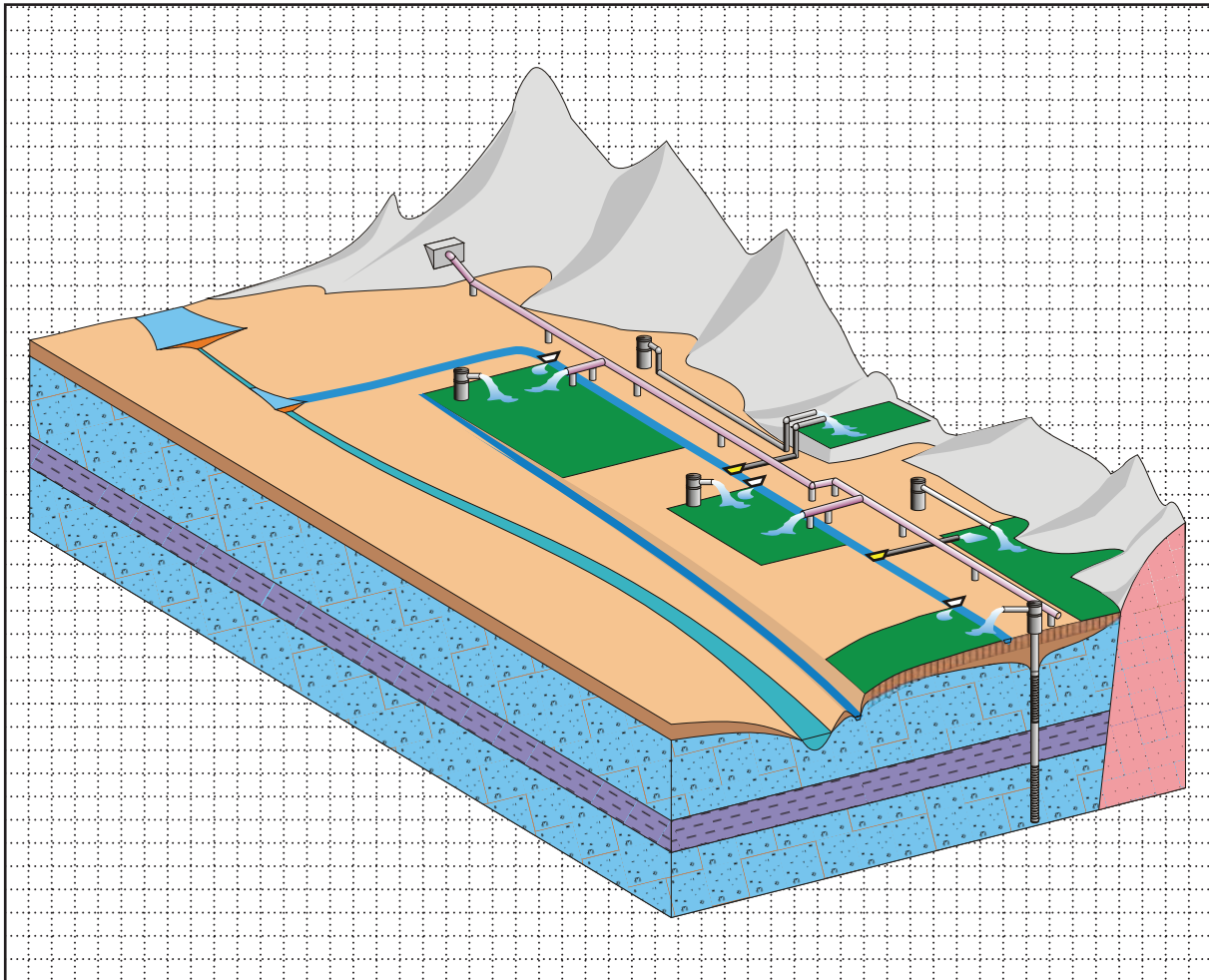


Prepared by the U.S. Geological Survey,
Office of Ground Water, Ground-Water Resources Program

User Guide for the Farm Process (FMP1) for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, MODFLOW-2000

Chapter 17 of
**Section A, Ground Water, of
Book 6, Modeling Techniques**



Techniques and Methods 6–A17

User Guide for the Farm Process (FMP1) for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, MODFLOW-2000

By Wolfgang Schmid¹, R.T. Hanson, Thomas Maddock III², and S.A. Leake

¹Research Hydrologist, Department of Hydrology and Water Resources,
University of Arizona

²Professor and Department Head, Department of Hydrology and Water Resources,
University of Arizona

Prepared by the U.S. Geological Survey,
Office of Ground Water, Ground-Water Resources Program

Techniques and Methods 6–A17

**U.S. Department of the Interior
U.S. Geological Survey**

U.S. Department of the Interior
P. Lynn Scarlett, Acting Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

For product and ordering information:

World Wide Web: <http://www.usgs.gov/pubprod>

Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:

World Wide Web: <http://www.usgs.gov>

Telephone: 1-888-ASK-USGS

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Suggested citation:

Schmid, Wolfgang, Hanson, R.T., Maddock, Thomas, III, Leake, S.A., 2006, User guide for the farm process (FMP1) for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, MODFLOW-2000: U.S. Geological Survey Techniques and Methods 6-A17, 127 p.

Preface

This report presents a computer program for simulating the consumption and redistribution of surface water and ground water from farming in the U.S. Geological Survey (USGS) ground-water model, MODFLOW. The performance of this computer program has been tested in models of hypothetical ground-water flow systems; however, future applications of the programs could reveal errors that were not detected in the test simulations. Users are requested to notify the USGS if errors are found in the report or in the computer program. Correspondence regarding the report or program should be sent to:

U.S. Geological Survey
Water Resources Discipline
4165 Spruance Road, Suite 200
San Diego, CA 92101
Attention: Randall T. Hanson

Although this program has been used by the USGS, no warranty, expressed or implied, is made by the authors, the USGS, or the United States Government as to the accuracy and functioning of the program and related program material. Nor shall the fact of distribution constitute any such warranty, and no responsibility is assumed by the authors or the USGS in connection therewith.

The computer program described herein consists in part of copyrighted scientific methodologies obtained from the copyright holder (Schmid, 2004). The copyright holder has granted full quotation, copy and use of these methods to the USGS and to the public. Requests for modification of copyrighted methods and for publication of such can be made to the copyright holder or to the address listed above.

