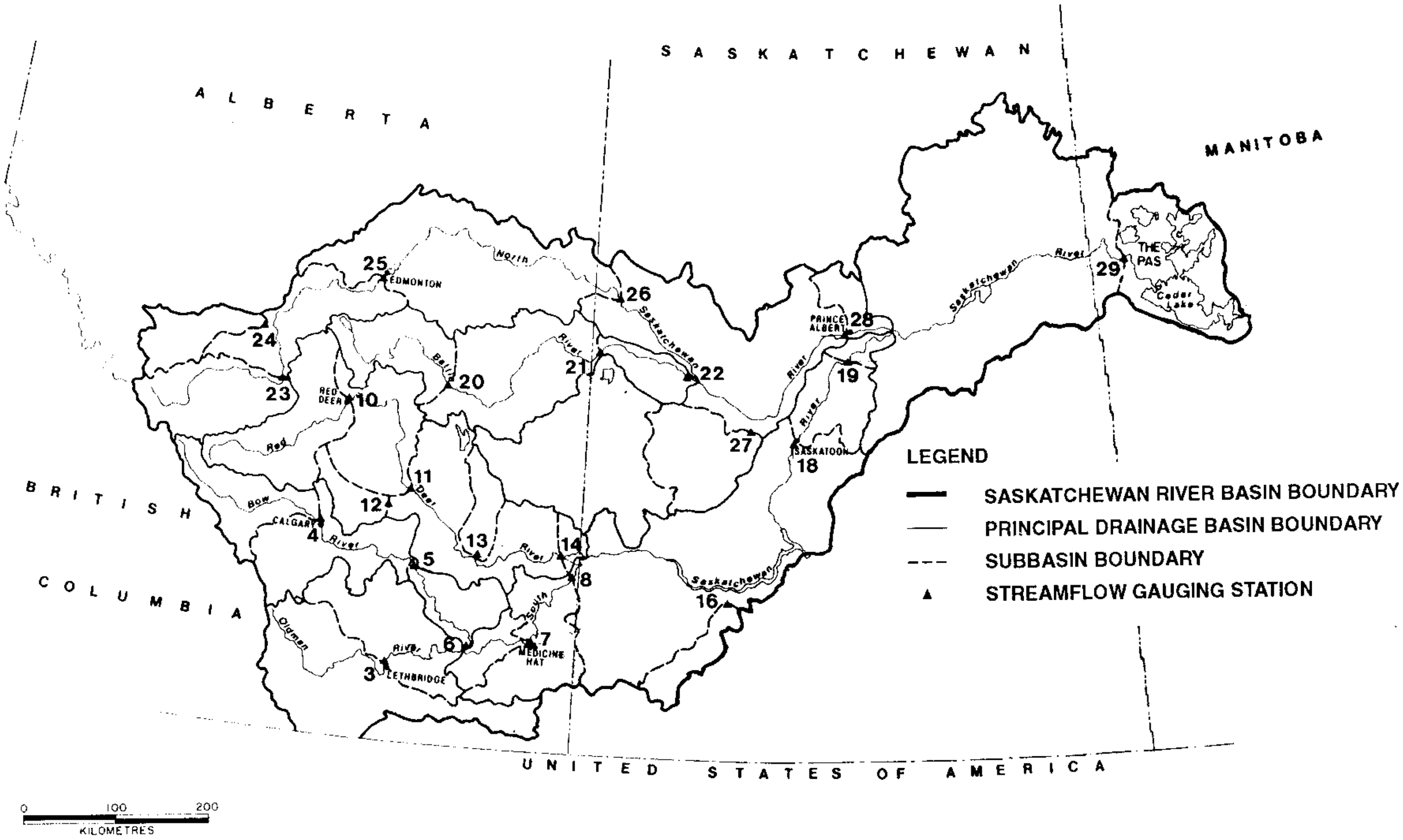

Figure A-2. Subbasins and gauging stations in the Saskatchewan River basin.

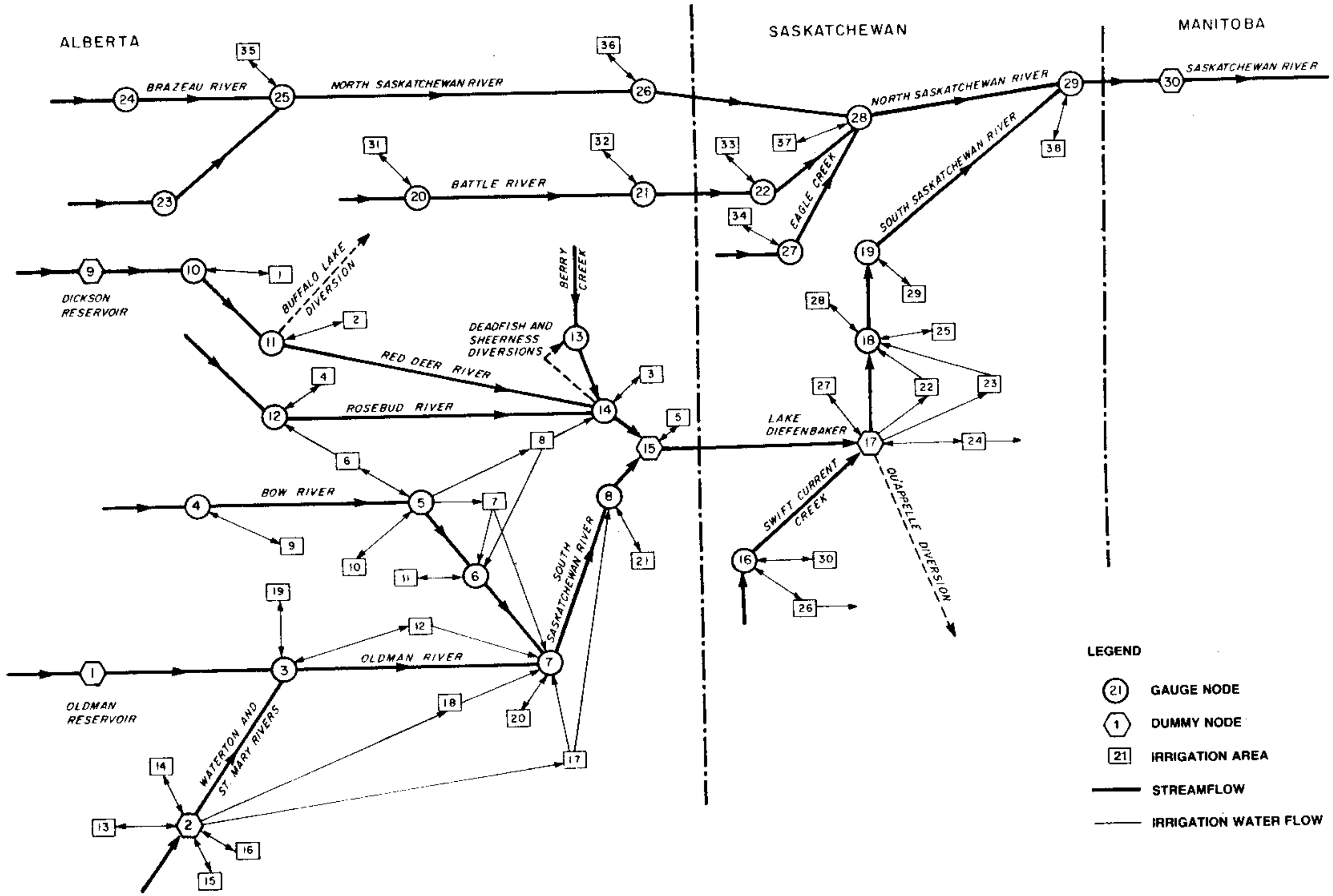

Figure A-3. WUAM flow network for the Saskatchewan River basin.

Irrigation areas are defined independent of subbasins because they are seldom confined to one subbasin. These irrigation areas are linked to the network by defining the supply nodes and return flow nodes. Dummy nodes can be introduced into the network to serve specific purposes, such as the representation of reservoirs, water diversions, interjurisdictional boundaries, etc.

A.3 CALCULATION PROCEDURES

In setting up the model, the user specifies the hierarchical relationship of the subbasins and the irrigation areas within them in the re-gion under study. The network must be den-dritic and converging towards the downstream. Initially, water use projections for each node are made (see following section) based upon the user's assumptions about the future. The model performs water balance calculations starting at the upstream nodes and proceeding down-stream in a cascading manner. The entire network for a study area is dealt with for a given time horizon before moving on to the next time period. Two main water use parameters are calculated. The first is water intake, which is the amount of water with-drawn for a particular use, a portion of which is returned to the source. The second parameter is water consumption, which is the difference between water intake and return flow.

The calculation details at each node are illustrated in Figure A-4. At each node, the projected water uses are compared to available supplies. Any surplus water is passed to the next downstream node. When water supplies are found to be insufficient to meet the projected demands at any particular node, the model will first attempt to eliminate the deficit by releasing additional water from upstream reservoirs if allowed by the reservoir operational rules. Otherwise, water rationing and consumptive use cutbacks are recommended, based on a user-specified priority system of water allocations.

To account for instream water uses, the user specifies the minimum required monthly flows to satisfy these uses. This information can be supplied at any network node. The model calculates the net outflow from a subbasin as the difference between the available supply and the total consumptive uses within the subbasin. This outflow is then compared to the user-defined

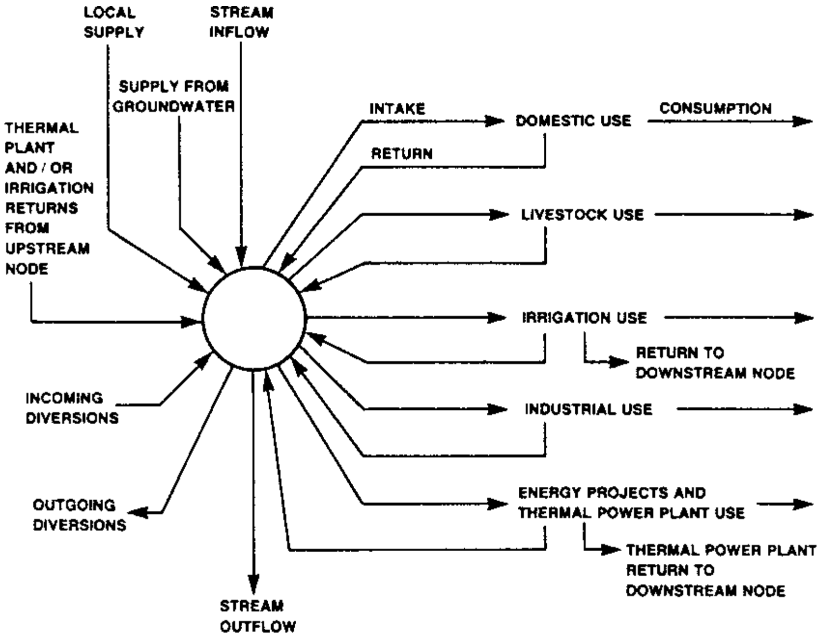

Figure A-4. Calculation detail at each node.

minimum flows. Any violations are thus reported, indicating the severity and frequency of occurrence.

Minimum flow requirements at interjurisdictional nodes are assigned first priority in WUAM in terms of water allocation. When these minimum flows are violated, water use cutbacks in the upstream jurisdiction are indicated, unless reservoirs in the upstream jurisdiction could be drawn down to eliminate the deficit. Water use cutbacks in this case, if required, occur in a prespecified manner among all water uses and are assumed to be evenly distributed among all upstream nodes.

A.4 WATER USE MODELLING

In general, water use projections employ "activity level" forecasts (such as population or economic output), water pricing, technological conditions, water use practices, and natural and climatic conditions (e.g., precipitation and evapotranspiration). With the exception of the irrigation sector, water use is projected based on coefficients of water use per unit of activity level and future activity (e.g., future population). A series of modifying factors lets the user augment the "coefficient-based" forecasts to allow for changes in technology, water use practice trends, and policy assumptions regarding water pricing.

A.4.1 Urban-Municipal and Rural-Domestic Water Uses

Urban-municipal and rural-domestic water uses are projected based on population levels and water intake coefficients expressed in litres per capita per day. Consumption is expressed as a percentage of intake. Within each of these two categories, further subdivision of water use is possible (e.g., residential, commercial, institutional, etc.). The model may default to provincial average coefficients included in its core database if subbasin-specific data are unavailable. The industrial portion of the urban-municipal water uses may also be included here, or it can be simulated within the industrial water use component of WUAM.

A.4.2 Industrial Water Uses

Industrial water uses are categorized into 30 basic industrial sectors[2]. These basic sectors can be further subdivided to include industrial subsectors. Industrial water uses are assumed to be a function of activity level of each industry in the study area. These uses are measured by the economic output and the associated water use coefficients per unit of activity. Future activity levels in each industrial sector can be derived based on general (regional or provincial) growth factors. The growth factors used in this approach can, however, be modified to allow for differential industrial growth among subbasins and changes in water use practices such as increasing recirculation.

WUAM also employs national and provincial input–output matrices to allow the analyst to cascade a user-generated industrial growth forecast through the national and provincial economies to examine inter-industry growth impacts. (Details on the input–output techniques can be found in Miernyk [1966] and Tate [1986].)

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[2] The industrial sectors are agriculture, forestry, *metal mines, *mineral fuels, *nonmetal mines, *food and beverages, tobacco, *rubber and plastics, leather, *textiles, *wood, furniture, *paper, printing, *primary metals—iron, primary metals—other, *metal fabricating, machinery, *transportation equipment, electrical products, *nonmetal minerals, *petroleum and coal, *chemicals, miscellaneous manufacturing, construction, transportation, *electric power, other utilities, trade, and other. (An asterisk indicates that the industry has been surveyed and water use data collected.)

Although the agricultural sector is included in the list, all calculations for agricultural water uses are carried out separately in the submodels for the irrigation and livestock sectors. The purpose of including agriculture in the list is to ensure that any economic growth in agriculture is reflected in the growth of the other sectors by routing the growth through the input–output matrices.

The electric power sector is also handled separately in the electric energy water use submodel. It is included in the list for the same reason that the agriculture sector was included.

A.4.3 Power Generation

WUAM contains a separate submodel dealing exclusively with power generation water uses. The Electric Energy Water Use Submodel (EEWUS) is divided into two modules, one dealing with thermal energy and the other dealing with hydroelectric energy.

The steam–thermal power plant water uses are calculated for each plant given the monthly energy generation at the plant and water intake and consumption coefficients (in million cubic metres per gigawatt hour). To reflect the fact that thermal plants will produce more energy in a dry year than in a wet year (to compensate for lower hydroelecric generation), a range of monthly energy generation must be specified for a variety of hydrologic conditions (e.g., wet, average, and dry). Thermal power plant water use coefficients are calculated based on fuel type, cooling method, and condenser type (Acres International Limited 1987; Kassem 1992, Appendix B).

WUAM does not simulate the demands for hydroelectric power; rather, it estimates the hydroelectric energy generation from the simulated streamflows at the nodes that contain hydropower plants, together with data on gross operating head and efficiency of each plant. If the hydropower plant is located far from a simulated node, a flow factor may be applied to allow for flow adjustment between the node and the hydropower site. The calculated energy output is restricted to the plant's maximum generating capacity.

A.4.4 Agricultural Water Uses

Agricultural water uses are estimated separately for the irrigation and livestock subcategories. For the irrigation portion, WUAM contains a comprehensive irrigation water use submodel. The irrigation submodel estimates monthly water requirements for crops, irrigation diversions, and return flows, giving consideration to crop types and mix, precipitation, crop evapotranspiration, soil properties, and moisture levels, as well as irrigation system type and management practices. Time series of historical precipitation and evapotranspiration data are utilized in the calculation of irrigation water requirements to account for the temporal and spatial variation and to ensure consistency with water supply conditions. The basic calculations are performed in units of millimetres per hectare within the cropping season (defined by the user) and for a historic period of years determined by the precipitation and potential evapotranspiration record. A detailed description of the irrigation submodel is given in Appendix C.

Livestock water uses are estimated based on animal populations and the associated water intake in units of litres per head per day for each livestock type. Consumption is expressed as a percentage of intake.

A.4.5 Special Development

For water uses that are not included in the main categories considered by WUAM, an additional water use sector, special development, is added to the model. The user has to define these special developments and establish a database on the types of activities (e.g., an oil sand project) and their associated water use coefficients (e.g., 0.9 m^3 per barrel of oil sand processed). For this type of project, the user can incorporate into a water use projection the associated volumes of water withdrawal and consumption by specifying the volume of production at the proposed plant.

A.4.6 Instream Water Uses

In many rivers, a minimum flow is required to satisfy instream uses (e.g., recreation, waste dilution, fishing, etc.). WUAM provides the option of specifying this minimum flow at the outlet of any subbasin on a monthly basis. Months in which the minimum flow requirements are violated are flagged in the output, and the severity and frequency of occurrence are documented.

A.5 WATER SUPPLIES

Surface water supplies are simulated based on natural streamflow data at the nodes. A relatively long period of hydrologic record should be used in order to account for the temporal variation in supply. Measured flows must be naturalized by removing the historical effects of regulation and water use. The quantities of water supplied from groundwater sources are considered as additional supplies (see Fig. A-4). WUAM, therefore, requires data on the proportion of the total water use that is supplied from groundwater sources.

A.6 RESERVOIR REGULATION

Reservoirs are assumed to be located at nodes in the WUAM network. The WUAM reservoir regulation submodel is a single reservoir simulation model driven by rule curves and operating constraints. To be consistent with the overall WUAM, the reservoir model uses monthly time intervals.