The computer program documented in this report is part of the MODFLOW-2000 ground-water flow model. These and other ground-water programs are available from the USGS at World Wide Web address:

<http://h2o.usgs.gov/software/>
or by anonymous ftp file transfer from directory:
[/pub/software/ground_water/modflow](ftp://pub/software/ground_water/modflow) at Internet address h2o.usgs.gov

Contents

Abstract	1
Introduction	2
Irrigation Water Demand and Supply	4
Previous Simulation of Crop Demand and Irrigation Water Supply	7
Modeling Agricultural Irrigation Supply and Demand.....	8
Purpose and Scope	8
Acknowledgements.....	8
Farm Process Capabilities.....	8
Consumptive Use	10
Transpiration for Water Levels between Ground Surface and Bottom of Root Zone	11
Consumptive-Use Concept 1.....	11
Consumptive-Use Concept 2.....	14
Transpiration for Water Levels between Bottom of the Root Zone and the Extinction Depth	15
Evaporation for Water Levels between Ground Surface and Extinction Depth.....	16
Head-Dependent Transpiration from Precipitation.....	16
Head-Dependent Crop Irrigation Requirement.....	16
Surface-Water Supply	17
Ground-Water Supply	19
Net Recharge.....	20
Water-Rights Allocation.....	22
Equal Appropriation with Specified Canal Diversions.....	22
Prior Appropriation with Simulated Canal Diversion.....	23
No Senior Farm Downstream of the Farm of Interest on the Same Canal.....	26
Senior Farm Exists Downstream of the Farm of Interest on the Same Canal.....	26
No Senior Farms Exist on Downstream Diverting Canal (Case A).....	27
Senior Farms Exist on Downstream Diversion Canal (Case B).....	27
Modification of Prior Appropriation System for Surface-Water Surplus.....	28
Drought Scenario Alternatives	30
Update of Source Term Flow Rates	30
Applicability and Limitations.....	33
General Data Requirements.....	33
Arrays and Lists of Spatially Distributed Data	33
Two-Dimensional Arrays	34
Ground-Surface Elevation	34
Identification Arrays.....	34
Multi-Dimensional Attribute Lists	35
Farm Wells	35
Stream Segments and Reaches	35
Data Requirements for Entire Simulation	36
Farm-Wells Data	36
Farm Data	40

Farm Irrigation Efficiency	40
Soil-Type Data	42
Crop-Type Data (Natural).....	44
Root-Zone Depth	44
Fraction of Transpiration and Evaporation of Consumptive Use.....	44
Fraction of Inefficiency Losses to Surface-Water Runoff	46
Root-Uptake Coefficients for Stress Response Function.....	46
Specific Crop Coefficients.....	47
Climate Data.....	48
Crop-Type Data (Agro-Economic)	49
Crop-Type-Related Fallow Flags.....	49
Crop-Type Benefits Data.....	49
Water-Cost Coefficients.....	51
Surface-Water Data	53
Nonrouted Deliveries	53
Routed Deliveries.....	53
Semi-Routed Deliveries	53
Fully-Routed Deliveries	54
Stream-Reach Data	54
Data Requirements for each Stress-Period	54
Farm-Wells Data	55
Nonparameter or Parameter Farm-Wells Lists.....	55
Farm Irrigation Efficiencies.....	56
Crop-Type Arrays and Data (Natural Attributes).....	56
Crop-Type Identification Array	56
Crop-Type Data.....	57
Climate Data.....	58
Precipitation Array	58
Crop-Type Data (Agro-Economic).....	58
Crop-Type Benefits Data.....	58
Water-Cost Coefficients.....	59
Surface-Water Data	59
Nonrouted Surface-Water Deliveries	59
Routed Surface-Water Deliveries	61
Water-Rights Data	63
Data Input Instructions	64
Input Data for the FMP1.....	65
Data for each Simulation	65
Data for each Stress Period.....	66
Input Structure of Array and List Reading Utility Modules	67
Control-Record Item a.....	67
Control-Record Item b.....	68
Explanation of Fields Used in the Input Instructions	69
Dimensions and Flags (item 2).....	69
Parameter Dimensions (item 2)	69

Farm-Well Related Variables (items 3, 4, 22, 23)	74
Farm Well Parameter Definition (item 3):.....	74
Two-Dimensional Arrays (items 5, 6, 8, 10, 25, 30)	75
Farm Related Data Lists (items 7, 19, 20, 24, 32, 33, 34, 36).....	75
Soil Type Related Data List (item 9).....	75
Crop-Type-Related Data List (Natural Crop Growth Parameters) (items 11–15, 25–29).....	76
Climate-Related Data (items 16, 30).....	76
Climate Time Series (item 16):.....	76
Precipitation Array (item 30):.....	77
Crop-Type-Related Data Lists (Agro-Economic Parameters) (items 17, 18, 31)	77
Fallow List (item 17):	77
Water Cost Coefficients (items 19, 32).....	77
Ground-Water Cost Coefficients:	77
Surface-Water Cost Coefficients:.....	77
Nonrouted Surface-Water Deliveries–Farm-Related Data List (item 33).....	77
Semi-Routed Surface-Water Deliveries–Farm-Related Data List (items 20, 34).....	78
Surface-Water Allotment (items 35, 36)	78
Equal Appropriation:.....	78
Prior Appropriation:.....	78
Output Data for Farm Process	78
Farm-Well Budget.....	79
Farm Net-Recharge Budget.....	79
Farm Supply and Demand Budget	79
Optimized Flow Rates and Optimized Acreage of Farms	80
Budgets at Points of Canal Diversion and Farm Diversion	81
Example Problems	82
References Cited.....	102
Appendix.....	105

Figures

Figure 1.	Diagram showing supply and demand components and relations to potential applications of MODFLOW-2000 with the FMP1.....	2
Figure 2.	Diagram showing supply and demand components and connections to other models and packages by the FMP1	3
Figure 3.	Diagram showing flow chart of the flow of water into and out of the Farm Budget as simulated by the FMP1	5
Figure 4.	Diagram showing cases of sufficiency and insufficiency of irrigation water supply in a surface-water dominated irrigation setting.....	9
Figure 5.	Graph showing transient course of root uptake and flux across the water table or different depths to water table	13
Figure 6.	Graph showing variation of actual root uptake from ground water, and of maximum actual root uptake from ground water and irrigation, with changing water level	13
Figure 7.	Graph showing linear approximation of pseudo-steady-state root uptake from ground water and maximum actual root uptake from ground water and irrigation water.....	14
Figure 8.	Graphs showing crop specific stress response function, and analytical function fitting the vertical pressure head distribution over depth	15
Figure 9.	Diagrams showing two conceptual approximations to change of crop consumptive-use components with varying head	16
Figure 10.	Diagram showing numerical procedure for determining the diversion rate to a canal for farms subject to a water-rights allocation hierarchy.....	24
Figure 11.	Graphs showing concept of Deficit Irrigation Policy	29
Figure 12.	Graphs showing concept of Water-Stacking Policy	29
Figure 13.	Flowchart showing the updating of source-term flow-rates depending on the drought-response policy chosen	32
Figure 14.	Map showing streamflow-routing segment-numbering scheme in relation to direction of flow and model grid	36
Figure 15.	Diagram showing transpiratory and evaporative fractions of consumptive use	45
Figure 16.	Diagram showing model domain and boundary conditions and initial heads for the FMP1 example problems	83
Figure 17.	Diagrams showing model domain with farms and related wells for example problems 1 and 2 and crops and soils for both problems	84
Figure 18.	Graphs showing irrigation demand and surface- and ground-water supply for Farms 1, 2, 3, and 4 for example problem 1.....	86
Figure 19.	Graphs showing irrigation demand and surface- and ground-water supply for Farms 1, 2, 3, and 4 for example problem 2	88
Figure 20.	Graph showing spatial distribution of fractions of crop acreage for farm cells in example problem 2	101