The reservoir simulation is based on the simple continuity equation:

$$S_i = S_{i-1} + I_i - Q_i - E_i$$

where

S_i = reservoir storage volume at the end of the current period, i
S_{i-1} = reservoir storage volume at the beginning of the time period, i.e., the end of the previous period, $i-1$
I_i = inflow volume during period, i
Q_i = outflow volume during period, i
E_i = net evaporation volume during period, i

Figure A-5 shows an example of a reservoir rule curve and operating constraints. The reservoir rule curve describes the pattern of desired reservoir elevations and flow

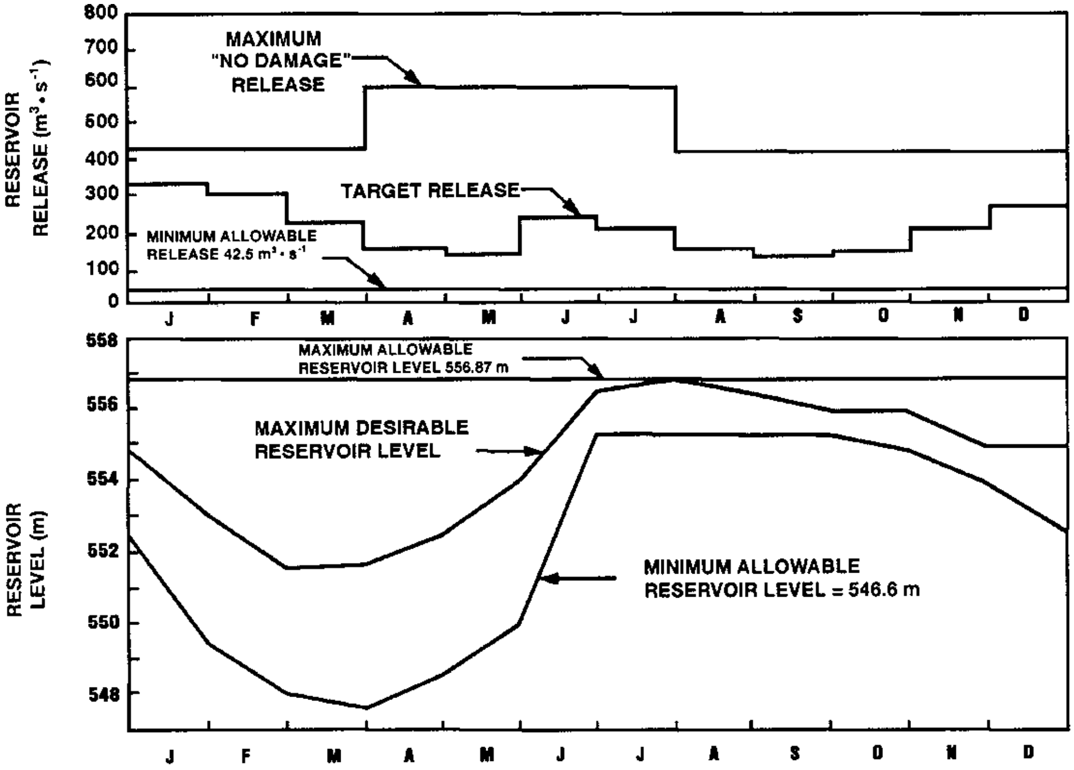

Figure A-5. Reservoir rule curve and operating constraints.

releases. Rule curve information consists of the following monthly data:

- maximum desirable reservoir levels
- minimum desirable reservoir levels
- target flow release
- maximum no-damage reservoir release

The operation pattern dictated by the rule curve is subject to the following constraints imposed by the physical characteristics of the reservoir and other operating regulations:

- maximum allowable reservoir level (i.e., full supply level)
- minimum allowable reservoir level
- minimum monthly riparian flow release
- maximum discharge capability for a given elevation

All targets and constraints are included in a decision hierarchy. The basic strategy is to try to keep the reservoir elevation between the maximum and minimum desirable monthly elevations. When this is satisfied, the target flow is released. The decision hierarchy of WUAM is outlined below, beginning with the highest priority rules.

- Under no circumstances will the reservoir ever be allowed to exceed full supply level. Any excess water will be released to draw the reservoir down to the full supply level.

- Minimum riparian release will always be met. If the reservoir is emptied to the minimum allowable elevation, only the available water above this elevation will be released.

- If the reservoir is below the minimum desirable elevation, the reservoir release will be cut back to allow the reservoir elevation to rise.

- If the reservoir is above the maximum desirable elevation, but below full supply level, the maximum no-damage flow will be released to draw the reservoir down to the maximum desirable reservoir elevation.

- If the reservoir is between the maximum and minimum desirable elevations, all elevations are deemed to be equally attractive, and the target flow will be released.

For each reservoir simulated, a complete set of data describing the physical and operational characteristics of the reservoir must be provided. The overall WUAM performs the simulation on a node-by-node basis starting from the upstream nodes and proceeding downstream in a cascading order. When a reservoir is encountered, the outflow from the node is calculated based on the specified operating rules of the reservoir.

Two feedback paths are built into the model to allow reservoirs to deal with two types of water deficits:

- If a node is experiencing a local consumption deficit, an upstream reservoir in the same jurisdiction, if any, is sought to eliminate this deficit. The reservoir can be drawn to the minimum desirable elevation. If the reservoir cannot eliminate the deficit, a search is made for another upstream reservoir and the same process is repeated.

- If an interjurisdictional minimum flow apportionment is violated at a boundary node, upstream reservoirs are sought to eliminate the violations in exactly the same way as laid out above.

A.7 OTHER FEATURES

A.7.1 Water Pricing

WUAM allows the user to investigate the impacts of water price changes on water demands in both the urban–municipal and the industrial sectors. Basically, the user defines a water demand curve as a table of points. The demand curve represents the relationship between the quantity of water used (litres per capita per day for urban-municipal supplies and million cubic metres [MCM] per dollar output for industries) and the corresponding price. The demand curve is used in conjunction with assumptions about future prices to arrive at the price-adjusted water demands, as illustrated in Figure A-6.

Two additional pricing algorithms, based on regression analysis of industrial water use/cost data collected by Environment Canada (Renzetti 1986, 1987), are also available in WUAM. They are known in the model as the price coefficient method and the price elasticity method and are described by Acres International Limited (1986) and Kassem (1992, Appendix C).

A.7.2 Water Diversions and Off-stream Storage

Water diversions may be either internal between two nodes in the network or external, whereby the watershed under study may gain or lose water through inflows to or outflows from adjacent basins. Diversion flows are specified on a monthly basis to allow for seasonal variation. Off-stream storage effects can be allowed for in the case of irrigation areas, special developments, and thermal power plants by specifying a redistribution of the corresponding intake requirements.

A.7.3 Apportionment Flows

For interjurisdictional river basins, the minimum flows required to be passed by the upstream jurisdiction to the downstream jurisdiction can be introduced into a WUAM simulation by specifying boundary flow data files.

A.7.4 Water Rationing and Consumptive Use Cutback

There are two types of water shortages that can arise in a WUAM application: consumption shortage, when the consumption demands exceed the available supply at a node, and boundary shortage, when the surplus water at a jurisdictional boundary node is found to be less than that required to be passed by the upstream jurisdiction.

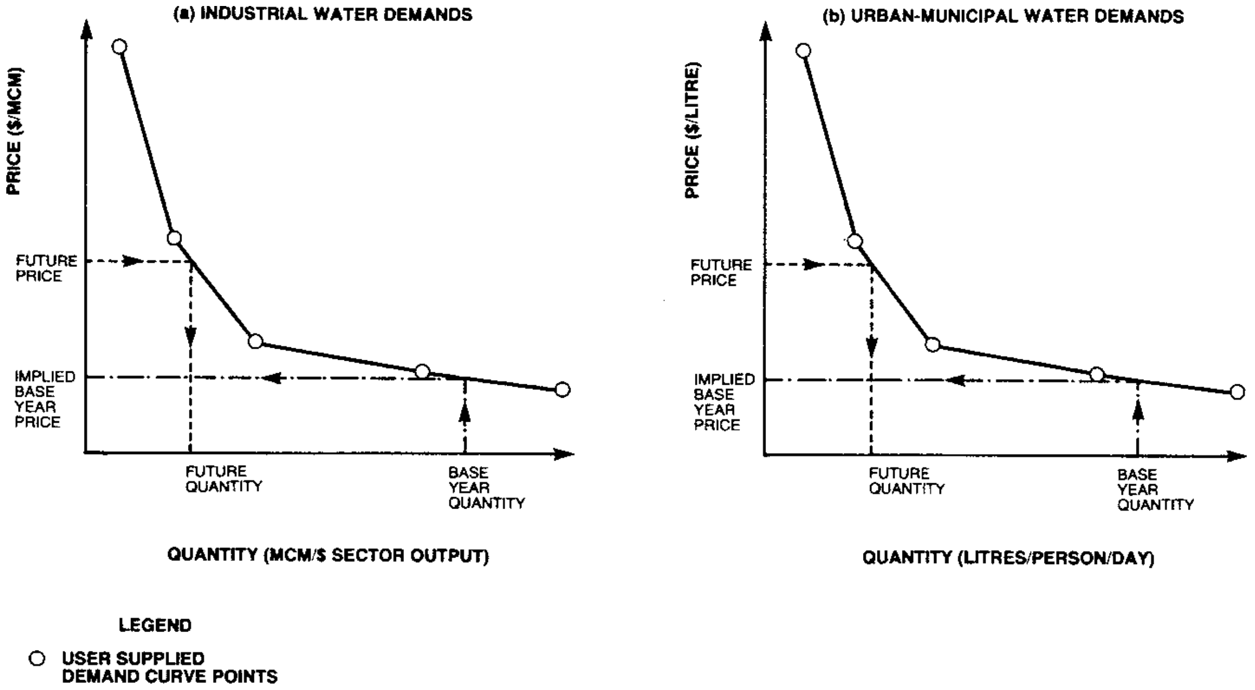

Figure A-6. Water demand curves.

The first type of shortage affects only one node, whereas the second type affects all nodes in the branch upstream from the boundary node where the shortage occurs. In both cases, the model will first attempt to satisfy the deficit by drawing the upstream reservoir(s) down to the reservoir lower rule curve (as discussed above). Otherwise, water rationing and consumptive use cutbacks are imposed. These cutbacks are assumed to occur among all water users according to a prespecified order of priorities. This order is specified by the model user among the urban-municipal, irrigation, livestock, and industrial sectors.

Each use category is given a rank (from 1 to 4, 1 being the first to undergo rationing). In addition to providing a priority ranking of the various consumptive uses, the model user also specifies a number of cutback increments for each category. Only the first increment of the least important use will be cut before the first increment of the next category is cut. If shortage still persists after cutting the first increment in all categories, the cutback proceeds to the second increment and so on.

A.8 OUTPUT

WUAM output is provided in tabular and graphical forms on a monthly, irrigation season, and annual basis and includes the following:

- water use summaries (intake and consumption) for the forecast year by use category (average values for irrigation) for every subbasin in the study area

- detailed water balance results at the network nodes

- summary statistics of water shortages and consumptive use cutback for each node, supplemented with water intake and consumption statistics under minimum, average, and maximum supply conditions

- supplementary print-outs:
  - output files for every irrigation area simulated, tracing the moisture balance, monthly irrigation diversions, and return flows, etc.
  - output depicting the operation of all reservoirs included in the simulation, tracing the reservoir levels and releases, etc.
  - water use requirements of each thermal power plant simulated
  - summary of monthly hydroelectric power generation for each hydroelectric plant simulated

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Appendix B

Natural Streamflow Data and Boundary Flow Data at the Alberta–Saskatchewan Border

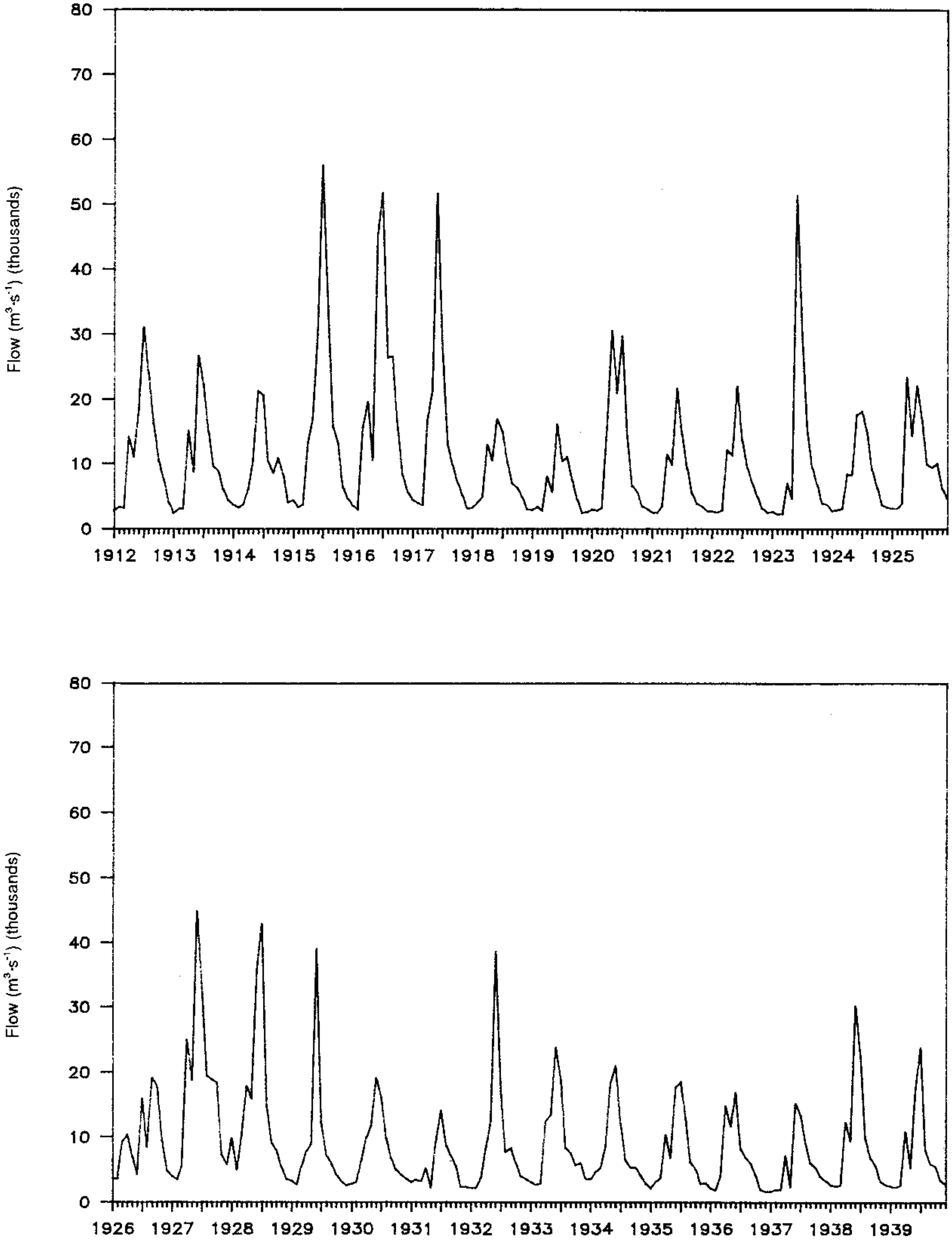
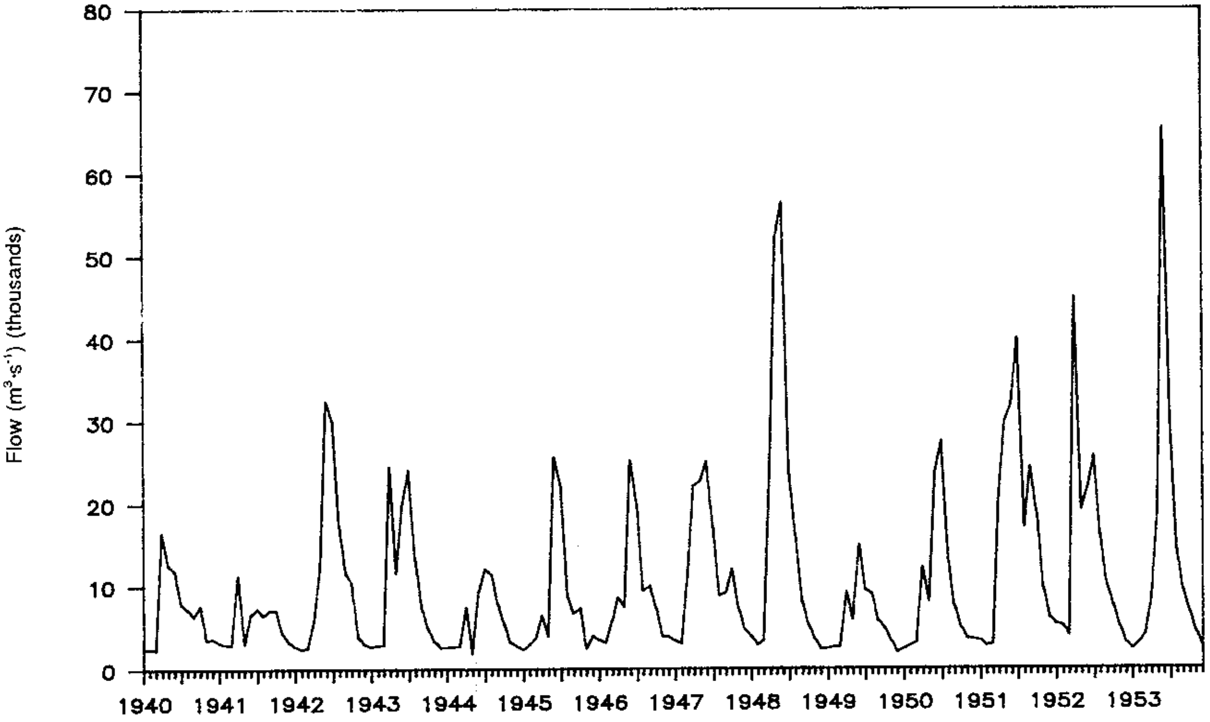


Figure B-1. Natural streamflow, gauge 05HH001, South Saskatchewan River at St. Louis.



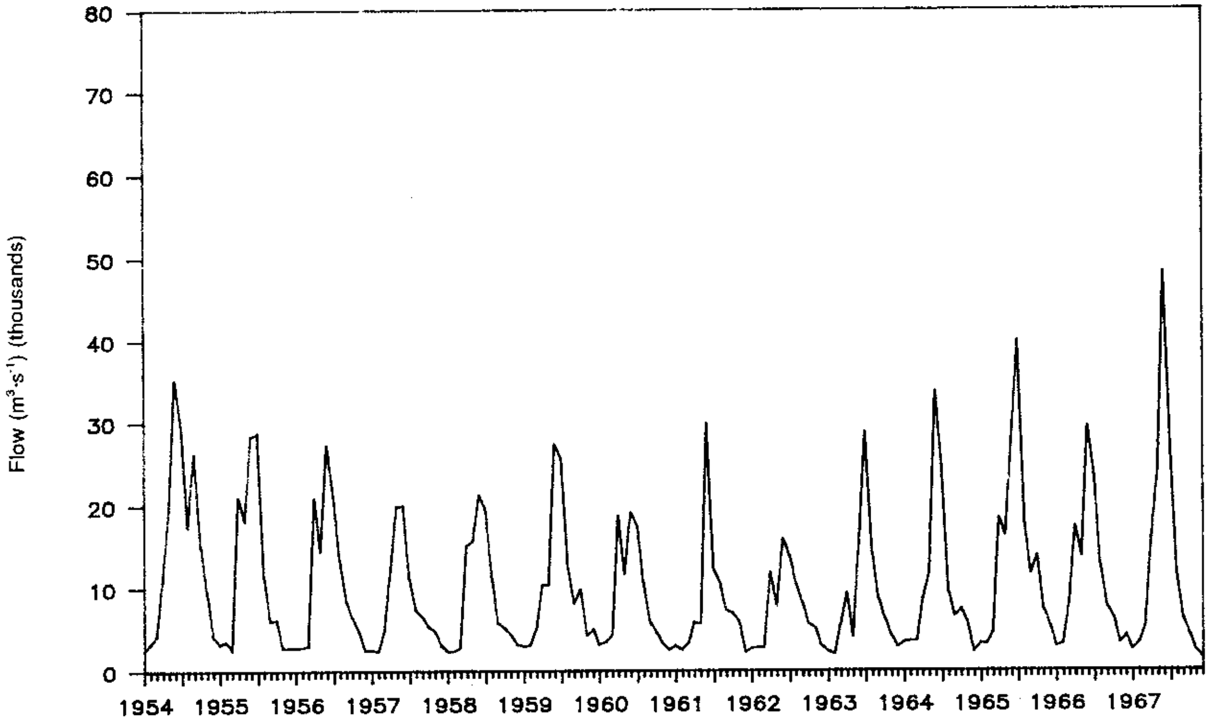


Figure B-1. Continued.