Tables

Table 1. Summary of variably saturated flow equations and soil-water constitutive functions used in HYDRUS2D to develop unsaturated-flow approximations incorporated in the FMP1.....	12
Table 2. Example of soil-type attributes associated with the Soil-Type ID	42
Table 3. Summary of Farm Budget Components.....	80
Table 4. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 1.....	92
Table 5. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 2.....	96

Conversions, Datum, Abbreviations, Acronyms, and Variable Definitions

Pound/SI

Multiply	By	To obtain
acre	4,047	square meter (m ²)
acre	0.4047	hectare (ha)
foot (ft)	0.3048	meter (m)
square foot (ft ²)	929.0	square centimeter (cm ²)
square foot (ft ²)	0.09290	square meter (m ²)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
pound per square foot (lb/ft ²)	0.04788	kilopascal (kPa)

SI/Pound

Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
cubic meter per day (m ³ /d)	0.000811	acre-foot per day (acre-ft/d)
square meter (m ²)	0.0002471	acre
square centimeter (cm ²)	0.001076	square foot (ft ²)
square meter (m ²)	10.76	square foot (ft ²)
square centimeter (cm ²)	0.1550	square inch (ft ²)
hectare (ha)	0.003861	square mile (mi ²)
kilogram (kg)	2.205	pound avoirdupois (lb)
kilogram per cubic meter (kg/m ³)	0.06242	pound per cubic foot (lb/ft ³)
kilograms per hectare (kg/ha)	0.8921	pounds per acre (lb/acre)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$$

Elevation as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft³/d)/ft²]²ft. In this report, the mathematically reduced form, foot squared per day (ft²/d), is used for convenience.

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm²) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm³) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter. Metric ton (t) as a name for megagram (Mg) should be restricted to commercial usage, and no prefixes should be used with it.

Abbreviations, Acronyms, and Variable Definitions

$a(\psi)$	= dimensionless water stress response function [-]; $\forall 0 \leq a \leq 1$
ψ	= pressure head [L]
[-]	= signifies dimensionless units
AI	= average available irrigation per cell, in case of irrigation insufficiency [L^3/T]
AVI	= actual available irrigation per cell, in case of irrigation insufficiency [L^3/T]
ARU_{max}	= maximum actual root uptake = $T_{c-act-max}$ [L/T] \cdot [L^2]
ASR	= aquifer storage-and-recovery
AZ	= depth of anoxia zone [L]
CIR	= crop irrigation requirement per cell (CIR = $E_i + T_i$) [L/T] \cdot [L^2]
CU	= consumptive use per unit area [L/T], or per cell [L/T] \cdot [L^2]
DEL_{act}	= actual surface-water delivery from a head gate at a canal to a farm [L^3/T]
DEL_{pot}	= potential surface-water delivery to a farm's head gate [L^3/T]
DRZ	= depth of depleted root zone = part of root zone at which pressure heads ψ increase with depth from a minimum pressure head ψ_4 to 0 ($\forall \psi_4 < \psi < 0$). [L]
E_{c-act}	= actual evaporative consumptive use per cell [L/T] \cdot [L^2]
E_{c-pot}	= potential evaporative consumptive use per cell = $(1-K_t) \cdot ET_{c-pot}$ [L/T] \cdot [L^2]
E_{gw-act}	= actual evaporation uptake from ground water per cell [L/T] \cdot [L^2]
$E_{gw-act-max}$	= maximum evaporation uptake from ground water per cell [L/T] \cdot [L^2]
E_i	= evaporation requirement from irrigation = $T_i \cdot (K_e^i/K_t)$, $\forall 0 \leq K_e^i < 1$, $0 < K_t \leq 1$ [L/T] \cdot [L^2]
E_p	= evaporation from precipitation per cell [L/T] \cdot [L^2]
E_{p-act}	= actual evaporation from precipitation per cell [L/T] \cdot [L^2]
E_{p-pot}	= potential evaporation from precipitation per cell [L/T] \cdot [L^2]
ET	= evapotranspiration
ET_{c-act}	= actual crop evapotranspiration = actual crop consumptive use [L/T] \cdot [L^2]
ET_{c-pot}	= potential crop evapotranspiration = potential crop consumptive use [L/T] \cdot [L^2]
ET_{gw}	= evapotranspiration from ground water per cell [L/T] \cdot [L^2]
ET_p	= evaporation and transpiration from precipitation per cell [L/T] \cdot [L^2]
FMP	= Farm Process
GDD(d)	= Growing Degree Days for a certain crop and a certain day d [$^{\circ}F$ or $^{\circ}C$]
GSE	= ground surface elevation [L]
h	= aquifer head; potentiometric head [L]
I	= applied irrigation per cell [L^3/T] [sufficiency case: $I = TDR$ or insufficiency case: $I = AVI$]
IE_{sw}^i	= fraction of inefficient losses to surface-water runoff related to irrigation [-]
IE_{sw}^p	= fraction of inefficient losses to surface-water runoff related to precipitation [-]
IGSM	= Integrated Ground-Water and Surface-Water Model
IWFM	= Integrated Water-Flow Model
K_e^i	= evaporative fraction of consumptive use related to irrigation [-]
K_e^p	= evaporative fraction of consumptive use related to precipitation [-]
K_t	= transpiratory fraction of consumptive use [-]
MF2K	= MODFLOW-2000
MNW	= Multi-Node Well Package
n	= sinuosity coefficient, expressing curvature of the vertical pressure head configuration over the depth of the root zone in analytical solution [-] (unless n does not represent a dimension or numbering index)
$NRD_{act}^{f,t}$	= actually used nonrouted delivery of type t to farm f [L^3]
$NRD_{pot}^{f,t}$	= potentially available nonrouted delivery of type t to farm f [L^3]
$NRD_{use}^{f,t}$	= binary "NRD _{use} -Flag" of a nonrouted delivery type t to a farm f

OFE	= on-farm efficiency (fraction of applied irrigation, which is needed for evapotranspiration by the crop to avoid undesirable water stress) [-]
P	= precipitation per unit area [L/T], or per cell [L/T]·[L ²]
QAVF	= average required discharge per farm well = QREQ/number of wells in a farm [L ³ /T]
Q ⁱ _{max}	= maximum capacity of each well i = QMAX [L ³ /T]
Q _{diversion}	= diversion applied in simulation [L ³ /T]
Q _{spec-div}	= user-specified diversion inflow into first reach of diversion segment [L ³ /T]
Q _{stream-inflow}	= stream-inflow into the last reach of an upstream segment [L ³ /T]
Q _{spec-max}	= user-specified maximum streamflow for last reach of upstream segment [L ³ /T]
QMAXF	= cumulative maximum capacity of all farm wells in a farm [L ³ /T]
QREQ	= a farm's ground water pumping requirement = TFDR-DEL _{act} [L ³ /T]
RD(d)	= root depth for a specific crop and a certain day d [L]
SFR1	= Streamflow Routing Package
T _{c-act}	= actual transpiratory consumptive use per cell [L/T]·[L ²]
T _{c-act-max}	= maximum actual transpiratory consumptive use per cell = T _{c-pot} · [1-AZ/TRZ] [L/T]·[L ²]
T _{c-pot}	= potential transpiratory consumptive use per cell = K _t · ET _{c-pot} [L/T]·[L ²]
TDR	= total irrigation delivery requirement per cell (TDR = CIR/OFE) [L ³ /T]
TFDR	= total farm irrigation delivery requirement of any one farm [L ³ /T]
T _{gw-act}	= actual transpiration uptake from ground water per cell [L/T]·[L ²]
T _{gw-act-max}	= maximum actual transpiration uptake from ground water per cell = T _{c-pot} · [1-(AZ+WZ)/TRZ] [L/T]·[L ²]
T _i	= transpiration requirement from irrigation per cell = T _{c-act} - T _{gw-act} - T _{p-act} [L/T]·[L ²]
TNRD ^f	= total of all types of actually used nonrouted deliveries to farm f
T _p	= transpiration from precipitation per cell [L/T]·[L ²]
T _{p-act}	= actual transpiration from precipitation per cell [L/T]·[L ²]
T _{p-pot}	= potential transpiration from precipitation per cell [L/T]·[L ²]
TRZ	= depth of total root zone [L]
WZ	= depth of wilting zone [L]

Organizations

CADWR	California Department of Water Resources
USGS	U.S. Geological Survey

User Guide for the Farm Process (FMP1) for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, MODFLOW-2000

By Wolfgang Schmid¹, R.T. Hanson, Thomas Maddock III², and S.A. Leake

Abstract

There is a need to estimate dynamically integrated supply-and-demand components of irrigated agriculture as part of the simulation of surface-water and ground-water flow. To meet this need, a computer program called the Farm Process (FMP1) was developed for the U.S. Geological Survey three-dimensional finite-difference modular ground-water flow model, MODFLOW-2000 (MF2K). The FMP1 allows MF2K users to simulate conjunctive use of surface- and ground water for irrigated agriculture for historical and future simulations, water-rights issues and operational decisions, nondrought and drought scenarios. By dynamically integrating farm delivery requirement, surface- and ground-water delivery, as well as irrigation-return flow, the FMP1 allows for the estimation of supplemental well pumpage. While farm delivery requirement and irrigation return flow are simulated by the FMP1, the surface-water delivery to the farm can be simulated optionally by coupling the FMP1 with the Streamflow Routing Package (SFR1) and the farm well pumping can be simulated optionally by coupling the FMP1 to the Multi-Node Well (MNW) Package. In addition, semi-routed deliveries can be specified that are associated with points of diversion in the SFR1 stream network. Nonrouted surface-water deliveries can be specified independently of any stream network. The FMP1 maintains a dual mass balance of a farm budget and as part of the ground-water budget.

Irrigation demand, supply, and return flow are in part subject to head-dependent sources and sinks such as evapotranspiration from ground water and leakage between the conveyance system and the aquifer. Farm well discharge and farm net recharge are source/sink terms in the FMP1, which depend on transpiration uptake from ground water and other head dependent consumptive use components. For heads rising above the bottom of the root zone, the actual transpiration is taken to vary proportionally with the depth of the active root zone, which can be restricted by anoxia or wilting. Depths corresponding to anoxia- or wilting-related pressure heads within the root zone are found using analytical solutions of a vertical pseudo steady-state pressure-head distribution over the depth of the total root zone (Consumptive Use Concept 1). Alternatively, a simpler, conceptual model is available, which defines how consumptive use (CU) components vary with changing head (CU Concept 2).

Subtracting the ground water and precipitation transpiration components from the total transpiration yields a transpiratory irrigation requirement for each cell. The total farm delivery requirement (TFDR) then is determined as cumulative transpiratory and evaporative irrigation requirements of all farm cells and increased sufficiently to compensate for inefficient use from irrigation with respect to plant consumption. The TFDR subsequently is satisfied with surface- and ground-water delivery, respectively constrained by allotments, water rights, or maximum capacities.

Five economic and noneconomic drought response policies can be applied optionally, if the potential supply of surface water and ground water is insufficient to meet the crop demand: acreage-optimization with or without a water conservation pool, deficit irrigation with or without water-stacking, and zero policy.

¹Research Hydrologist, Department of Hydrology and Water Resources, University of Arizona

²Professor and Department Head, Department of Hydrology and Water Resources, University of Arizona

Introduction

The estimation of irrigation demand from a combination of surface water and ground water is a fundamental requirement that is a widely needed feature of ground-water models, such as MODFLOW (*fig. 1*). The current simulation capability of irrigation demand and irrigation water supply in MODFLOW, however, has required prior estimation of the fundamental components of irrigation that may include plant consumption, evaporation, effective precipitation, surface-water delivery, supplemental pumpage of ground water, irrigation runoff, and deep percolation through the partially saturated root zone of excess applied irrigation. Conjunctive use of surface water and ground water commonly is complex for most modern agricultural settings. Typically conjunctive use is complicated by the fact that ground-water pumpage is not always metered and estimation of pumpage is required for simulation of ground-water flow in agricultural areas. The integrated estimation of plant and soil consumption of precipitation, as well as applied surface- and ground-water deliveries, is needed to estimate a complete farm budget and related inflow and outflow components that are connected to the surface- and ground-water flow systems. In addition, it is critical that the farm budget be implicitly linked to these systems through head-dependent relations that allow the consumptive requirements of the crops and the natural evaporation of the soils to be dependent on the water-level in the uppermost aquifer. Heads in aquifers below the irrigated agriculture, therefore, are coupled to the evaporation and transpiration that occurs in the root zone of the soils on a cell-by-cell basis. The simulation of inflows and outflows to the farm and ground-water systems also should represent fallow or noncultivated regions, as well as urban irrigation located within the modeling domain.