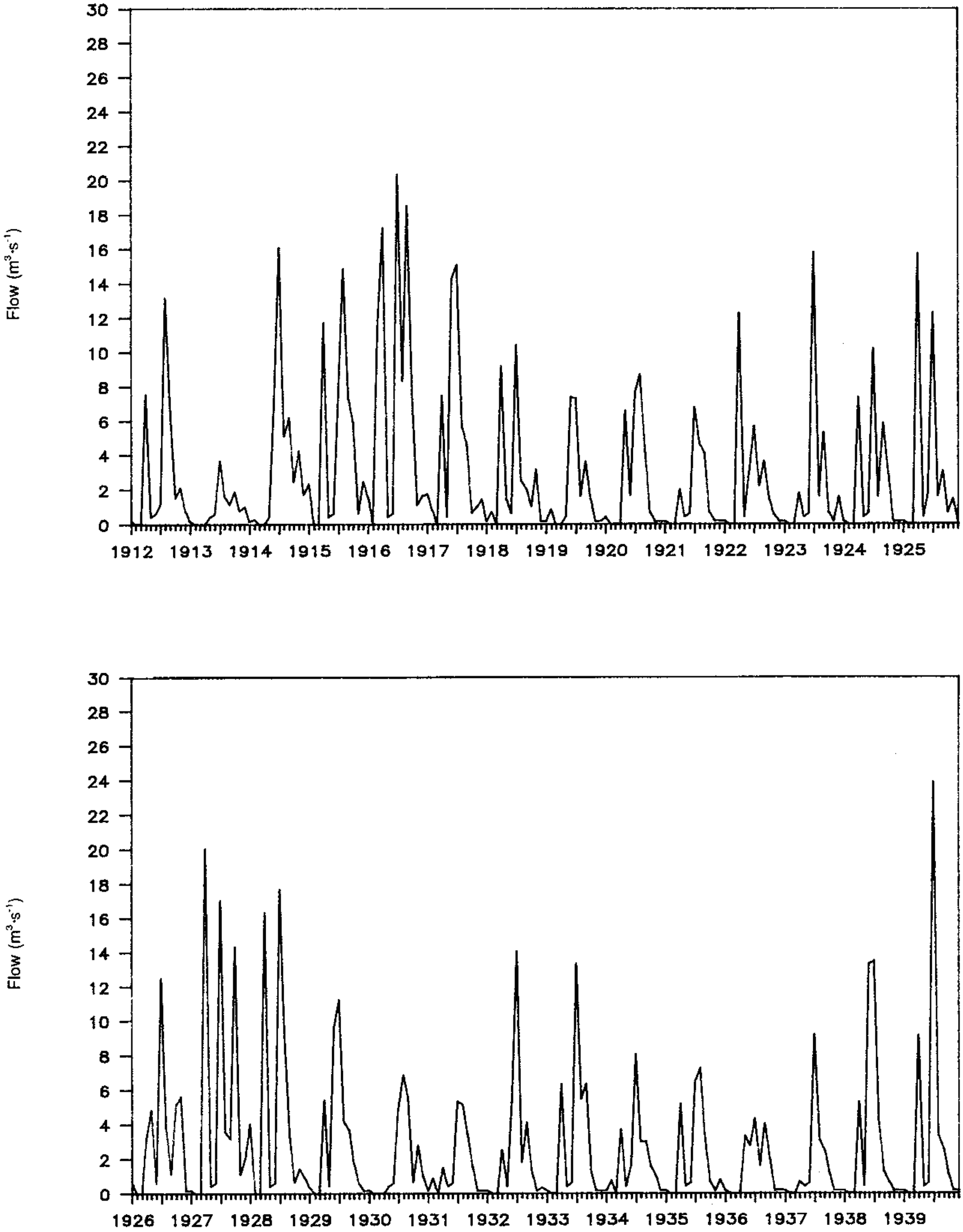


Figure B-2. Natural streamflow, gauge 05HD039, Swift Current Creek at Leinan.

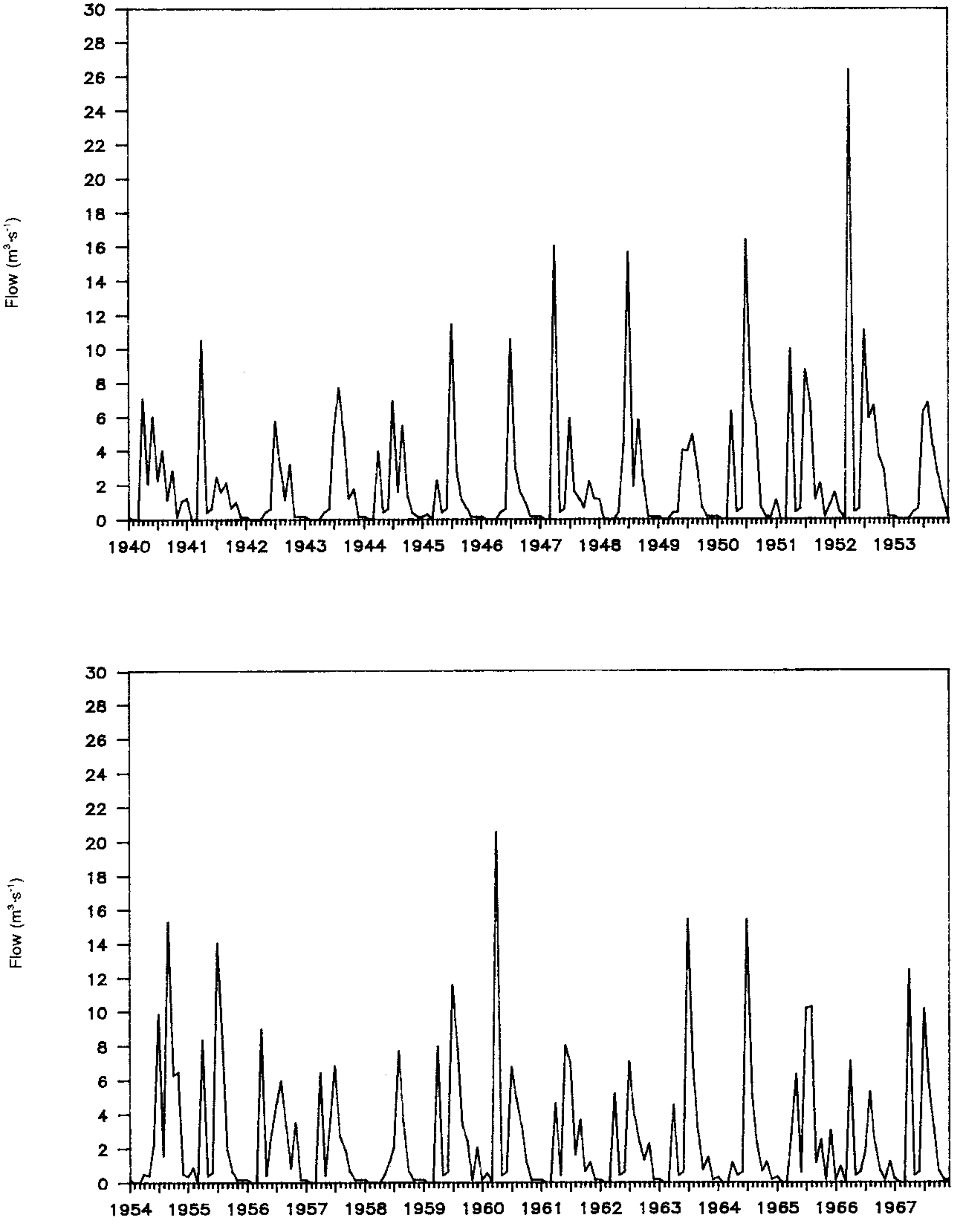
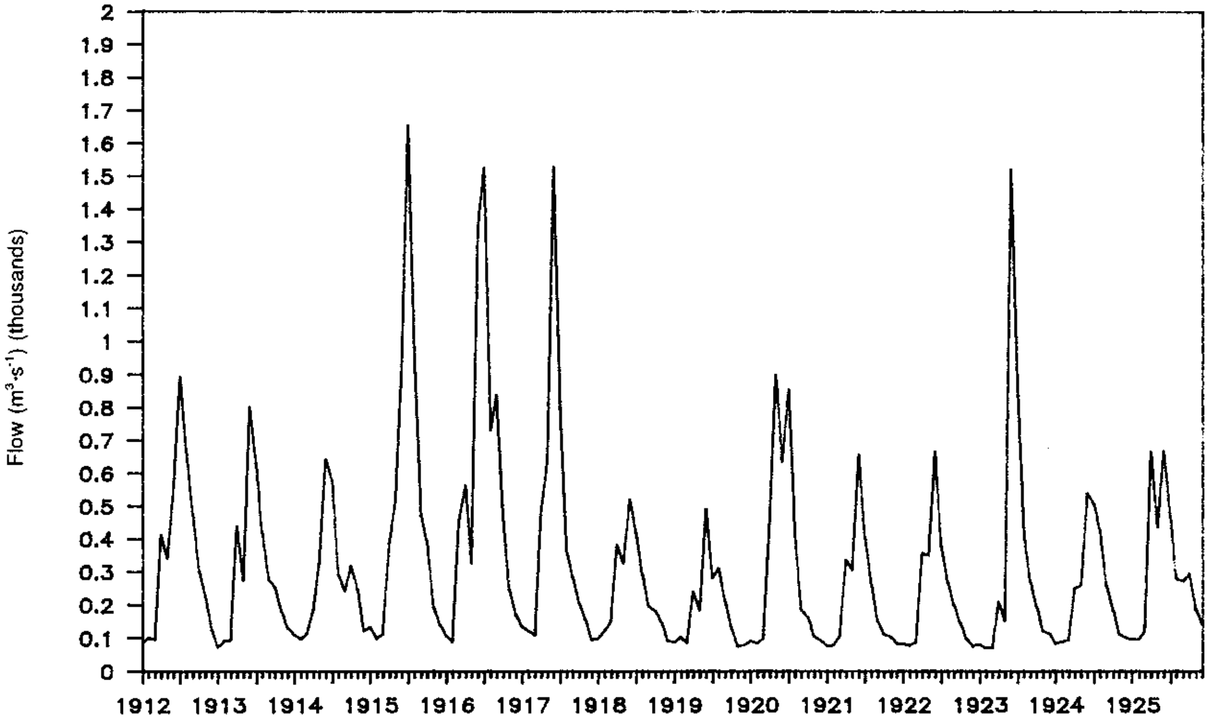


Figure B-2. Continued



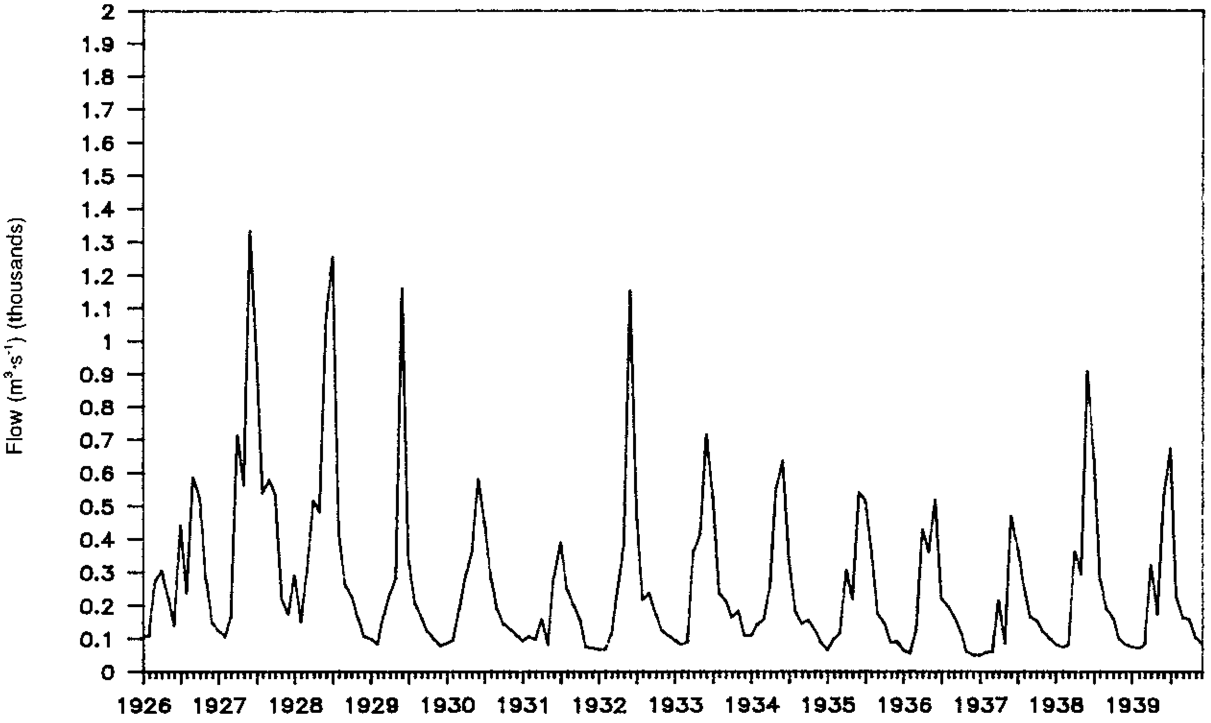
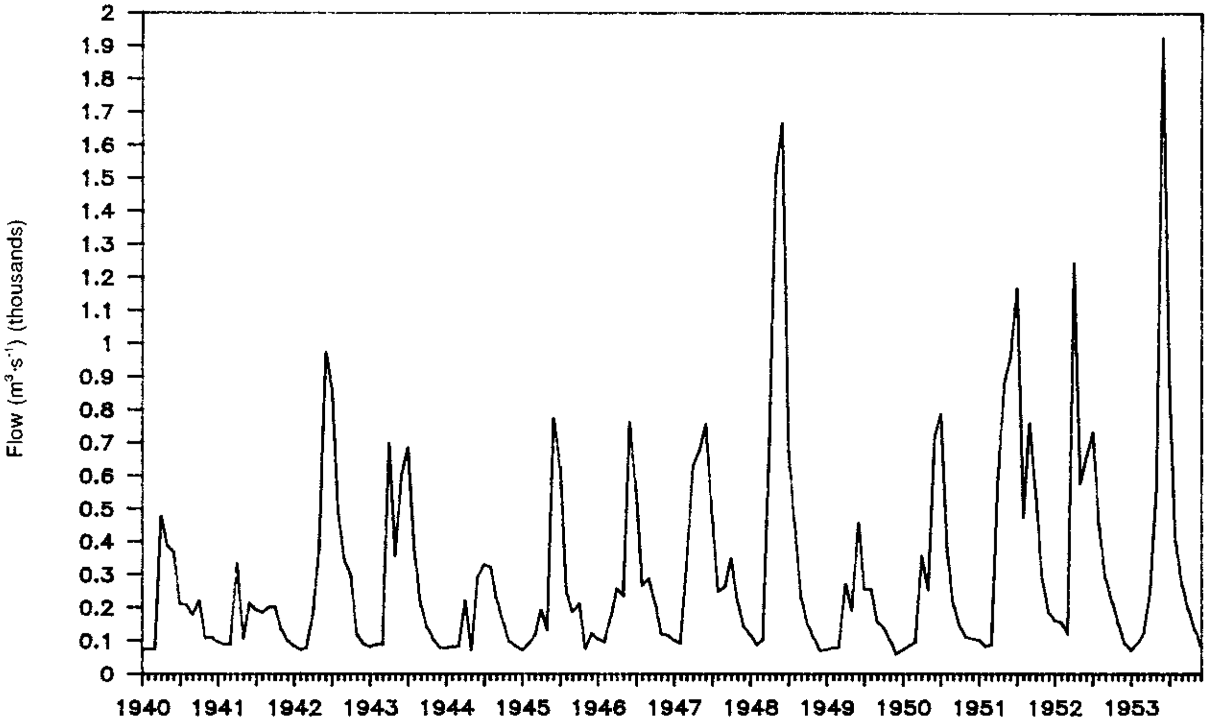


Figure B-3. Natural streamflow, gauge 05HG001, South Saskatchewan River at Saskatoon.