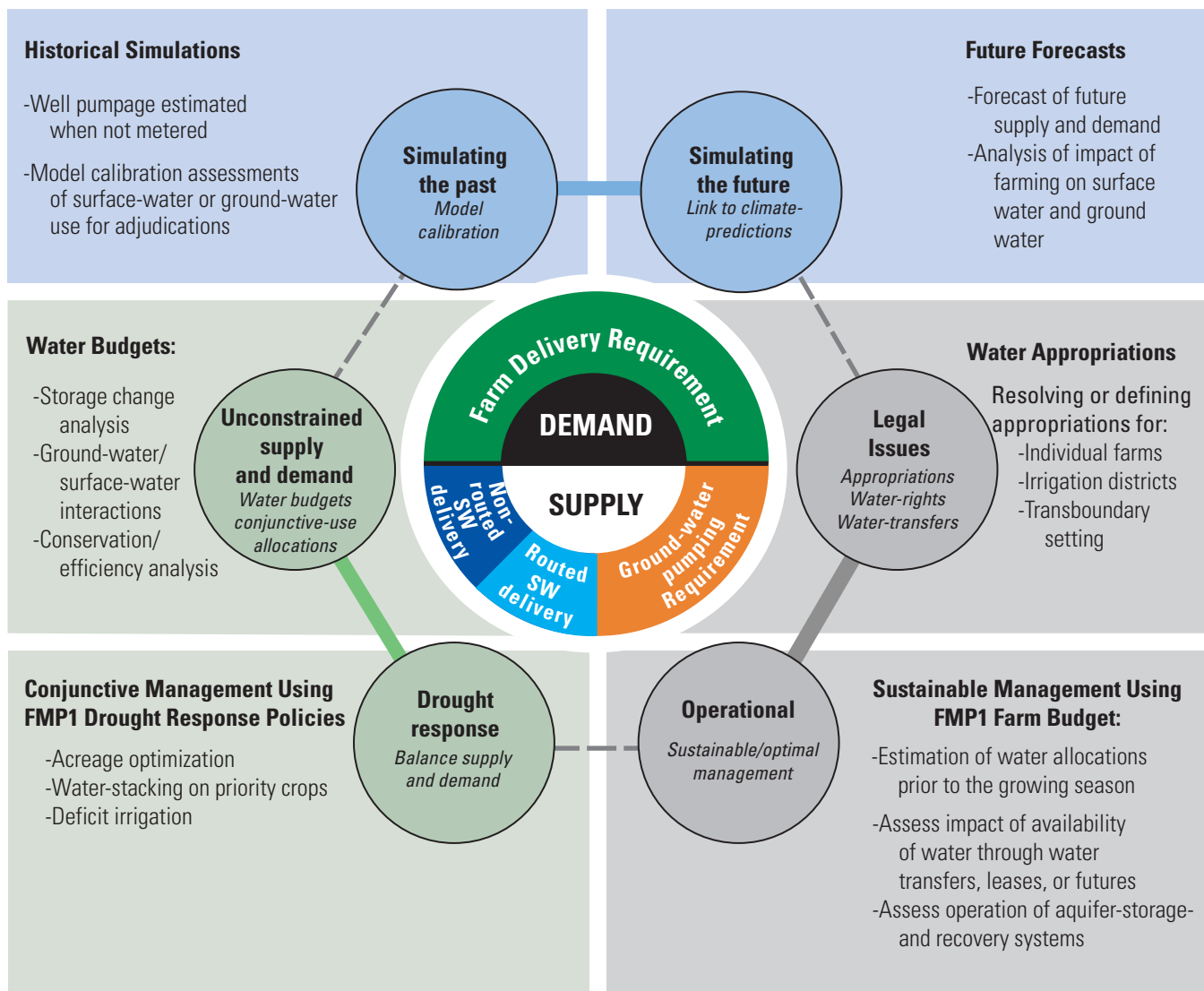


Figure 1. Supply and demand components and relations to potential applications of MODFLOW-2000 with the FMP1.

The Farm Process (FMP1) described in this user’s manual is designed to simulate demand components representing crop irrigation requirement and on-farm inefficiency losses, and the supply components representing surface-water deliveries and supplemental ground-water pumpage, as well as additional head-dependent inflows and outflows such as canal losses/gains, surface runoff, surface-water return flows, and deep percolation of excess water (fig. 2). Data input requirements for these components are discussed in more detail in the section “General Data Requirements.” In addition, the FMP1 also has the capability to estimate economically optimal allocations through acreage optimization of water supplied by surface- and ground-water deliveries when demand exceeds supply. Other noneconomic drought-response scenarios also are available, such as deficit irrigation and water stacking.

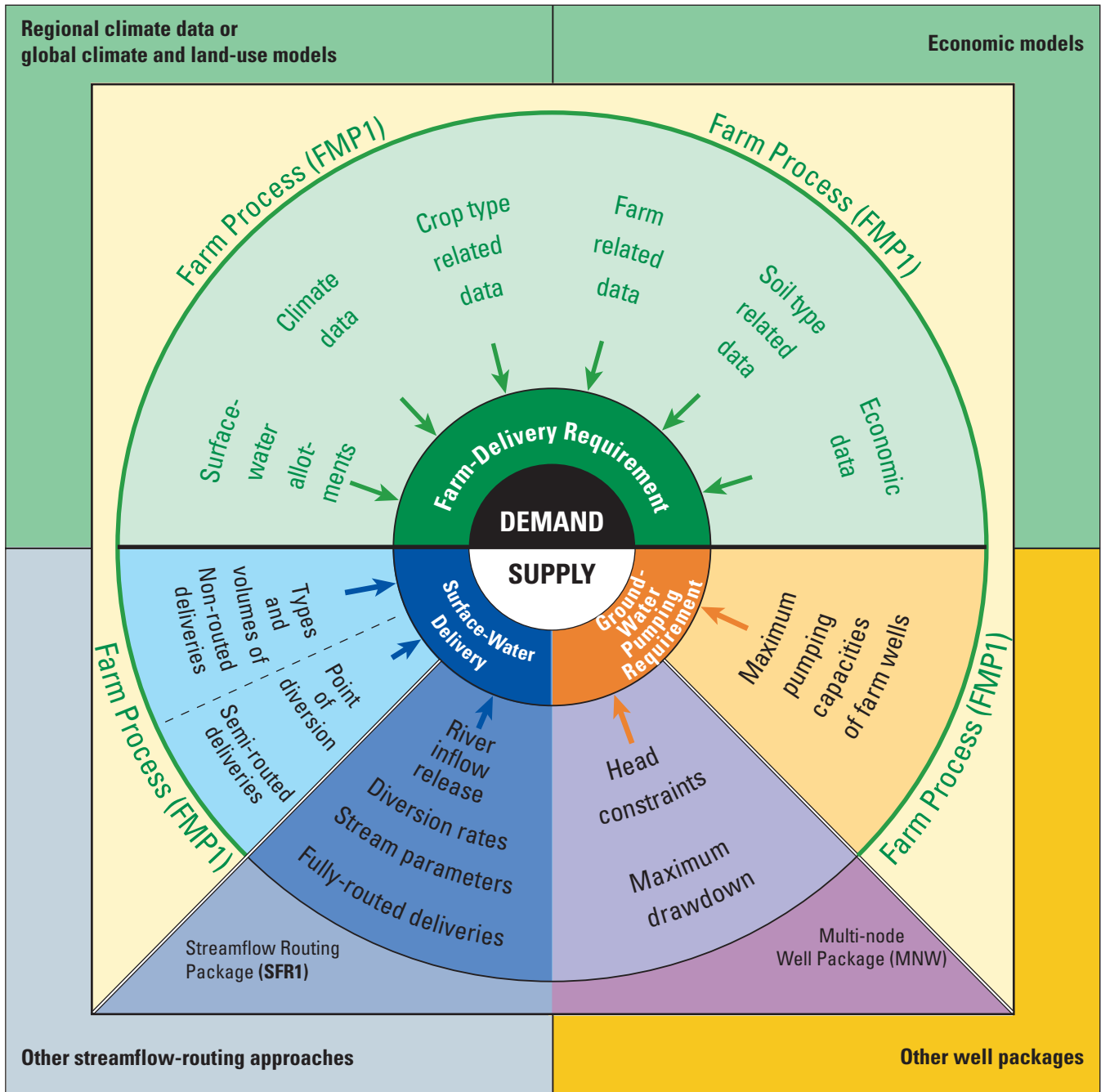


Figure 2. Supply and demand components, data requirements, and connections to other models and packages by the FMP1.

4 User Guide for the Farm Process (FMP1) for the U.S. Geological Survey's MODFLOW-2000

As part of the U.S. Geological Survey's ground-water modeling program MODFLOW-2000 (MF2K) (Harbaugh and others, 2000), the FMP1 provides four objectives for determining the major supply and demand components (*fig. 2*):

- Estimation of consumptive use;
- Simulation of surface-water supply distribution;
- Simulation and estimation of ground-water pumpage supplemental to surface-water supply, to meet the irrigation water demand of each farm unit;
- Identify whether irrigation water supply to a farm unit from surface water and ground water is sufficient to meet the farm's irrigation water demand or else to apply a user-specified drought³ response policy.

Combined with other MODFLOW-2000 packages such as the streamflow routing (SFR1) and multi-node well (MNW) packages, the FMP1 helps to transform MF2K from a predominantly ground-water-flow model to a more complete hydrologic model that simulates the hydrologic components of land-use as well as surface-water and ground-water-flow processes. In addition to linkage with other packages, FMP1 facilitates more direct linkage with other models such as Global Climate models (also referred to as General Circulation Models) for potential projections of future conditions, economic models for assessment of additional economic aspects of water policy and water projects as well as other surface-water routing approaches such as reservoir models and other ground-water sources such as springs or aquifer-and-storage facilities (*fig. 2*).

The FMP1 integrates various components of supply and demand data that can be variously specified over the different time frames of time steps, stress periods, or held constant for the entire simulation (*fig. 2*). The Farm Delivery Requirement requires soil, crop, and climate data to compute consumptive use. In addition, if drought policy scenarios are invoked to estimate the adjustments needed to balance demand with reduced supplies, economic data are also used to estimate the reduced consumptive use (*fig. 2*). Similarly, the water supply requires surface-water delivery and farm-well data to estimate the routed and nonrouted surface-water deliveries and the ground-water pumping requirements, respectively (*fig. 2*). Data input requirements for these components are discussed in more detail in the section "General Data Requirements."

The FMP1 dynamically simulates these supply and demand features for a farm unit within MF2K by integrating the following computational features (*fig. 3*):

(1) Total farm delivery requirement (irrigation demand), which depends on changing climate (evapotranspiration and precipitation) and variable aquifer head (*fig. 3: 1*);

(2) Actual surface-water delivery to the farm, which may be driven by irrigation demand, but limited to canal stream inflow at the farm's diversion head gate, or limited by allotments or by semi- or nonrouted deliveries (*fig. 3: 2*);

(3) Supplemental ground-water pumpage, which is estimated as the irrigation demand minus the actual surface-water delivery, but limited by a specified maximum farm well-pumping capacity (*fig. 3: 3*);

(4) Net recharge to ground water, which is taken to be the excess irrigation plus excess precipitation minus surface-water runoff minus the evapotranspiration from ground water (*fig. 3: 4*); and

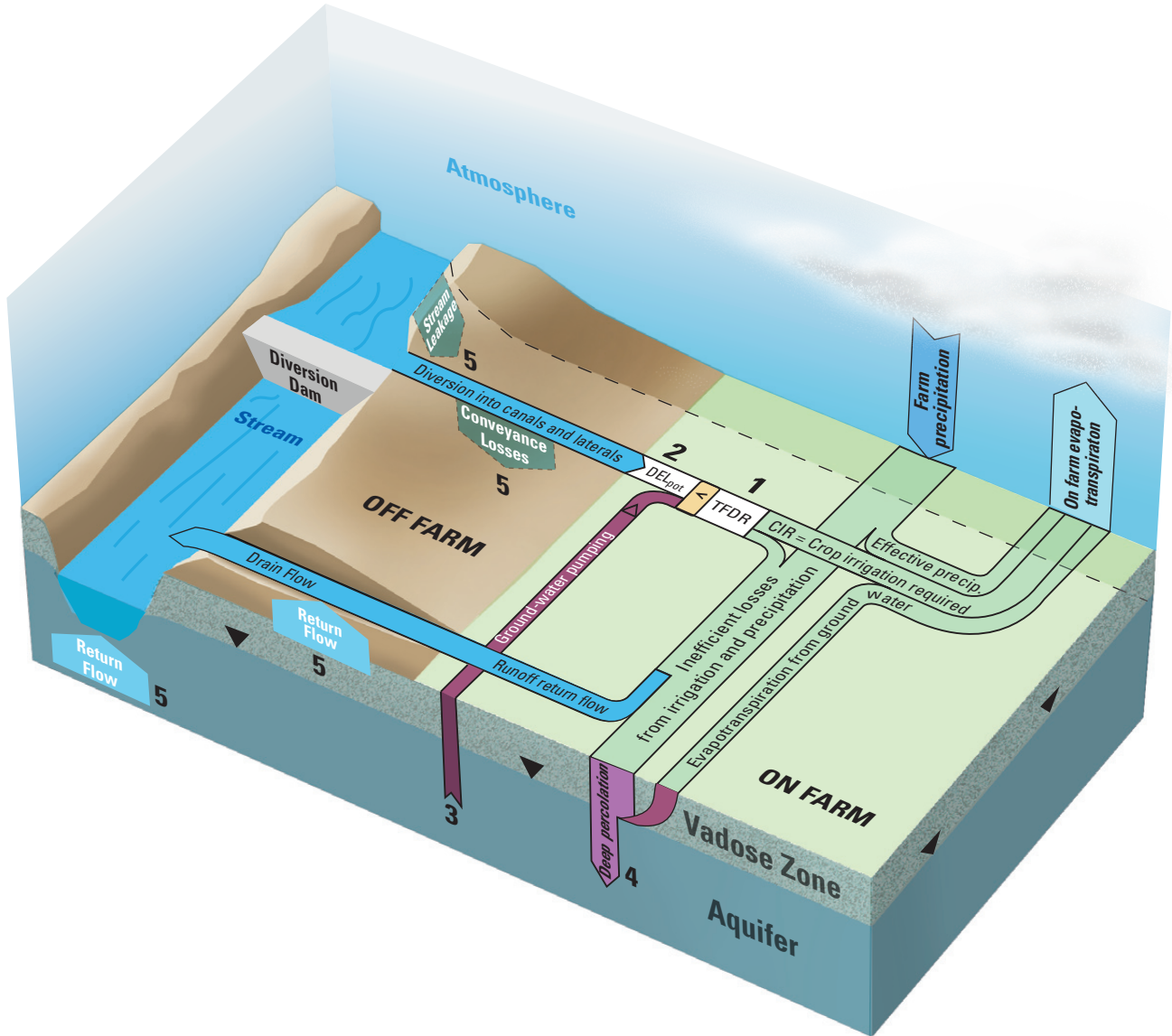
(5) Identification of the irrigation water supply insufficiency and application of a user-specified drought response policy (not shown in *fig. 3*).