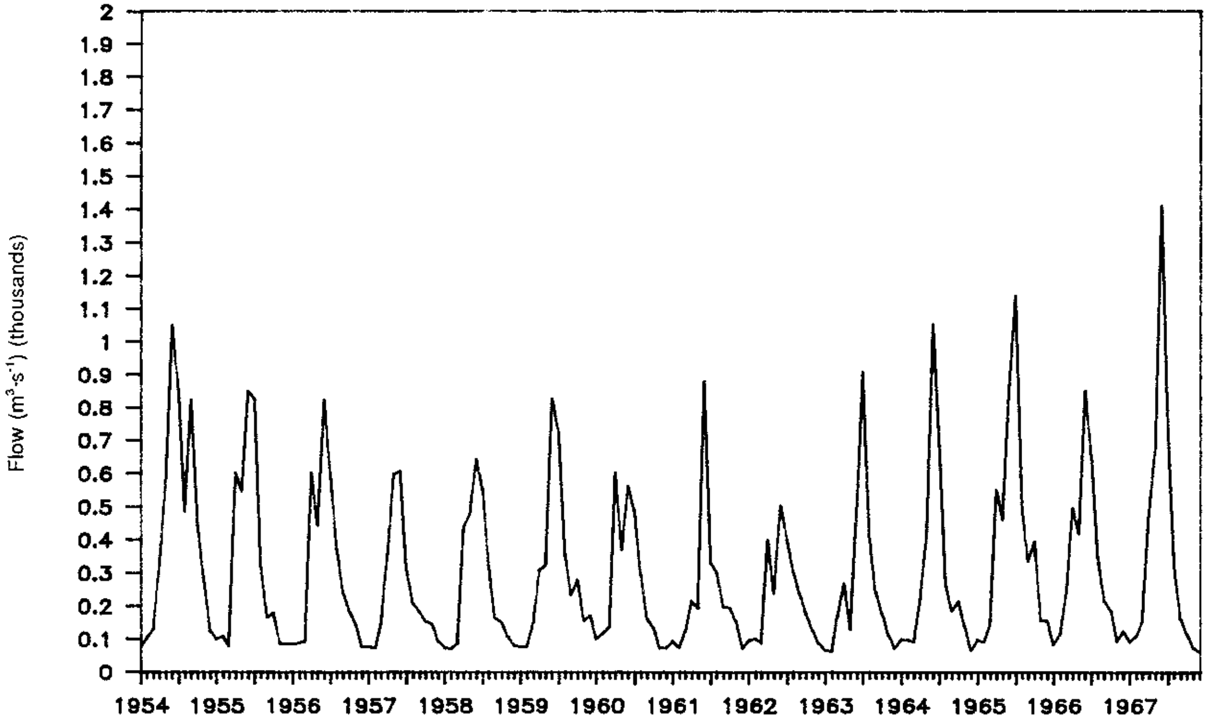
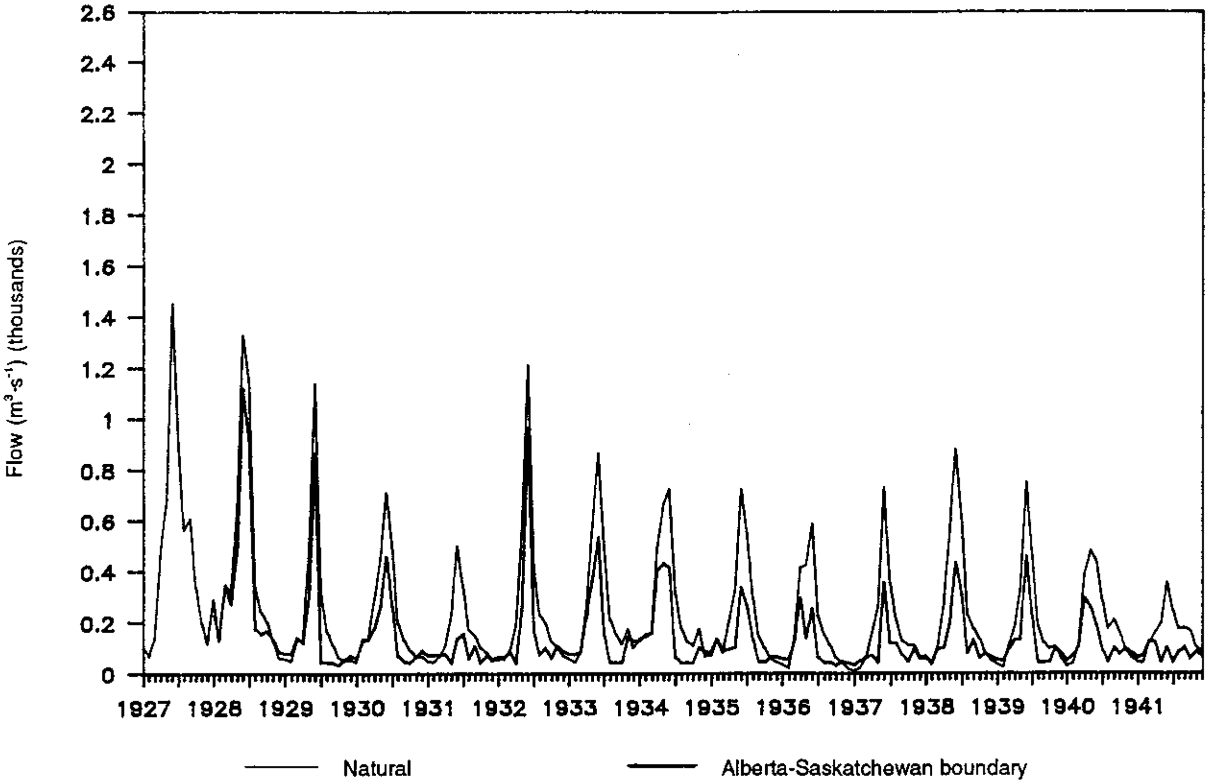


Figure B-3. Continued



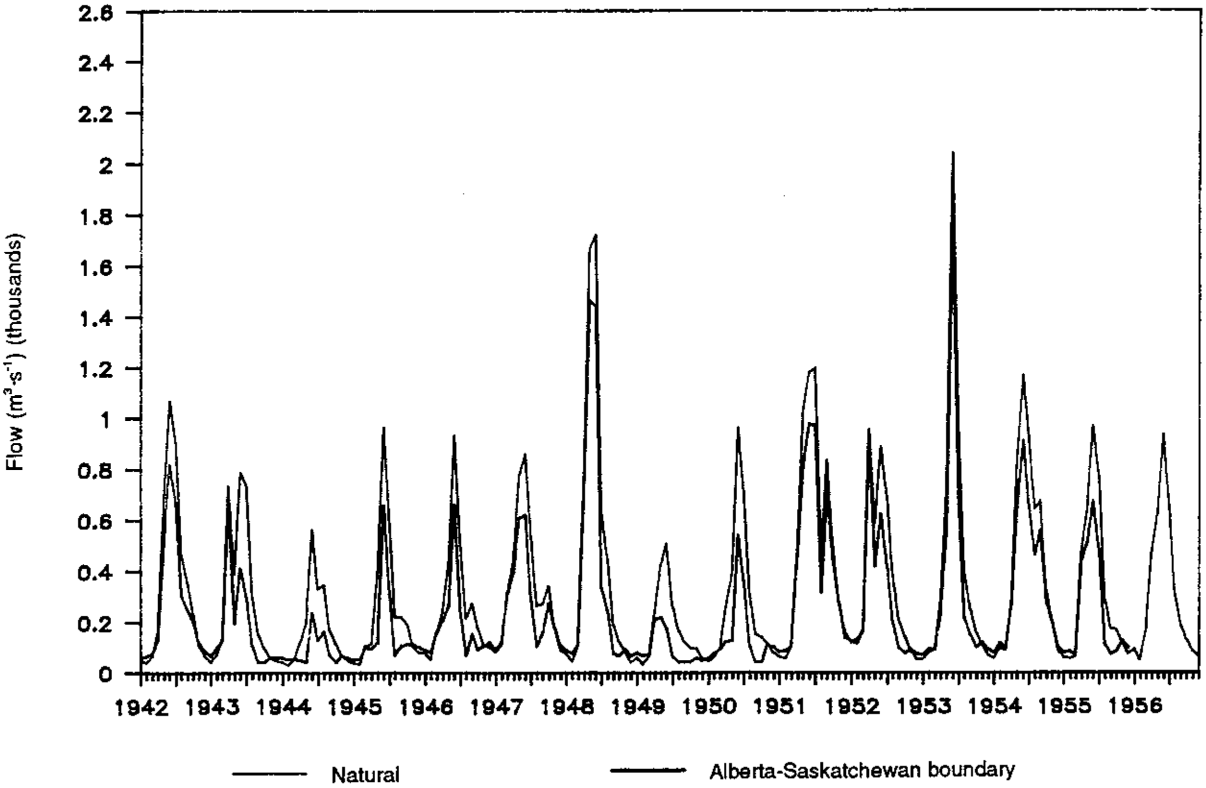


Figure B-4. Natural and scenario 1 boundary flows.

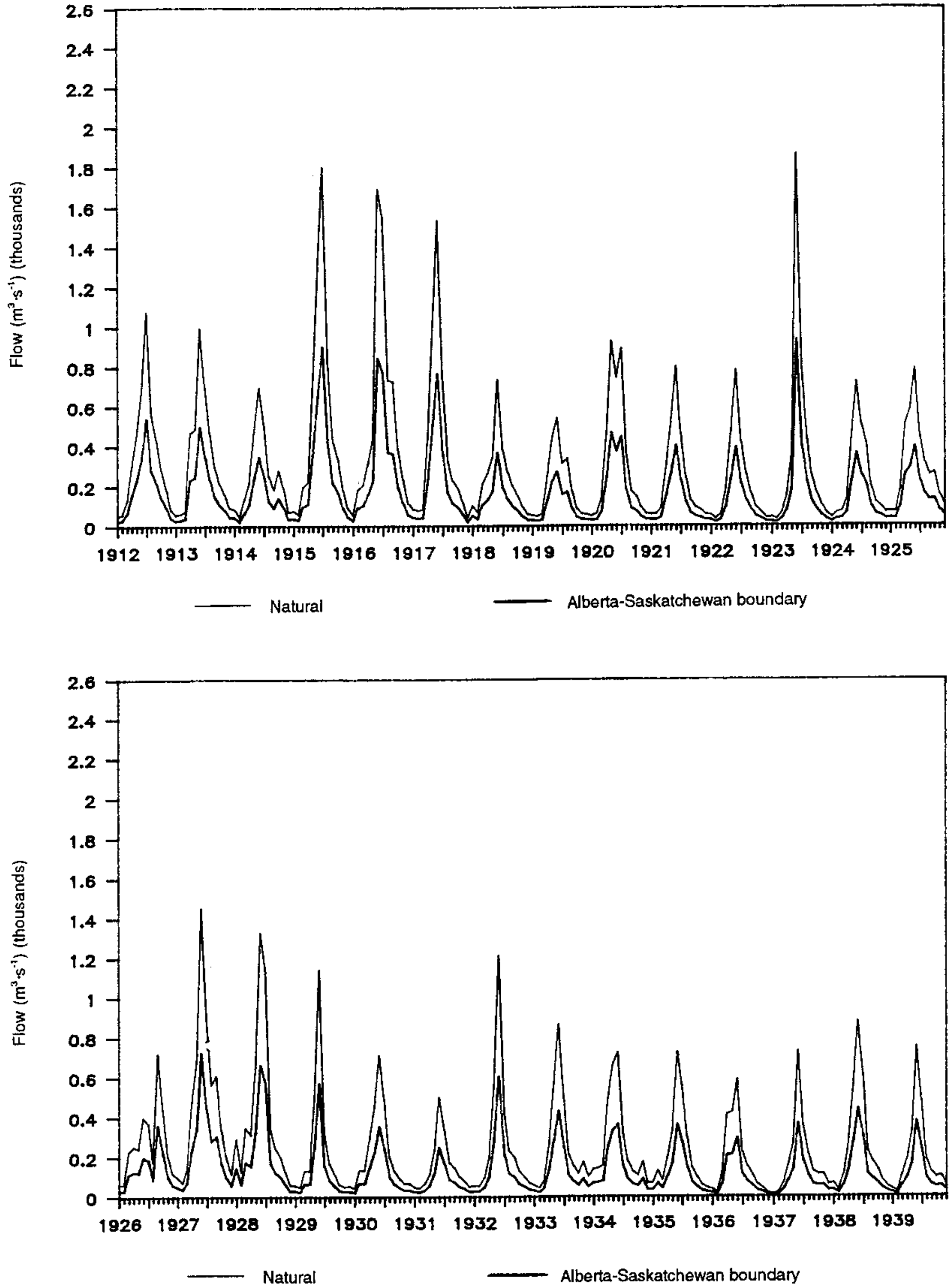


Figure B-5. Natural and scenario 2 and 4 boundary flows.

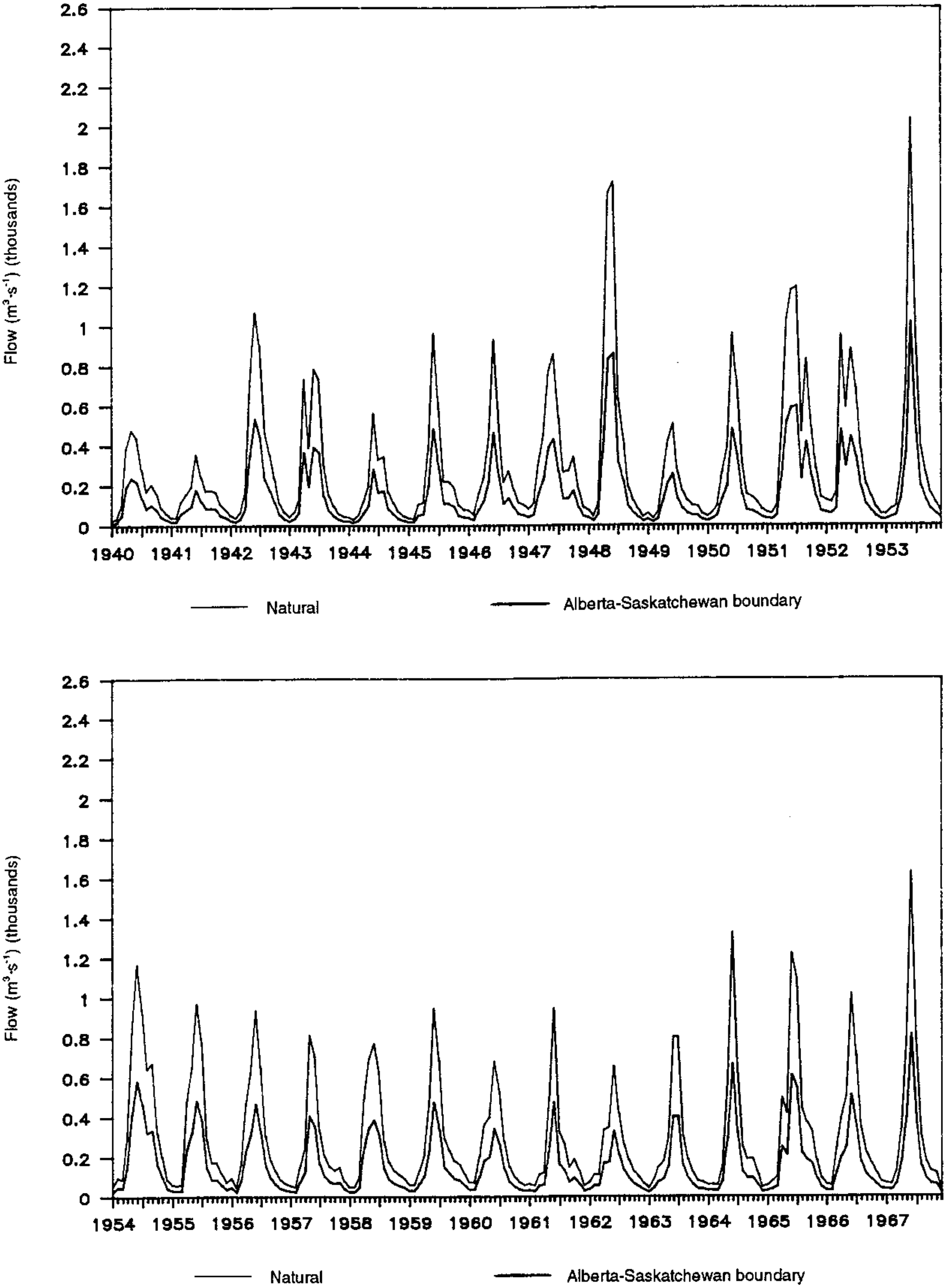


Figure B-5. Continued.

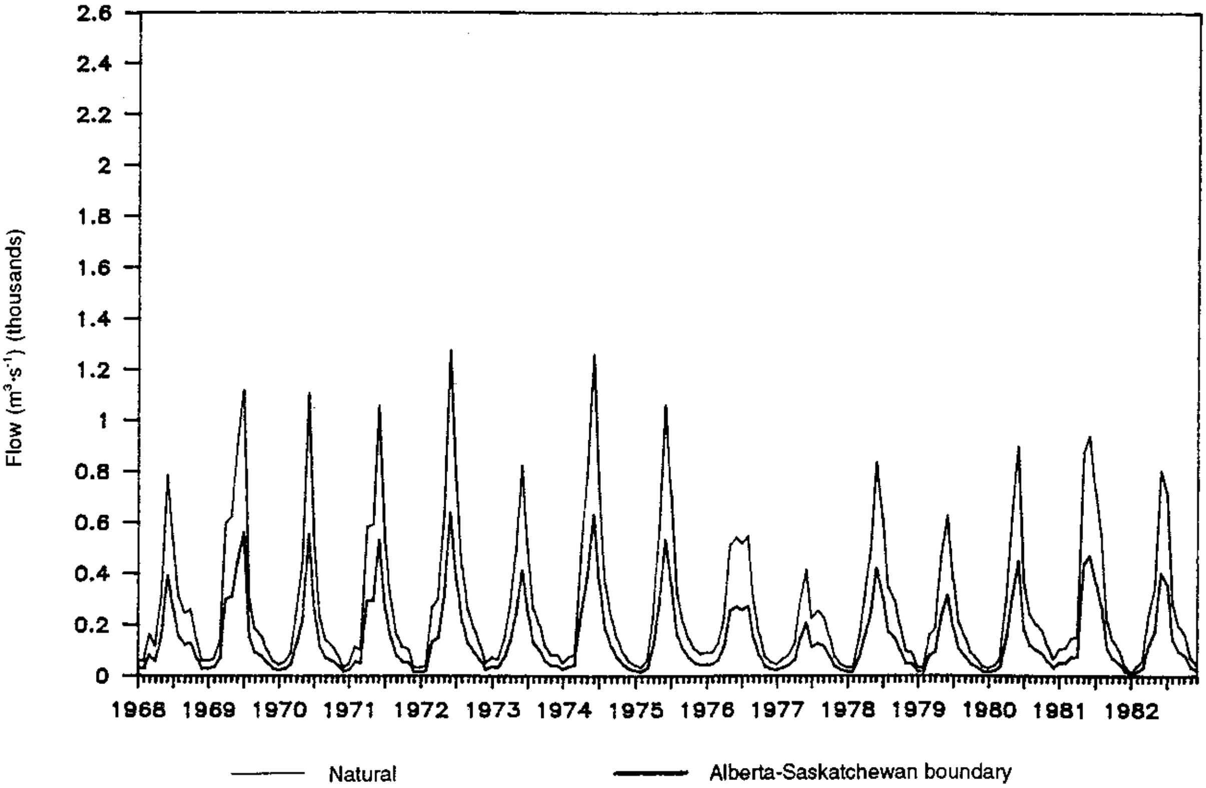
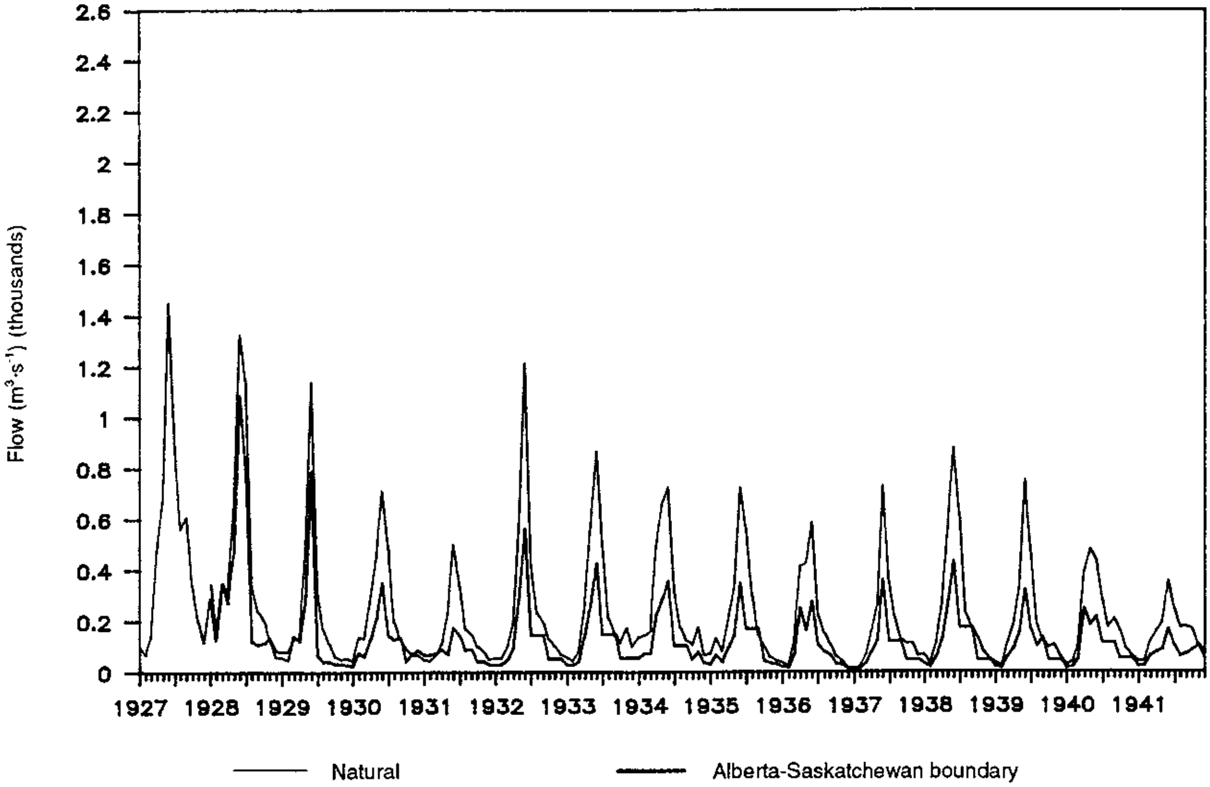


Figure B-5. Continued.



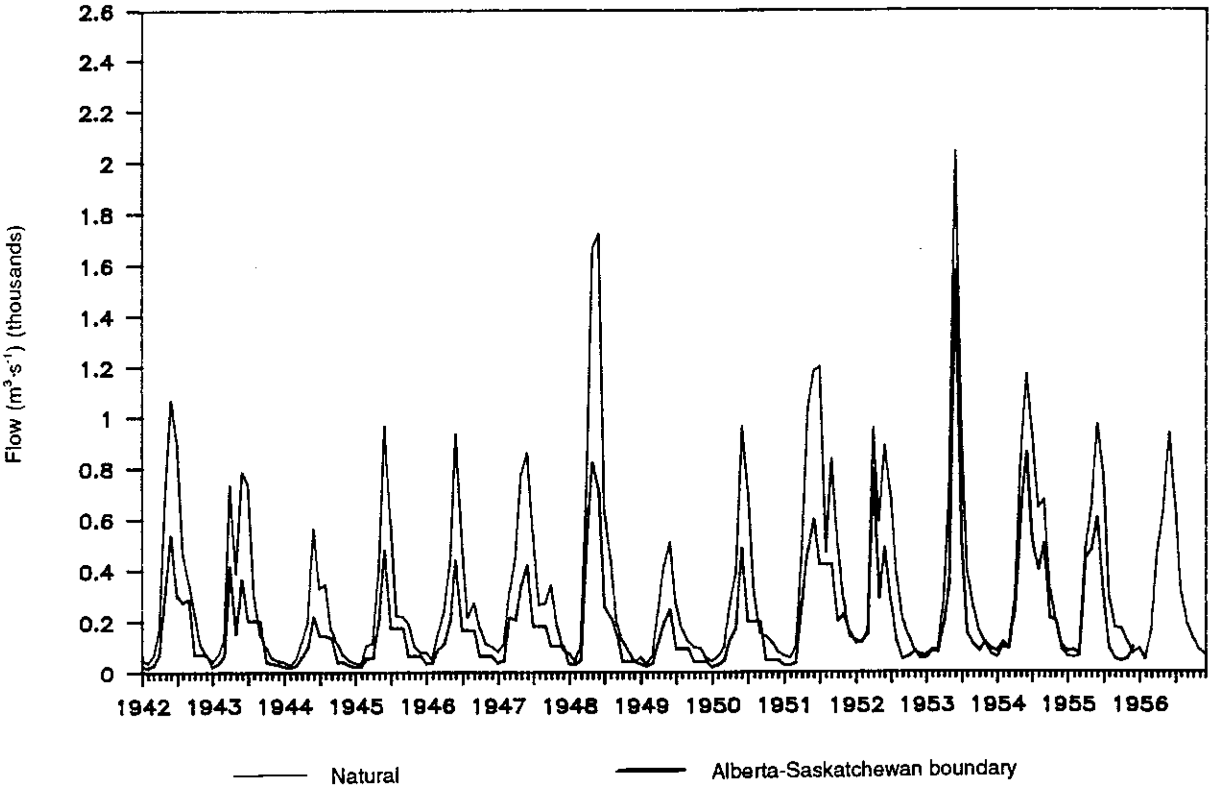


Figure B-6. Natural and scenario 3 boundary flows.

Appendix C

Irrigation Component of the Water Use Analysis Model[1]

C.1 Introduction

The primary purpose of the irrigation submodel is to provide realistic estimates of irrigation water diversion and return flow. These estimates are then combined with the other water uses in WUAM. Unlike other water uses, irrigation water use can be highly variable from year to year in response to climatic factors, primarily precipitation and crop potential evapotranspiration. Other factors affecting irrigation water use are properties of crops and soils, irrigation systems and efficiencies, and economic and social factors.

Development of the irrigation submodel was approached with a number of clear objectives in mind:

- Reasonable accuracy - taking account of the key parameters affecting irrigation water requirements.
- At the same time, it was considered important to maintain simplicity as far as possible, in keeping with the overall pro-spective of WUAM. Complex modelling of processes and operations at individual field or farm level was to be avoided.
- A high degree of compatibility with the main model, both in model structure and data handling.
- Flexibility to allow the investigation of the water demand impacts of future changes in irrigation practices.
- Ease of use.

This appendix describes the irrigation submodel in detail, including discussions of the main parameters, model philosophy, data requirements, and the methodologies/ algorithms applied. The submodel was developed by Acres International Limited (1984).

C.2 Factors Affecting Irrigation Water Use

Water use for irrigation depends on many factors—physical, climatic, economic, social, and political. Physical factors which, if changed, can affect irrigation water use include area irrigated, crop type/mix, and methods, intensities, and efficiencies of irrigation. Some combinations of these can result in little or no change in overall water use, while substantially increasing crop production. Climatic factors are dominated by precipitation and potential evapotranspiration. The cost component will affect the degree of physical changes. Social and political factors can in their turn override other factors.

The irrigation submodel considers only the climatic and physical factors; these are discussed below.

C.2.1 Precipitation and Soil Moisture

Agriculture in Canada is seasonal, with cropping taking place generally from May to September. Much of the precipitation during these months enters the soil directly to contribute moisture to the crop root zones. Outside of the cropping season the proportion of precipitation contributing to soil moisture is small.

The effectiveness of precipitation for crop water consumption purposes is the fraction of total precipitation entering the soil or remaining on the

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[1] This is a revision of material published in Kassem (1992, Appendix A).

surface, which contributes to soil moisture in the root zone or to plant evapotranspiration. Noneffective precipitation either runs directly off the soil surface to surface drainage or percolates through the root zone to underlying groundwater and subsurface drainage.

The following are some of the factors controlling effectiveness of precipitation:

- total amount of precipitation and duration and frequency of precipitation events
- potential evapotranspiration (the evaporation from the soil and transpiration from crops which could occur given sufficient moisture availability)
- the level of moisture in the soil
- the state of precipitation (rain or snow)
- the state and condition of the soil (unfrozen or frozen, surface crusting or cracking, ice lenses or snow and ice cover, tilled or with stubble or vegetation)
- properties related to soil texture, which affect infiltration, moisture storage capacity, and percolation losses from the root zone

C.2.2 Evapotranspiration

The available soil moisture in the spring, added to the in-season effective rainfall, represents the water naturally available for cropping. This is a major parameter determining the desirable amount of extra water to be applied by irrigation.

Evapotranspiration, ET, is the measure of water consumption by crops; it cannot exceed effective rainfall plus available soil moisture. When crop requirements exceed this available supply, the plants wilt and die, unless additional moisture is supplied by irrigation. Furthermore, even if the wilting point is not reached, crop yields are lower than potential yields if certain minimum levels of moisture are not maintained.

Unlike precipitation, evapotranspiration is a quantity that is normally calculated rather than measured. This is because measurement techniques are generally costly and complex, and because the parameter is dependent not only on climatic factors but also on soil and vegetation conditions. There are many calculation techniques available to estimate evapotranspiration, and the results can be very divergent between techniques.

All estimation techniques are based on a reference crop potential ET (ETP_r). To evaluate crop water use, estimated monthly reference potential ET must be adjusted to give crop potential ET (ETP_c), using appropriate crop factors. The method of evaluation of reference potential ET must be compatible with the crop factors to be used. Furthermore, the suitability of a method may vary from region to region, and different methods may have been researched or calibrated in different regions. In any case, it is often desirable to apply more than one method to examine discrepancies and select the most appropriate method.

The foregoing considerations have led to the decision that a method of evaluation of reference potential ET should not be incorporated into the submodel. Estimates of reference potential ET would often be available from previous studies, together with an indication of appropriate crop factors. Alternatively, estimates can be derived in advance using data from selected climato-logical stations. In the absence of locally appropriate estimates or methods, it is strongly recommended that use be made of one of the FAO methods, together with their correspond-ing crop factors (Doorenbos and Pruitt 1975). Selection of the specific method will largely depend on availability of climatic data.

C.2.3 Application and Delivery Efficiency

Irrigation efficiencies describe the proportion of total irrigation water which is actually useful in meeting irrigation requirements. Physical factors that determine irrigation efficiencies include soil properties, methods of irrigation, field design and preparation, evaporation levels, canal and reservoir type (lined or unlined), and quality of system construction. Some approximate quantification of these factors is possible. However, operational factors, which can account for substantial inefficiency, are less easily quantified. Poor control and planning of irrigation water use can lead to substantial wastage, usually by runoff and tail end discharge.

Effective irrigation is a parallel concept to effective rainfall. It is the applied irrigation water which collects on or enters into the soil and remains on or in the plant and root zone until evapotranspired. Application efficiency is the effective fraction of the total irrigation water applied to a field. As with rainfall, the noneffective portion either runs off to subsurface drainage or percolates through the root zone to subsurface drainage.

Water arrives at the field after diversion from the river and conveyance through a delivery system which can include reservoirs, canals, hydraulic structures, channels, and pipes. Losses are also incurred in this delivery system, and the delivery efficiency is therefore the fraction of total water diverted which reaches the field. Losses are accounted for by evaporation, seepage, and runoff to drainage from the tail ends of canals. In some studies, a reservoir efficiency and a distribution efficiency are defined separately. The delivery efficiency would then be the product of these two.

The overall efficiency for an irrigation area is then the product of the application and delivery efficiencies, and is the effective fraction of the total water diverted.

C.2.4 Level of Irrigation

It was mentioned in section C.2.2 that a minimum level of soil moisture is required to achieve maximum potential crop yields. This assumes, of course, that other factors such as fertilizer application, pest control, and farm operations in general are also optimal.

Optimal irrigation is aimed at maintaining optimal soil moisture levels which, in turn, ensure that potential evapotranspiration is achieved. A study of centre pivot irrigation in Alberta (Pohjakas 1981) showed that optimal irrigation was not being achieved. From an analysis of the field trial results, it has been deduced that the average level of irrigation was about 50% of optimal for all full season crops. This is an important characteristic of irrigation practice on the Canadian prairies, which is contributed to by numerous technical, economic, and social factors.

Modelling of the effects of suboptimal irrigation is significantly more complex than assuming optimal levels of irrigation at all times, but it was considered essential in this case in order to ensure reasonable accuracy.

C.2.5 Irrigation Water Salinity

Irrigation water applied to crops always contains some dissolved salts. Water consumed by crops during evapotranspiration is almost completely free of salts. Thus the evapotranspiration process results in an accumulation of salts in the crop root zone which acts to reduce water uptake to the plant. An excessive salt accumulation can adversely affect the plants, leading to reduced or zero yields.

The specific conductance (salinity) of water in a river, which supplies irrigation water and receives return flows from irrigated areas, will tend to increase from upstream to downstream. Therefore, diversions for irrigation in lower reaches will be more saline than those in upper ones.

The higher the salinity of the irrigation water, the greater will be the accumulation of salts. However, the critical levels of salt concentration vary according to crop type and desirable yield levels.

Excess salts are leachable from the root zone by water percolating through the soil to groundwater and subsurface drainage. Some portion of rainfall and irrigation applications percolates downward in this way, and in many irrigation areas worldwide this water is sufficient to maintain an acceptable salt balance in the soil without need for extra water applications.

In the Canadian context, given the high quality of irrigation water and periods of moderately heavy rainfall to assist with leaching, the calculation of salt balance is not considered a priority in the irrigation submodel. However, for completeness, a simple routine for leaching evaluation was included. This routine may be useful for testing the effects of possible future increases in water salinity.

C.3 Main Considerations

Several issues related to the development of the irrigation component of WUAM were discussed earlier. Specific considerations pertinent to the actual structure of the model are outlined below.

C.3.1 Irrigation Areas

In WUAM, all calculations are carried out at the subbasin level, each subbasin cor-responding to a streamflow gauging station at the downstream point. If the subbasin con-tains large organized irrigation areas, each with its own records of water use, cropping, and other irrigation-related factors, then each area would need to be treated separately to analyze water use. Therefore, it was decided that the submodel could not operate on a sub-basin basis, and an irrigation area basis was selected instead.

It should be noted that in river basins which do not have organized irrigation areas, another type of division may be more appropriate. This could be the subbasins themselves, census districts, or counties. This flexibility is possible in the submodel because the constraint of a gauging station is not present. However, reconciliation with the main model will always require identification of subbasins providing or receiving flows and the proportions of these flows.

C.3.2 Irrigation Season

As mentioned earlier, seasonal cropping in Canada generally takes place from May to September. It was decided, however, to include the irrigation season as a variable in the model. This adds to the flexibility and applicability of the model.

C.3.3 Time Unit

The primary purpose of the irrigation submodel is to provide estimates of irrigation water diversion (and return flow). This information is then combined with other water uses calculated in the main model. For compatibility purposes, the monthly time unit adopted in the main model was used in the irrigation submodel. The time unit of a month may not be adequate to account for the effects of rapid changes in crop growth and soil moisture levels during a season. However, in keeping with the overall purpose of the model as a planning tool, the monthly time unit is considered appropriate.

C.3.4 Precipitation and Evapotranspiration

Unlike other water uses, irrigation use is highly dependent on climatic variations. Annual variations in precipitations can be very significant and are the dominant factor in evaluating the irrigation water demands. Potential evapotranspiration, which is dependent on climatic factors, can also vary significantly from year to year.

It was decided, therefore, to account for the variations in both precipitation and potential ET, following an approach similar to that adopted for the simulation of streamflow conditions in the main model. The main model operates with full historic records of natural monthly flows at each gauging station. Likewise, the irrigation submodel was designed to evaluate irrigation water uses on a year-by-year and month-by-month basis using historical data on precipitation and potential ET.

C.3.5 Distribution of Parameters

After precipitation and reference potential ET, the principal parameters controlling irrigation water use are crop type, soil type, and irrigation type. It was established that information concerning the distribution of each of these within an irrigation area would either be readily available or could be approximated with relative ease. What could not be done without extensive research was to subdivide each area into portions each uniquely defined by all three characteristics. Even if it were feasible to do this, the large number of such portions would again entail unjustifiably excessive data handling in the model.

Crop-specific parameters are the most numerous and also the most reliably defined. By contrast, the important soil-specific parameters are related to soil texture, the distribution of which is at best known only approximately, except at a very local level. The parameters of interest relating to irrigation types are operational parameters, whose values can also only be estimated approximately.

Therefore, it was decided to subdivide irrigation areas by crop type only. However, the distribution of soil types and irrigation types in an irrigation area is used to produce single representative values of each parameter by area weighting of parameter values.

C.3.6 Parameter Variations

The capability for investigation of alternative future scenarios has been kept as broad as possible. The following parameters, either singly or in any combination, are seen as the most useful ones to vary in such investigations:

- area irrigated
- crop mix
- mix of irrigation methods
- delivery efficiency
- application efficiency by irrigation type
- level of irrigation by crop and irrigation type
- irrigation water salinity

C.4 Model Description

C.4.1 Flowchart

The submodel outline is shown in the flowchart in Figure C-1. Reference is made in the flowchart to relevant portions of sections C.4.2 to C.4.7 that follow. These sections present the data requirements and logic of the submodel.

C.4.2 Data Requirements

Data requirements for application of the irrigation submodel are described in detail in Kassem (1992, Appendix D). There are three basic groups of data files required for the submodel: general data, irrigation area data, and climatic data. General data are those considered to be universally applicable to all irrigation areas in the region under study. They are included with the general database in the main model (see Kassem 1992, Appendix D1). Irrigation area data are those which will differ from one irrigation area to the other. They also represent scenario data which may be changed as appropriate for the investigation of future conditions. The irrigation data are described in detail in Kassem (1992, Appendix D6). Climatic data are represented by monthly precipitation and reference potential evapotranspiration. They are described in Kassem (1992), Appendices D7 and D8, respectively. A summary of the primary data is presented below.