The FMP1 dynamically links the demanded and actually supplied flow rates and related aquifer head (*fig. 3*).

Irrigation Water Demand and Supply

The ability to simulate allocations of surface-water and ground-water flow rates to a farm is desirable for incorporating legal requirements such as stream or ground-water adjudications into simulations, drought management, and for agro-economic decision making ahead of the cropping season (*fig. 1*). The need to specify these flow rates applies to simulation of historic and future periods. Estimation of these allocations may be necessary during periods when irrigation water supply is sufficient or insufficient to meet the irrigation water demand (*fig. 1*). Since well pumpage is not always metered in regional aquifer systems such as the areas of the southwestern and southeastern United States, it is of great advantage to simulate historical pumpage instead of estimating pumpage indirectly from power records or land-use maps (*fig. 1*). This approach was driven by the context of water use and water law from the western United States that is derived from the prior appropriation history of the Spanish. The application of the FMP1 to riparian water law and policies derived from the English that are more prevalent in the eastern United States, can still use the FMP1 by not employing any farm wells. Future versions of FMP1 will allow for more user options regarding the order of use of supply and demand components that also could facilitate urban use over agricultural use and ground-water use over surface-water supplies.

³For the purposes of this study, the definition of degrees of "drought" is operational, not climatic, and is defined as: first-degree drought = insufficiency of surface-water supply; second-degree drought = insufficiency of surface-water and ground-water supply.



EXPLANATION

Flux related to atmosphere

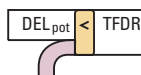
- Flux from atmosphere
- Flux to atmosphere

Flux related to stream-channel

- Flux out of stream
- Flux into stream

Flux related to aquifer

- Flux out of aquifer
- Flux into aquifer



Example of operational decision making

If surface-water budget between supply (Surface-Water Delivery) and demand (Total Farm Irrigation Delivery Requirement) is negative, then supplemental ground-water pumping is required

Computational features

- 1** Total farm delivery requirement (TFDR) (simulated by FMP1)
- 2** Actual surface-water delivery (minimum of TFDR and potential available surface-water delivery) (DEL_{pot}) (simulated by FMP1)
- 3** Supplemental well pumpage from farm wells (on or off farm) (simulated by FMP1)
- 4** Net recharge, on farm (simulated by FMP1)
- 5** Off-farm leakage between stream-canal-drain network and aquifer (simulated by SFR1)

Figure 3. Flow chart of the flow of water into and out of the farm budget as simulated by the FMP1.

6 User Guide for the Farm Process (FMP1) for the U.S. Geological Survey's MODFLOW-2000

The core concept of estimating crop irrigation requirement and the potentially related ground-water pumpage is based on a simple farm irrigation water budget (herein referred to as the farm budget). The FMP1 estimates budget components of (1) farm irrigation demand, and (2) water supply from surface-water and ground-water sources. The FMP1 does not account for water storage in a farm or water storage in the unsaturated zone.

(1) Irrigation water demand is simulated by the FMP1 as part of the farm budget. The FMP1 estimates the Total Farm Delivery Requirement (TFDR) as the sum of the Crop Irrigation Requirements (CIR) of all finite difference cells in any farm divided by the On-Farm Irrigation Efficiency (OFE). Each farm's TFDR (*fig. 3*) includes all crop transpiratory and evaporative needs from irrigation in a farm, and accounts in addition for the level of efficiency of water use. Subtracting the transpiration components that are supplied by uptake from ground water and by precipitation from the total transpiration yields a transpiratory irrigation requirement for each cell. The total farm delivery requirement (TFDR) then is determined as cumulative transpiratory and evaporative irrigation requirements (T_i and E_i) of all finite difference cells in a farm, increased sufficiently to compensate for inefficient use. The TFDR subsequently is satisfied with surface- and ground-water delivery, respectively constrained by allotments, water rights, or maximum capacities. The TFDR is simulated for each farm unit by FMP1 as:

$$TFDR = \sum_{Farm} (CIR / OFE), \quad (EQ.1)$$

with

$$CIR = T_i + E_i$$

where

CIR	= Crop Irrigation Requirement of any model cell in a farm
T_i	= Transpiration supplied by irrigation ($T_i = T_{c-act} - T_{gw-act} - T_{p-act}$)
T_{c-act}	= Actual crop transpiration requirement at steady state
T_{gw-act}	= Portion of actual transpiration supplied by ground water at steady state
T_{p-act}	= Portion of actual transpiration supplied by precipitation at steady state
E_i	= Evaporation losses from irrigation (E_i is an estimate of the compensation needed for surface-evaporative losses, and defined to vary proportionally to T_i), and
OFE	= On-Farm Irrigation Efficiency, defined as fraction of beneficially applied irrigation water to the field (OFE is specified by the user).

The CIR is the supplemental irrigation requirement needed to supply crop transpiration after water supplied from effective precipitation and uptake of ground water. The transpiration and evaporation components, T_{c-act} , T_{gw-act} , T_{p-act} , and E_i , are assumed to occur at steady state for each model time step, and are dependent on climatic factors and aquifer head.

(2) Irrigation water supply is simulated by the FMP1 as part of the farm budget, which estimates additional water supplied by two potential components: surface-water deliveries and ground water. Surface-water supplies can be simulated as routed, semi-routed, and nonrouted deliveries. Ground water can be supplied through ground-water pumpage. The FMP1 can be used to simulate supplies that include any one or any combination of these supply components. Surface-water supplies that are fully or semi-routed can be simulated in combination with the SFR1 package (Niswonger and others, 2005). The streamflow network can represent any combination of natural or artificial channels that are capable of conveying surface water to the adjacent farms. These deliveries are simulated as diversions onto a farm from a head-gate adjacent to a farm for fully routed deliveries or from a remote specified point of diversion for semi-routed deliveries.

Previous Simulation of Crop Demand and Irrigation Water Supply

Numerous regional ground-water flow models have used estimates of crop demand and irrigation water supply. However, most of these models simulated the components of irrigated agriculture through a priori estimates of supply and demand with related inflows and outflows. Previous ground-water simulations required estimating the consumptive use supplied by ground-water pumpage and the related irrigation efficiencies that collectively represent the amount of applied water supplied with ground water. Since most agricultural areas do not have metered pumpage, typically these estimates of ground-water pumpage were made through indirect estimates from other types of data. For example, Williamson and others (1989) used electrical power records to make detailed estimates of ground-water pumpage for the Central Valley, California. In other areas where many of the pumps are powered by diesel or gasoline engines in combination with electrical power, indirect estimates of ground-water pumpage have been derived from land-use maps for selected periods of time using crop-specific consumptive use estimates and assumed irrigation efficiencies (for example, Hanson and others, 2003). In yet other regions, reporting pumpage may be required as a basis for taxation. In these settings, the reported pumpage can provide a first-order validation of the pumpage estimated by FMP.