C.4.2.1 General Data

General data are considered to be universally applicable to the region being

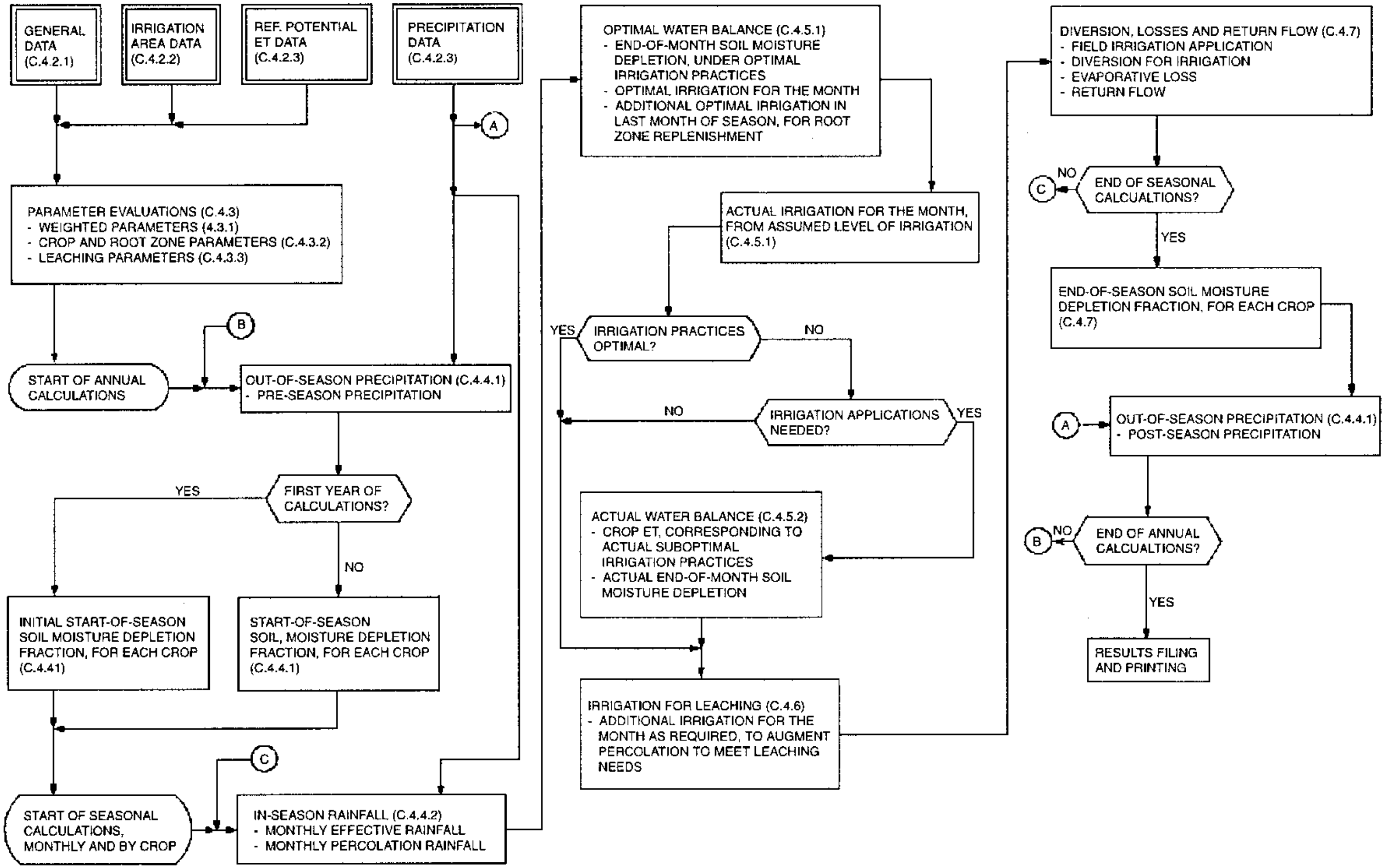


Figure C-1. Flowchart for evaluation of irrigation area water use.

studied and not to require changes from run to run. They include crop, soil, and irrigation type parameters.

(a) Total number of crops or crop types.

(b) Information for each crop or crop type:
  - monthly crop factors: CF
  - minimum optimal soil moisture depletion fraction: DFO_{min}
  - maximum optimal soil moisture depletion fraction: DFO_{max}
  - two constants for evaluation of DFO_{max}: DFA and DFB
  - monthly adjustment factor for DFO_{max}: DFOA
  - maximum root zone depth: RD_{max} (m)
  - root zone depth adjustment factor for RD_{max}: RDA
  - maximum soil salinity for 90% of potential crop yield: $ECEN_{max}$ (mmho/cm)
  - maximum soil salinity for 0% of potential crop yield: $ECEZ_{max}$ (mmho/cm)
  - soil salinity adjustment factor for $ECEN_{max}$ and $ECEZ_{max}$: ECEA
  - three constants for evaluation of actual crop ET: DF95, DF10, and ETF80

(c) Total number of soil types.

(d) Information for each soil type:
  - soil moisture storage capacity: SC (mm/m)
  - leaching efficiency: EL (%)
  - percolation efficiency: EP (%)

(e) Total number of irrigation types.

(f) Information for each irrigation type:

  - application frequency code: 1 = high, 2 = low.

C.4.2.2 Irrigation Area Data

Each irrigation area requires a set of data specific to the area. This includes scenario data, which would be changed as appropriate for investigation of alternative scenarios.

- total irrigated area: AT (ha)
- delivery evaporative losses: ELD (%)
- delivery efficiency: ED (%)
- monthly irrigation water salinity: ECW (mmho/cm)
- number of crops or crop types considered
- information for each crop or crop type
  - cropped area percentage: AP_c (%)
  - crop-specific level of irrigation: ILC (%)
- number of soil types considered
- information for each soil type
  - soil type percentage: AP_s (%)
- number of irrigation types considered
- information for each irrigation type
  - irrigation type area percentage: AP_i (%)
  - application efficiency: EA (%)
  - irrigation type adjustment to level of irrigation: ILCA
- in-season rainfall application efficiency: EAR (%)

C.4.2.3 Precipitation and Reference Potential ET Data

In addition to the irrigation area data set, each irrigation area needs to be associated with a separate set of data both for monthly precipita-tion, P, and for monthly reference potential ET, ETP_r. Both precipitation and evapotranspiration data are required for each year to be analyzed. Reference potential ET has been kept separated from the remaining irrigation area data to pro-vide the option of generating it in advance from climatic data.

C.4.3 Parameter Evaluations

C.4.3.1 Weighted Parameters

In the case of both soil type and irrigation type parameters, single working values repre-sentative of the irrigation area are derived as weighted averages by area. Using moisture storage capacity and application efficiency as examples, the weighted parameters SC_w and EA_w would be set as follows:

$SC_w = SC \times (AP_s / 100)$ and

$EA_w = EA \times (AP_i / 100)$,

respectively. AP_s and AP_i are the soil type and irrigation type percentages of total irrigated area. The remaining weighted parameters obtained in this way are leaching efficiency, EL_w, percolation efficiency, EP_w, and irrigation type adjustment to level of irrigation, $ILCA_w$. In addition, the percentages of total area under high and low irrigation application frequencies, AP_{ih} and AP_{il}, respectively, are calculated.

C.4.3.2 Crop and Root Zone Parameters

Crop and root zone parameters include an adjusted level of irrigation and monthly values of crop potential ET, maximum optimal depletion fraction, root zone depth, and irrigation application depths.

(a) Adjusted Level of Irrigation

The adjusted level of irrigation, ILA, is the crop-specific level of irrigation, ILC, modified by applying the weighted irrigation type adjustment to level of irrigation, $ILCA_w$

$$ILA = ILC \times ILCA_w \ (\%)$$

The irrigation type adjustment to level of irrigation, ILCA, allows for the effects of irrigation type on the level of irrigation to be accounted for. Thus the adjusted level of irrigation reflects differences both between crops and between irrigation types. ILA is constrained to be not greater than 100%.

(b) Crop Potential ET

Monthly crop potential ET, ETP_c, is obtained by applying monthly crop factors, CF, to monthly reference potential ET, ETP_r

$$ETP_c = CF \times ETP_r \ (mm)$$

It should be noted that reference potential ET corresponds to a fully developed, actively growing reference crop, normally either grass or alfalfa, and that crop factors applied to it must correspond to the appropriate reference crop and to the method of evaluation. Reference potential ET is evaluated at any and all times of year, but can only physically occur when the assumed conditions actually prevail. In Canada, this can only be in midseason, and even then perhaps only momentarily in the case of grass or alfalfa if it is cut subsequent to full development. On the other hand, crop potential ET can physically occur at all times when soil moisture is sufficient. This is because the crop factors applied to reference potential ET account for the variations in both crop type and stage of crop development.

With regard to crop factors, one is required for every month of the cropping season over which irrigation is evaluated. If the crop is planted late or harvested early, the crop factors outside of the cropping period should reflect bare soil conditions.

(c) Optimal Depletion Fractions

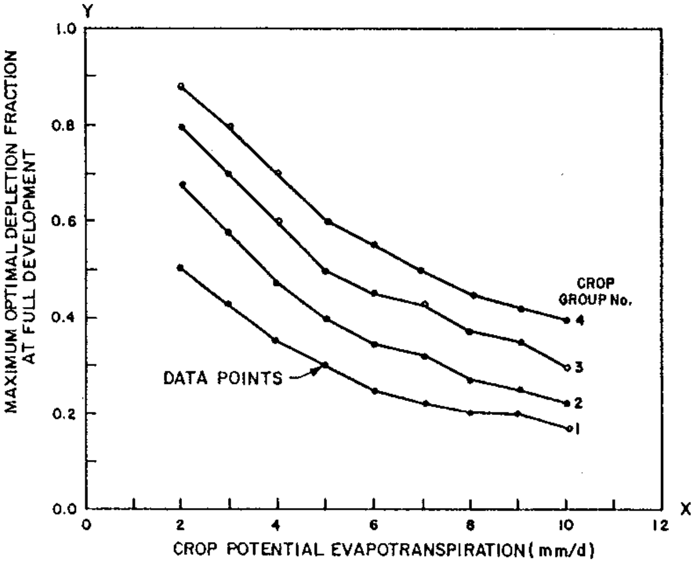
The maximum optimal soil moisture depletion fraction, DFO_{max}, is that fraction of the potentially available soil moisture in the root zone which can be depleted without causing actual crop ET to drop below crop potential ET. This fraction is often taken as 0.5, but in fact it depends on both crop type and potential crop ET, and to some lesser degree on soil type and crop stage of growth.

Values of DFO_{max} for four crop groups and a range of crop potential ET are available from the FAO (Doorenbos and Pruitt 1975; Doorenbos and Kassam 1979). These correspond to full development of the crop. The data were fitted to power curves, one for each crop group, and provision was made to apply monthly adjustment factors, DFOA, to account for growth stage. The resulting equation is

$$DFO_{max} = [DFA\ (ETP_c\ /\ NDM)^{DFB}\ ] \times DFOA$$

where DFA and DFB are power curve constants (see Figure C-2), and NDM is the number of days in the month.

The option of defining a constant value of DFO_{max} for each crop is available. Such a value is included in the database, and would be used



POWER CURVE FITTING

CROP GROUP	1	2	3	4
DFA	0.854	1.188	1.309	1.353
DFB	-0.677	-0.695	- 0.602	-0.517
CORR.COEF.	0.986	0.982	0.977	0.977

CROP GROUP	CROPS
1	ONION, PEPPER, POTATO
2	BANANA, CABBAGE, GRAPE, PEA, TOMATO
3	ALFALFA, BEAN, CITRUS, GROUNDNUT, PINEAPPLE, SUNFLOWER, WATERMELON, WHEAT
4	COTTON, MAIZE, OLIVE, SAFFLOWER, SORGHUM, SOYBEAN, SUGARBEET, SUGARCANE, TOBACCO

SOURCE:
DOORENBOS AND KASSAM, 1979

POWER CURVE EQUATION:
$Y = DFA \times X^{DFB}$

Figure C-2. Maximum optimal depletion curves.

if zero values were assigned to the power curve constants.

As ETP_c decreases, DFO_{max} increases (the sign of DFB is negative in the above equation). In some instances where ETP_c is very low, such as at the start of the growing season, the above equation produces unrealistically high values of DFO_{max}. Therefore, DFO_{max} has been limited to a value of depletion fraction corresponding to an actual crop ET of 95% of crop potential ET. The concept is discussed further in Section C.4.5.2.

In addition to DFO_{max}, a minimum optimal soil moisture depletion fraction, DFO_{min}, is also used. This fraction is defined as a constant for each crop. It is intended to account for irriga-tion practices which may be oriented toward maintaining optimal soil moisture levels but at the same time not fully eliminating soil moisture deficits. Maintaining a small depletion can allow earlier access to the crop and easier work-ing conditions in the fields following irrigation.

(d) Root Zone Depth

Root zone depth defines the depth of soil from which roots extract moisture for evapotranspiration. As with crop potential ET, root zone depth is dependent on the crop growth stage. Monthly root zone depth, RD, for each crop is taken as the maximum root zone depth, RD_{max}, modified by monthly root zone depth adjustment factors, RDA

$$RD = RD_{max} \times RDA \text{ (m)}$$

(e) Irrigation Depths

An irrigation depth is a depth of water which, when applied to a field, will fully enter the soil and remain in the root zone for use by crops. It is defined in terms of root zone depth, RD, and weighted soil moisture storage capacity, SC_w, as well as current and desired soil moisture depletions.

Soil moisture storage capacity, SC, defines the storage capacity within the soil for moisture which will be readily available for use by crops. It does not represent the total pore space which could be filled with water. At a low level of soil moisture, termed the wilting point, crops cannot extract moisture. At a high level of soil moisture, termed the field capacity, extra moisture cannot be retained in the root zone. Storage capacity is the moisture-holding capacity between field capacity and wilting point, sometimes expressed as a fraction or percentage of soil volume or, as in the present case, as a depth of water per depth of soil (mm/m).

The root zone depth and storage capacity are used to estimate the total depth of water which can be accommodated in the root zone. The irrigation depth is then an amount less than or equal to this total depth. For the purposes of the module, three irrigation depths have been defined.

- standard irrigation depth, DIS, which would fill the root zone from its maximum optimal depletion level to field capacity

  $DIS = DFO_{max} \times SC_w \times RD$ (mm)

- optimal irrigation depth, DIO, which would replenish the root zone between maximum and minimum optimal depletion levels

  $DIO = (DFO_{max} - DFO_{min}) \times SC_w \times RD$ (mm)

- actual irrigation depth, DIA, which would modify the optimal irrigation depth according to the adjusted level of irrigation

  $DIA = DIO \times (ILA/100)$ (mm)

C.4.3.3 Leaching Parameters

Leaching requirements are estimated for each crop and for two alternative scenarios of irrigation application frequency. A high application frequency implies longer intervals between irrigations. The FAO/Rhodes method is used (Ayers and Westcot 1976; Doorenbos and Pruitt 1975).

Maximum soil salinities, $ECEN_{max}$ and $ECEZ_{max}$, at which 90% and 0%, respectively, of potential crop yield can be obtained, are taken as applying to crops at full development. Monthly soil salinity adjustment factors, ECEA, are then applied to give corresponding monthly tolerable soil salinities, ECEN and ECEZ, for each of the two crop yield levels

$ECEN = ECEN_{max} \times ECEA$ (mmho/cm)

$ECEZ = ECEZ_{max} \times ECEA$ (mmho/cm)

Monthly tolerable soil salinities, as above, together with irrigation water salinity, ECW, and weighted leaching efficiency, EL_w, are used to evaluate leaching requirement fractions, LRFN and LRFZ, for low and high irrigation application frequencies, respectively:

$LRFN = [ECW/(5 \times ECEN - ECW)] \times (100/EL_w)$

$LRFZ = [ECW/(2 \times ECEZ)] \times (100/EL_w)$

Leaching efficiency, EL, is the portion of total percolation water which is effective in dissolving and removing salts from the root zone. Variations in leaching efficiency are significant between soil types, ranging from 30% in heavy clays to 100% in sand (Doorenbos and Pruitt 1975).

A weighted average leaching requirement fraction, LRF, is then obtained by applying the appropriate percentages of total area under high and low irrigation application frequencies, AP_{ih} and AP_{il}

$LRF = LRFN \times (AP_{il}/100) + LRFZ \times (AP_{ih}/100)$

The leaching requirement fraction, derived as above, is a fraction of the total amount of water which enters the soil. The crop leaching requirement, LR_c, is therefore the product of the leaching requirement fraction and the total amount of water entering the soil. If this total amount of water were to exactly satisfy both crop potential

ET, ETP_c, and the crop leaching requirement, LR_c, then it would equal the sum of the two. The crop leaching requirement is therefore given by

$LR_c = LRF \times (ETP_c + LR_c)$ (mm)

which when solved for LR_c gives

$LR_c = [LRF/(1 - LRF)] \times ETP_c$ (mm)

C.4.4 Precipitation

Having completed parameter evaluations for an irrigation area as described above, the module performs evaluations on a year-by-year, month-by-month, and crop-by-crop basis. Each year has an in-season component and an out-of-season component. Annual calculations commence in January.

C.4.4.1 Out-of-Season Precipitation

At the start of the irrigation season in each year for each crop, an initial actual soil moisture depletion fraction, DFAI, is defined. In the case of the first year of calculation, this is set at 0.5, but in subsequent years the effect of total out-of-season precipitation, PTO, is allowed for.

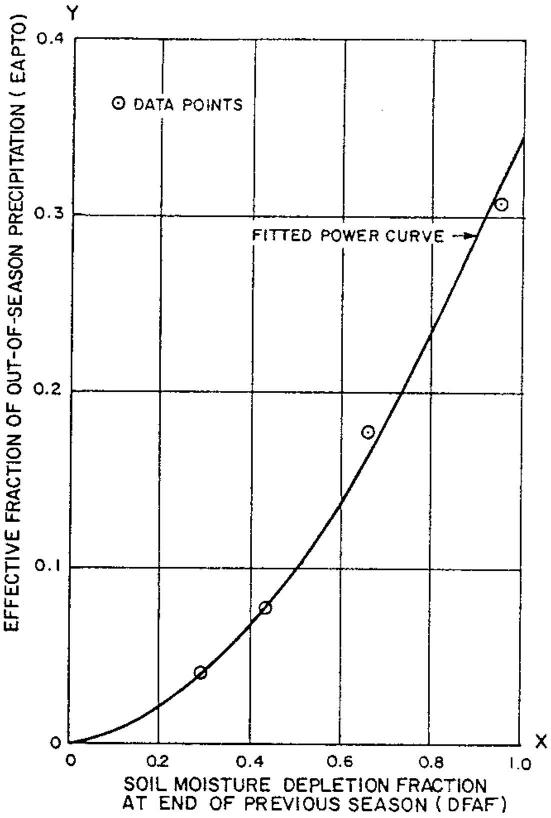
The efficiency of application of total out-of-season precipitation, EAPTO, is the effective fraction of out-of-season precipitation which enters and is retained in the root zone area of the soil for use by crops during the following season. It has been assessed using results of research by Hobbs and Krogman (1971).

Data relating EAPTO to final actual soil moisture depletion fraction, DFAF, as evaluated at the end of the previous season, were fitted to a power curve (see Figure C-3):

$EAPTO = 0.3448 \times DFAF^{1.7244}$

Effective out-of-season precipitation, is then taken to be

$PTOE = EAPTO \times PTO$ (mm)



SOURCE:
HOBBS AND KROGMAN, 1971

POWER CURVE EQUATION:
$Y = 0.3448 \times X^{1.7244}$
(CORRELATION COEFFICIENT = 0.9983)

Figure C-3. Out-of-season precipitation application efficiency.

and the depletion fraction is reduced by the replenishment provided by PTOE over the maximum root zone depth of the forthcoming crop

$DFAI = DFAF - PTOE/(SC_w \times RD_{max})$

The value of DFAI is constrained to be greater than or equal to zero.

C.4.4.2 In-Season Rainfall

Monthly effective in-season rainfall is evaluated in the first instance using the USDA/SCS method (U.S. Department of Agriculture 1967). A depth-of-application factor, DAF, is first evaluated, based on the standard irrigation depth, DIS

$$DAF = 0.531747 + 0.295164\ (DIS/25.4) - 0.057697\ (DIS/25.4)^2 + 0.003804\ (DIS/25.4)^3$$

Monthly effective rainfall, RE1, is then estimated using monthly precipitation, P, and monthly crop potential ET, ETP_c, as well as DAF

$$RE1 = [0.70917\ (P/25.4)^{0.82416} - 0.11556] \times 10^{0.02426\ (ETP_c/25.4)} \times DAF \times 25.4\ (mm)$$

The above two equations are those of the USDA/SCS method (U.S. Department of Agriculture 1967), modified to allow for metric units. Monthly effective rainfall evaluated as above is constrained to be not greater than monthly precipitation, and not greater than monthly crop potential ET.

The above method is still generally recognized as the best available for estimating this complex parameter. However, it does not consider as effective that rainfall which may exceed crop potential ET and yet be available for replenishing the crop root zone. For this reason, a second evaluation of monthly effective rainfall, RE2, is made, using an in-season rainfall application efficiency, EAR,

$$RE2 = P \times (EAR/100)\ (mm)$$

This value is constrained to be not greater than monthly precipitation.

The greatest of the two estimates is taken as the monthly effective rainfall, RE. This is then the rainfall contribution toward evapo-transpiration and root zone replenishment.

It is also of importance to estimate the monthly rainfall contribution toward leaching requirements. This contribution originates from the percolation component of rainfall, RP, which is itself a component of the noneffective rainfall, RN.

The noneffective rainfall is precipitation less effective rainfall

$$RN = P - RE\ (mm)$$

and if RN is zero then RP is also zero. Otherwise, use is made of the actual rainfall application efficiency, EARA, defined by

$$EARA = (RE/P) \times 100$$

and the weighted percolation efficiency, EP_w, to obtain the percolation component of rainfall from noneffective rainfall

$$RP = [EP_w/(100 - EARA)] \times RN\ (mm)$$

Percolation efficiency, EP, is the portion of total water added to the field which enters the soil but does not remain in the root zone and percolates down to groundwater and sub-surface drainage. It is dependent primarily on soil type, but is affected by several other factors, including irrigation type and field operations. Values selected may sometimes conflict with those for application efficiency, in which case the latter should take precedence.

Depending on the choice of values for percolation efficiency, RP could be calculated to be greater than RN. In such a case, RP is set equal to RN. The rainfall balance is completed by defining runoff rainfall, RR, as

$$RR = RN - RP\ (mm)$$

C.4.5 Crop Irrigation and Soil Water Balance

The initial actual soil moisture depletion fraction, DFAI, defined in section C.4.4.1, is taken to apply over the maximum root zone depth of the crop, RD_{max}. However, in the months prior to full development of the root system, only the soil moisture available within the current root zone depth, RD, can be accessed by the crop.

At the start of any month, the actual soil moisture depletion, DMA, is taken as the depletion at the end of the previous month, within the previous month's root zone, plus the depletion at the start of the season, within the current month's addition to the root zone. This is similar to the approach of Burt et al. (1981). Thus

$$\mathrm{DMA} = [\mathrm{DFAA} \times \mathrm{SC}_w \times \mathrm{RD}_{(m-1)}] + [\mathrm{DFAI} \times \mathrm{SC}_w \times (\mathrm{RD}_m - \mathrm{RD}_{(m-1)})] \text{ (mm)}$$

In the above expression, DFAA is the actual soil moisture depletion fraction, evaluated at the end of every month, while m and (m − 1) refer to the current and previous months, respective-ly. In the first month of the season, the first term of the expression is zero, while after the root zone has reached maximum depth, the second term is zero.

C.4.5.1 Optimal Water Balance

At this stage, a water balance for the month is computed to determine the irrigation needs of the crop in that month. The evalua-tion assumes optimal irrigation practices, which means that

- soil moisture depletions are maintained between minimum and maximum optimal depletions
- optimal irrigation depths as defined in section C.4.3.2 are achieved at all irrigations
- actual crop ET is equal to crop potential ET

At the end of the optimal water balance calculation, the obtained optimal irrigation for the month is factored by the adjusted level of irrigation, ILA, to give the actual irrigation for the month.

For this purpose an initial optimal soil moisture depletion for the month, DMOI, is set equal to the actual soil moisture depletion, DMA, defined above. The final optimal soil moisture depletion for the month, DMOF, is then estimated from effective precipitation and crop potential ET, initially assuming no irrigation:

$$\mathrm{DMOF} = \mathrm{DMOI} - \mathrm{RE} + \mathrm{ETP}_c$$

According to the value of DMOF, one of three possible procedures is followed, as summarized below and shown in Figure C-4.

(a) DMOF Less Than Zero

When DMOF is less than zero, a final soil moisture level greater than field capacity has occurred due to surplus effective rainfall. The final optimal soil moisture surplus, SMOF, is set equal to DMOF, with a change of sign, and DMOF is set to zero.

If the current root zone has reached the maximum root zone depth, then SMOF is added to the previously evaluated percolation component of rainfall, RP. It is also subtracted from effective rainfall, RE. Otherwise, the sur-plus can reduce the depletion in the root zone area beneath the current root zone. This means that the initial depletion fraction, DFAI, in the unexploited root zone can be reduced as follows.

$$\mathrm{DFAI} = \mathrm{DFAI} - \{\mathrm{SMOF}/[\mathrm{SC}_w \times (\mathrm{RD}_{max} - \mathrm{RD})]\}$$

If this results in a negative value of DFAI SC_w, then there is still a surplus defined by

$$\mathrm{SMOF} = -\mathrm{DFAI} \times \mathrm{SC}_w \times (\mathrm{RD}_{max} - \mathrm{RD}) \text{ (mm)}$$

and DFAI is set to zero. The surplus is then added to percolation rainfall and subtracted from effective rainfall, as before.

(b) DMOF Greater Than or Equal to DIS

The standard irrigation depth, DIS, is also the maximum optimal depletion. If DMOF is greater than DIS, then irrigation was required in the month. Irrigation is applied successively in units of the optimal irrigation depth, DIO, and DMOF is reduced by the same amount. The irrigation amounts are cumulated. After each irrigation application, DMOF is tested against DIS, and irrigations continue until DMOF is less than DIS.

(c) DMOF Between the Two Previous Limits

When DMOF is between the two previous limits, there is neither surplus nor required irrigation, and DMOF remains unchanged.

There is considerable importance attached to the level of soil moisture in the spring, and the dominant factor controlling this is the level of soil moisture the previous fall. Optimal irrigation practice would allow for a final irrigation at the end of the season to fill the root zone up to the minimum optimal depletion level.

The minimum optimal depletion is equivalent to (DIS − DIO). If in the last month DMOF is greater than this depletion, an irrigation of [DMOF − (DIS − DIO)] is added, and DMOF is set equal to (DIS − DIO). It is also optimal irrigation practice to allow for high depletions at harvest time. This might mean that a separate criterion should be applied for irrigation in the month of harvest. However, given that a postharvest replenishment is desirable, as discussed above, the cumulated irrigation amount would remain the same. If harvest occurs before the last month of the season, then the individual monthly totals as evaluated may not truly reflect this practice, but an adjustment was not considered to be warranted.

Having completed the optimal water balance, the resulting cumulative monthly optimal

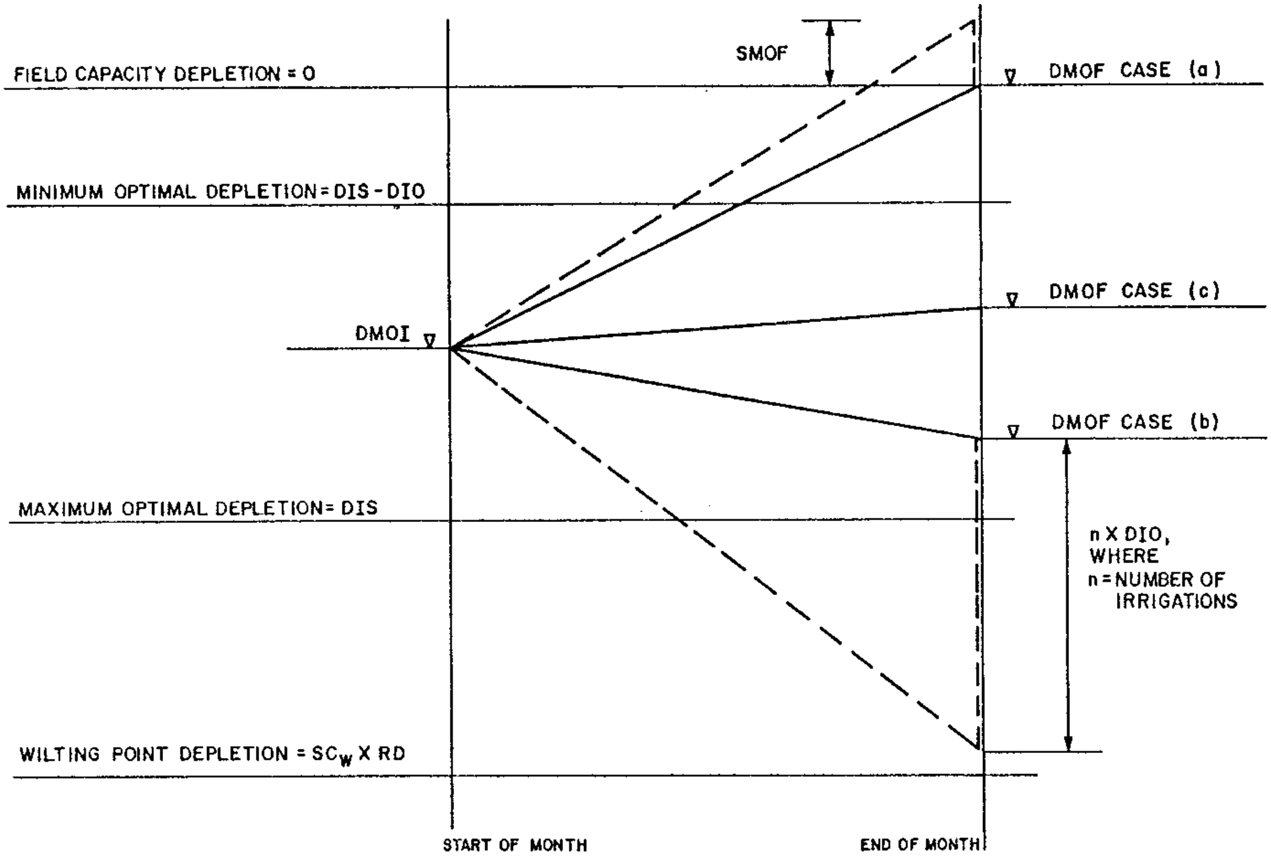


Figure C-4. Optimal water balance.

irrigation, CMIO, is used to define the cumulative monthly actual irrigation, CMIA, by applying the adjusted level of irrigation for the crop, ILA

$$CMIA = CMIO \times (ILA/100) \text{ (mm)}$$

The corresponding volumetric monthly irrigation, CMIV, for the crop is also obtained in millions of cubic metres using total irrigated area, AT, in hectares, crop type percentage of total area, APc, and a conversion factor to correct the units

$$CMIV = CMIA \times AT \times (AP_c/100)/10^5 \text{ (MCM)}$$

If optimal irrigation was actually practised (ILA not less than 100%), or if there was no irrigation required anyway (CMIO not greater than zero), then the actual soil moisture deple-tion at the end of the month, DMA, is set equal to DMOF. However, if this was not the case, then the effects of suboptimal irrigation on the soil moisture levels need to be determined, as detailed in the following section.

C.4.5.2 Actual Water Balance

The actual water balance is concerned with evaluating actual monthly crop ET, ETA_c, on the basis of cumulative monthly actual irrigation, CMIA, and establishing the corresponding actual soil moisture depletion at the end of the month, DMA.

An initial actual soil moisture depletion, DMAI, is set equal to the actual soil moisture depletion, DMA, which corresponds to the end of the previous month. A trial value of final actual soil moisture depletion, DMAF, is evalua-ted, assuming in the first instance that actual crop ET will equal crop potential ET, ETP_c. Both effective rainfall, RE, and cumulative monthly actual irrigation, CMIA, are accounted for.

$$DMAF = DMAI - RE - CMIA + ETP_c \text{ (mm)}$$

The procedure is to compare both DMAI and DMAF against the maximum optimal depletion level, i.e., DIS, in order to estimate whether, and for how long, this depletion was exceeded. During the period that was exceed-ed, the corresponding reduced level of evapotranspiration is estimated, and an overall revised estimate of monthly actual crop ET, ETA_c, is made. A new trial value of final actual soil moisture depletion, DMAFT, is obtained and compared with the previous trial value. If there is close correspondence, the balance is completed, otherwise the procedure is repeated. Up to five such iterations are performed if necessary, and if close correspondence is not achieved, then the average of the two current trial values is taken. An illustration of this procedure is given in Figure C-5.

The first part of the procedure is detailed in the flowchart of Figure C-6. Linear variation of soil moisture depletion through the month is assumed. The time fraction, TF, during the month, when actual crop ET equals crop potential ET, is deduced, together with initial and final depletion fractions, DF1 and DF2, corresponding to the fraction of time during the month when actual crop ET is less than crop potential ET. A mean depletion fraction, DF, for this time is then obtained as a simple average of DF1 and DF2.

The depletion fraction, DF, is then used to evaluate a corresponding evapotranspiration fraction, ETF, defined as the ratio of actual crop ET to crop potential ET.

The assumed form of the relationship between DF and ETF is shown in Figure C-7. The relationship is assumed to vary according to crop type only, but in fact there will also be variation according to soil type. However, it is assumed that, for a wide range of soils of intermediate texture, the variation will not be significant compared to other approximations in the evaluations.

The relationship in Figure C-7 was pre-pared for three representative crops, primarily using information presented by Burt et al. (1981). In that reference, crop evapotrans-piration fraction was related to soil moisture tension rather than to depletion fraction, and an intermediate step was

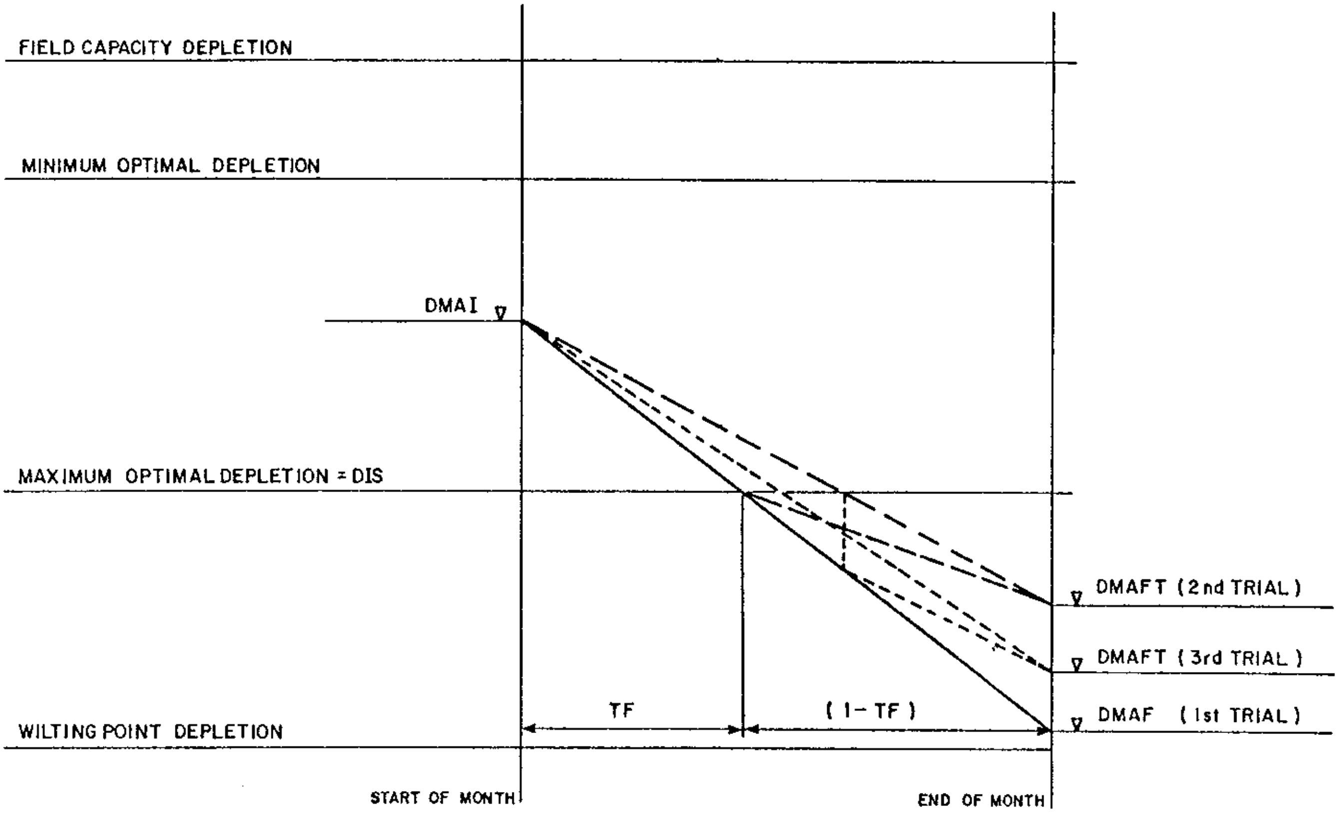


Figure C-5. Actual water balance.

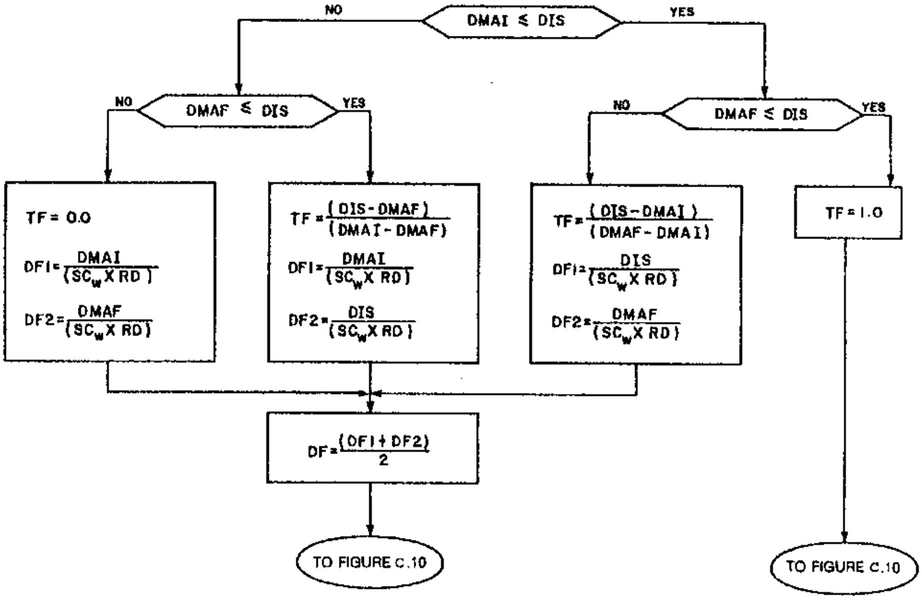
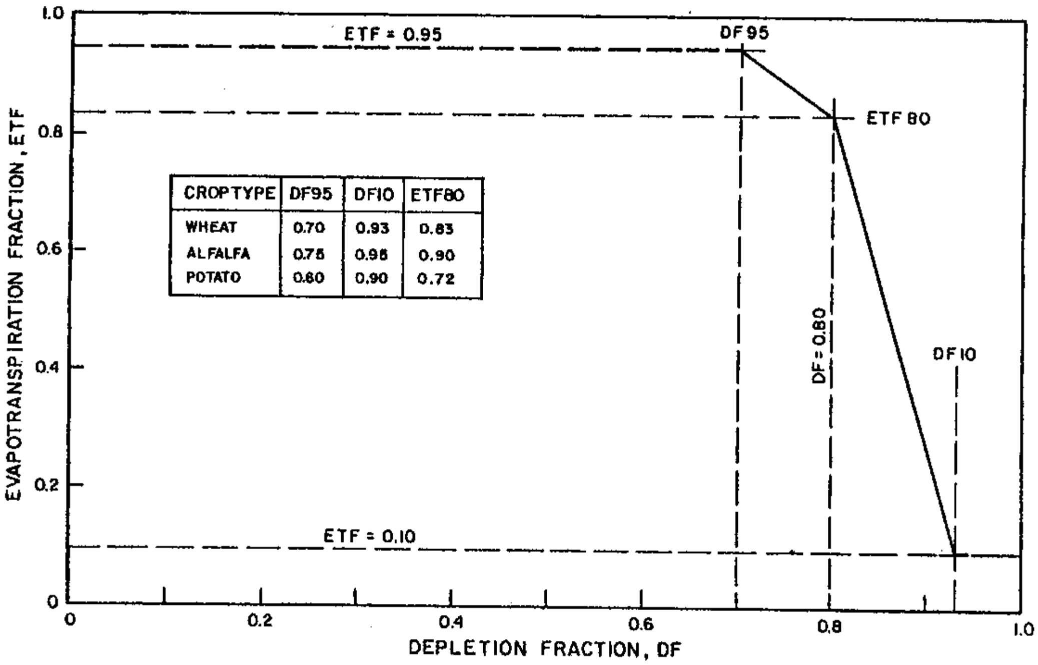


Figure C-6. Time and depletion fractions.



CROPTYPE	DF95	DF10	ETF80
WHEAT	0.70	0.93	0.83
ALFALFA	0.75	0.95	0.90
POTATO	0.60	0.90	0.72

Figure C-7. Definition curve for DF/ETF Relationship.

required to obtain soil soil moisture tension from depletion fraction according to soil type. This approach may be technically superior to the one used here, but the scarcity of regionalized data on soil texture classes and related properties seemed to justify a simpler approach.

Therefore, a relationship between soil moisture tension and depletion fraction was prepared for a soil of intermediate texture, based on information from three sources (Burt et al. 1981; Doorenbos and Pruitt 1975; Ilaco 1981), as shown in Figure C-8. This relationship should adequately represent the range of the predominant agricultural soils under irrigation for purposes of the module. It was then applied to the crop ETF curves used by Burt et al. (1981) to obtain the DF/ETF relationships of Figure C-7.

The DF/ETF relationship is defined uniquely for each crop type by specifying the depletion and evapotranspiration fraction parameters DF95, DF10, and ETF80, shown in Figure C-7 and explained as follows:

- DF95: the value of DF at ETF = 0.95
- DF10: the value of DF at ETF = 0.10
- ETF80: the value of ETF at DF = 0.80

These are used to evaluate ETF from DF by linear interpolation between the defined points, as detailed in the flowchart of Figure C-9.

The resulting estimate of monthly actual crop ET, ETA_c is then given by

$$ETA_c = [TF + (1 - TF) \times ETF] \times ETP \quad (mm)$$

and the new trial value of final depletion, DMAFT, becomes

$$DMAFT = DMAI - RE - CMIA + ETA_c \quad (mm)$$

The absolute value of the difference be-tween DMAFT and DMAF, as a fraction of DMAF, is

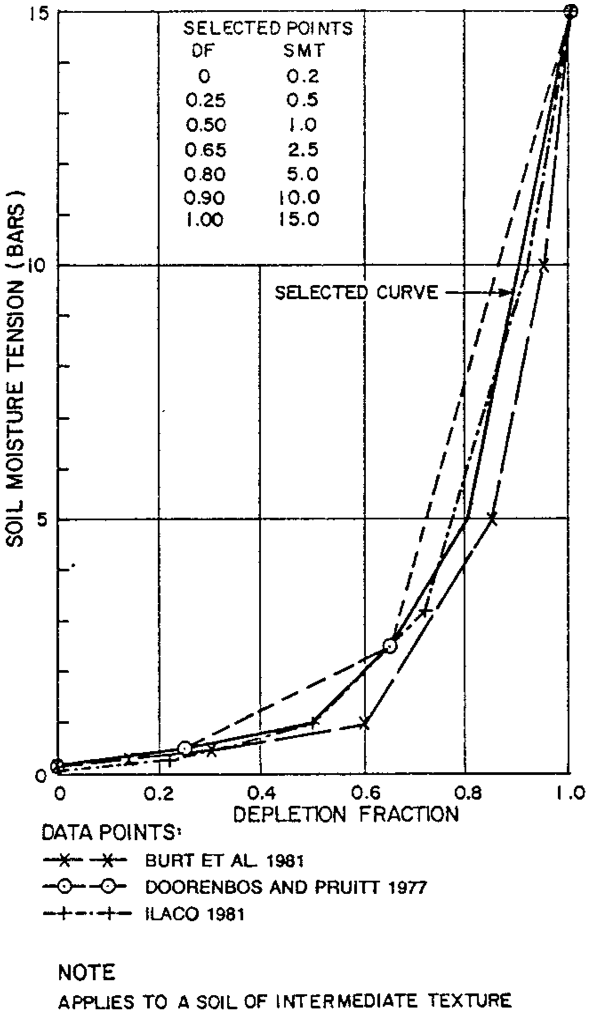


Figure C-8. Soil moisture tension curve.

compared with an acceptable value, taken as 0.01. If the value is exceeded and fewer than five iterations have been performed, then DMAF is set equal to DMAFT and the procedure is repeated. If five iterations have been performed without sufficient convergence of values, then the accepted end-of-month actual soil moisture depletion, DMA, becomes

DMA = (DMAFT + DMAF)/2

If sufficient convergence of values is obtained, then DMA is set equal to DMAFT.

C.4.6 Irrigation for Leaching

The monthly crop leaching requirement, LR_c, can be met in part by the percolation component of rainfall, RP, in part by the percola-tion component of water applied for crop irriga-tion, and in part by additional irrigation specifically for leaching, if required.

Under optimal irrigation, the monthly irrigation amount, CMIO, is fully utilized within the root zone. The water that must be applied to the field to achieve this replenishment is $CMIO/(EA_w/100)$, where EA_w is the weighted application efficiency. Application efficiency, EA, is the portion of total irrigation water applied to the field that enters and remains in the root zone to contribute to evapotrans-piration. The percolation component of this applied water is therefore $(CMIO/EA_w) \times EP_w$, where EP_w is the weighted percolation efficiency.

The additional monthly irrigation for optimal leaching, LMIO, then becomes

$LMIO = LR_c - RP - (CMIO/EA_w) \times EP_w$ (mm)

and if this is negative, then LMIO is set to zero.

It is assumed that suboptimal irrigation for crops implies suboptimal irrigation for leaching to the same extent. Therefore the adjusted level of irrigation, ILA, is used to obtain the actual monthly irrigation for leaching, LMIA, as follows

$LMIA = LMIO \times (ILA/100)$ (mm)

As with crop irrigation, the corresponding monthly volume of additional irrigation for leaching, LMIV, is evaluated as

$LMIV = LMIA \times AT \times (AP_c/100)/10^5$ (MCM)

C.4.7 Diversion, Losses, and Return Flow

Principal values resulting from the previous evaluations are the cumulative

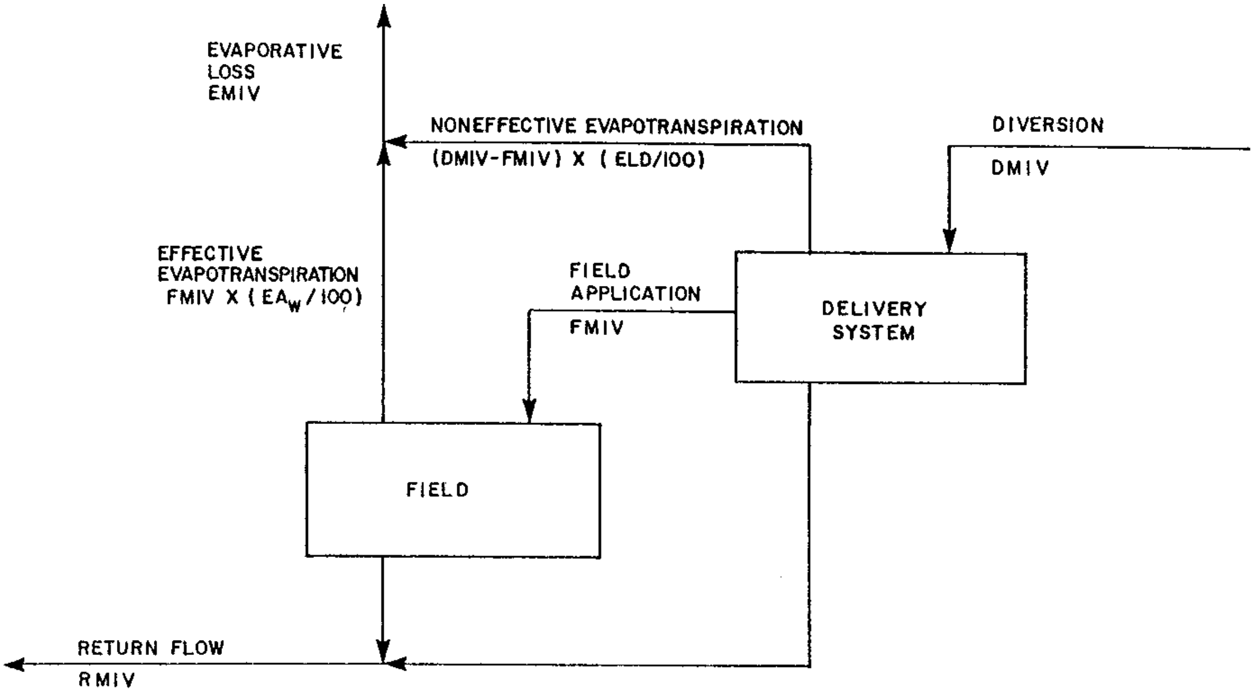


Figure C-9. Evapotranspiration fraction.

monthly actual irrigation amounts, CMIA and CMIV, the additional actual monthly irrigation amounts for leaching, LMIA and LMIV, and the actual moisture depletion, DMA, for the end of the month. This latter is converted to an actual soil moisture depletion fraction, DFAA, for use in the next month's evaluation,

$$DFAA = DMA/(SC_w \times RD)$$

and at the end of the last month of the season, the final actual soil moisture depletion fraction, DFAF, is set equal to DFAA.

The field application to provide the crop irrigation amount to the root zone is CMIV/EA_w/100). Similarly, the field application to provide extra percolation for leaching from irrigation is LMIV/(EP_w/100). Hence, the monthly field irrigation application, FMIV, is given by

$$FMIV = [CMIV/(EA_w/100)] + [(LMIV/ (EP_w/ 100)] \text{ (MCM)}$$

From this, the monthly diversion for irrigation, DMIV, is obtained, using the delivery efficiency, ED

$$DMIV = FMIV/(ED/100) \text{ (MCM)}$$

Delivery efficiency is the ratio of field irrigation application to total diversion, and accounts for all losses in the delivery system between the river and the field.

Of the monthly diversion for irrigation, DMIV, a portion is consumed by crops or retained in the root zone, and another portion is evaporated from open water surfaces in canals, drains, reservoirs, and seepage areas. Together these portions make up the monthly irrigation evaporative or consumptive losses, EMIV.

The in-field consumptive loss is taken as FMIV × (EA_w/100). The delivery system evaporative losses are defined as a percentage delivery evaporative loss, ELD, of the total delivery system losses, (DMIV − FMIV). Thus the overall evaporative (or consumptive) loss, EMIV, is

$$EMIV = FMIV \times (EA_w/100) + (DMIV - FMIV) \times (ELD/100) \text{ (MCM)}$$

The monthly irrigation return flow from the diversion, RMIV, is then

$$RMIV = DMIV - EMIV \text{ (MCM)}$$

This return flow thus accounts for both runoff and percolation components of the diversion at both field level and delivery system level. For regional water balance purposes, this is considered to be appropriate.

Return flow values obtained may not coincide with recorded runoff values in irrigation area outfall drains, since there may be a substantial percolation portion missing from such records. On the other hand, recorded drainage runoff includes rainfall runoff, if any, whereas the calculated diversion return flow does not.

A schematic representation of the balance between diversion, losses and return flow for an irrigation area is shown in Figure C-10.

The monthly irrigation diversion and return flows are output from Module 7B to File 24.

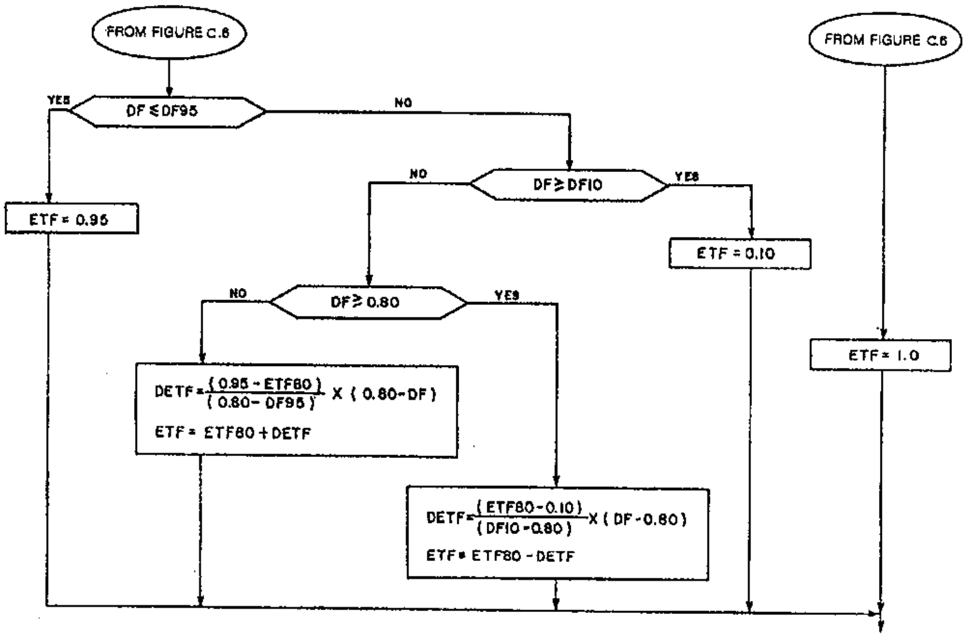


Figure C-10. Balance of diversion, losses, and return flow.

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Symbols

AP_c	Crop type percentage of total irrigated area
AP_i	Irrigation type percentage of total irrigated area
AP_{ih}	Percentage of total area under high irrigation application frequency
AP_{il}	Percentage of total area under low irrigation application frequency
AP_s	Soil type percentage of total irrigated area
AT	Total irrigated area
CF	Crop factor
CMIA	Cumulative monthly actual irrigation
CMIO	Cumulative monthly optimal irrigation
CMIV	Volumetric monthly irrigation
DAF	Depth-of-application factor
DETF	Increment of ETF
DF	Depletion fraction (average of DF1 and DF2)
DF1	Initial depletion fraction for which ETA_c is less then ETP_c
DF2	Final depletion fraction for which ETA_c is less then ETP_c
DF10	Value of DF at ETF = 0.10
DF95	Value of DF at ETF = 0.95
DFA	Constant for evaluation of DFO_{max}
DFAA	Actual soil moisture depletion fraction
DFAF	Final actual soil moisture depletion fraction
DFAI	Initial actual soil moisture depletion fraction
DFB	Constant for evaluation of DFO_{max}
DFO_{max}	Maximum optimal soil moisture depletion fraction
DFO_{min}	Minimum optimal soil moisture depletion fraction
DFOA	Monthly adjustment factor for DFO_{max}
DIA	Actual irrigation depth
DIO	Optimal irrigation depth
DIS	Standard irrigation depth
DMA	Actual soil moisture depletion
DMAF	Final actual soil moisture depletion
DMAFT	Trial value of DMAF
DMAI	Initial actual soil moisture depletion
DMIV	Monthly diversion for irrigation
DMOF	Final optimal soil moisture depletion
DMOI	Initial optimal soil moisture depletion
EA	Application efficiency
EA_w	Weighted application efficiency
EAPTO	Efficiency of application of total out-of-season precipitation
EAR	In-season rainfall application efficiency (selected)
EARA	Actual rainfall application efficiency

ECEA	Soil salinity adjustment factor
ECEN	Tolerable soil salinity for 90% of potential crop yield
$ECEN_{max}$	Maximum soil salinity for 90% of potential crop yield
ECEZ	Tolerable soil salinity for 0% of potential crop yield
$ECEZ_{max}$	Maximum soil salinity for 0% of potential crop yield
ECW	Irrigation water salinity
ED	Delivery efficiency
EL	Leaching efficiency
EL_w	Weighted leaching efficiency
ELD	Delivery evaporative loss
EMIV	Monthly irrigation evaporative loss
EP	Percolation efficiency
EP_w	Weighted percolation efficiency
ETA_c	Actual crop ET
ETF	Evapotranspiration fraction (ETA_c/ETP_c)
ETF80	Value of ETF at DF = 0.80
ETP_c	Crop potential ET
ETP_r	Reference potential ET
FMIV	Monthly field irrigation application
ILA	Adjusted level of irrigation
ILC	Crop level of irrigation
ILCA	Irrigation type adjustment to level of irrigation
$ILCA_w$	Weighted irrigation type adjustment to crop level of irrigation
LMIA	Actual monthly irrigation for leaching
LMIO	Monthly irrigation for optimal leaching
LMIV	Monthly volume of additional irrigation for leaching
LR_c	Crop leaching requirement
LRF	Weighted average leaching requirement fraction
LRFN	Leaching requirement fraction for low irrigation application frequency
LRFZ	Leaching requirement fraction for high irrigation application frequency
NDM	Number of days in the month
P	Precipitation
PTO	Total out-of-season precipitation
PTOE	Effective out-of-season precipitation
RD	Root zone depth
RD_{max}	Maximum root zone depth
RDA	Root zone depth adjustment factor
RE	Effective rainfall (greatest of RE1 and RE2)
RE1	Monthly effective rainfall (USDA/SCS)
RE2	Monthly effective rainfall (alternative)
RMIV	Monthly irrigation return flow
RN	Noneffective rainfall
RP	Percolation component of rainfall
RR	Runoff rainfall
SC	Soil moisture storage capacity
SC_w	Weighted soil moisture storage capacity
SMOF	Final optimal soil moisture surplus
TF	Time fraction for which ETA_c equals ETP_c
X	Independent variable
Y	Dependent variable