Perkins and Sophocleous provided a comprehensive large-watershed basin model, which links an agriculturally based watershed model, SWAT, to MODFLOW (McDonald and Harbaugh, 1988; Perkins and Sophocleous, 1999a,b). This linkage of SWAT and MODFLOW is also known as SWATMOD (Sophocleous and others, 1999). SWATMOD allows the spatial disaggregation and temporal aggregation of hydrologic flows yielded by SWAT from larger watershed subbasins to smaller MODFLOW model cells and from daily time steps to longer MODFLOW time steps (Sophocleous and Perkins, 2000). The SWAT model applies lumped, analytical models to represent ground water elevation and percolation out of the root zone, which are of limited use in representing the ground water and stream-aquifer hydraulics (Arnold and others, 1994; Neitsch and others, 2002a, b). SWAT as a stand-alone model does not have the ability to simulate how root uptake and capillary rise from ground water dynamically influence crop-water and irrigation-water demand and use, and soil-water storage. When the linked model, SWATMOD is used, it simulates a soil-water budget and allows the simulation of a “quasi root-uptake” by cumulating cell-by-cell evapotranspiration (ET) from shallow aquifers. This ET component is calculated by the ET package of MODFLOW over a subbasin, and by applying the corresponding evapotranspiration depth as capillary uptake into the soil profile. However, this procedure may widely overestimate root uptake from ground water due to the conceptual simplicity of the ET package of MODFLOW and, therefore, may underestimate irrigation demand. In addition, the simplicity of applying a uniform capillary uptake over a subbasin may result in additional estimation errors, since phreatophytic uptake often occurs only locally. While SWATMOD does return a basin-wide hydrologic balance, it does not allow for a water budget on the scale of individual water accounting units, such as farms or irrigation districts, for the components of irrigation demand, surface water and ground water supply, and net recharge. In addition, SWATMOD models are limited to watersheds boundaries. Constraints on surface-water and ground-water supply are present in SWATMOD, but it does not account for constraints from water-rights ranking in the sense of water-rights seniority, or account for maximum pumping capacity or head-constraints imposed on well pumpage.

Further advances in the simulation of irrigated agriculture resulted in a limited inclusion of the supply and demand components into ground-water flow models that represent decoupled sources of ground-water pumpage and deep percolation of excess applied water. For example, in a finite-element model, Integrated Ground-water/Surface-water Model (IGSM) (Montgomery Watson, 1993), flows between agricultural demand and surface-water supply, as well as ground water, were not fully coupled. Another finite-element model, the Integrated Water Flow Model (IWF) (California Department of Water Resources, 2005a, b) provides full coupling between agricultural demand and the surface-water supply with flow from the root zone to ground water. A more dynamic linkage was provided with MODFLOW with the MODRIGHT Package (McCurry, 2000), which simulates surface-water diversions based upon Colorado water rights delivered to farm areas and the subsequent simulation of consumptive use, deep percolation, and irrigation return flow to the surface-water system. While these flows estimated consumptive use on the basis of user-specified agricultural properties, these components were not linked to the ground-water or surface-water-flow systems through head-dependent relations. In addition, this approach delivered an allotment to the farm equal to the full water right not bounded by crop demand. Thus, few models have been capable of dynamically integrating these supply and demand components based on actual crop demand in a head-dependent context of regional ground-water and surface-water flow.

Modeling Agricultural Irrigation Supply and Demand

There are three main classes of problems that are facilitated in the simulation of conjunctively managed surface water and ground water supply and demand components for irrigated agriculture. The FMP1 allows MF2K users to simulate conjunctive use of surface water and ground water for simulation and estimation of irrigated agriculture for historic and future periods, for analysis of water-rights issues and operational decisions, and for analysis of nondrought and drought situations (*fig. 1*). By dynamically integrating farm delivery requirement, surface- and ground-water delivery, and irrigation return flow, the FMP1 allows the direct estimation of supplemental ground-water pumping. While the farm delivery requirement and irrigation return flow are simulated by the FMP1, the surface-water delivery to the farm can optionally be simulated by coupling the FMP1 with the Streamflow Routing Package (SFR1) and the farm ground-water pumping can be simulated optionally by coupling the FMP1 to the Multi-Node Well (MNW) Package. One of the most significant contributions of the FMP1 is the ability to dynamically estimate the amount of unmetered ground-water pumpage through the coupling of supply and demand water-resource components.

Purpose and Scope

The purpose of this report is to describe the organization, structure, and use of the FMP1, a head-dependent package for use with the ground-water/surface-water flow model, MF2K. The scope includes a brief description of the theory and implementation of the FMP1 that are derived from the more detailed documentation of the development and the basic procedures (Schmid, 2004). Additional description of newer features, such as nonrouted and semi-routed surface-water deliveries, head-dependent irrigation efficiencies, water-rights allocations, and connection to the Multi-Node Well Package, also are provided. The purpose of this package is to provide MF2K with the additional capability of simulating cell-by-cell crop demand for every user-specified farm and the related supply components. The estimated crop demand is supplied from surface-water and ground-water deliveries to each farm and, as such, the FMP1 also maintains an additional farm budget independent from the ground-water budget. An additional purpose of this package is to provide a means to potentially balance demand and supply components by estimating a limited demand through acreage optimization, water stacking, or deficit irrigation.

Acknowledgements

The development of the FMP1 initially was supported by SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) under the STC Program of the National Science Foundation, Agreement No. EAR-9876800, and from funding provided by the U.S. Geological Survey (USGS). This final version of the FMP1 and additional development was supported from the USGS Central Valley RASA project of the Ground-Water Resources Program (CADWR). We also acknowledge additional collaboration during the development of the FMP1 with Phil King and Sue Tillery (New Mexico State University), as well as David Prudic, Charles Brush, Claudia Faunt, and Ken Belitz (USGS).

Farm Process Capabilities

The FMP1 was developed to simulate, within MF2K (Harbaugh and others, 2000), the surface water and ground water inflows and outflows required to sustain irrigated agriculture. For the purposes of this report, the farm represents the basic unit of water consumption. Each farm can include one or more model cells in model layer 1. On the basis of cell-by-cell estimations for each farm, the FMP1 first calculates crop water demand as the transpiration from plant-water consumption and the related evaporation. The FMP1 then determines a residual crop water demand that cannot be satisfied by crop-effective precipitation or by root uptake from ground water. The FMP1 then equates this residual crop water demand with the crop irrigation requirement. This amount is then increased by accounting for evaporative losses from irrigation and other inefficiency losses to yield a final 'total farm delivery requirement.' The FMP1 then attempts to satisfy the total farm delivery requirement with first priority by the nonrouted supply components and, with second priority, by the semi- and fully routed deliveries. If the supply components are constrained by a water-rights allocation hierarchy, the supply components are adjusted accordingly. Lastly, by third priority, the FMP1 determines the amount of supplemental ground-water pumping necessary to satisfy the total farm delivery requirement. The FMP1 then calculates the amount of excess water from irrigation or precipitation that is not effectively used for crop growth, which becomes either overland runoff or ground-water recharge. All of the supply and demand components are then tabulated into a farm budget that compliments the ground-water-flow budget. Finally, the FMP1 allows for user-specified scenarios that can estimate optimal distributions of supply components if the irrigation demand exceeds the supply components (*fig. 4*).

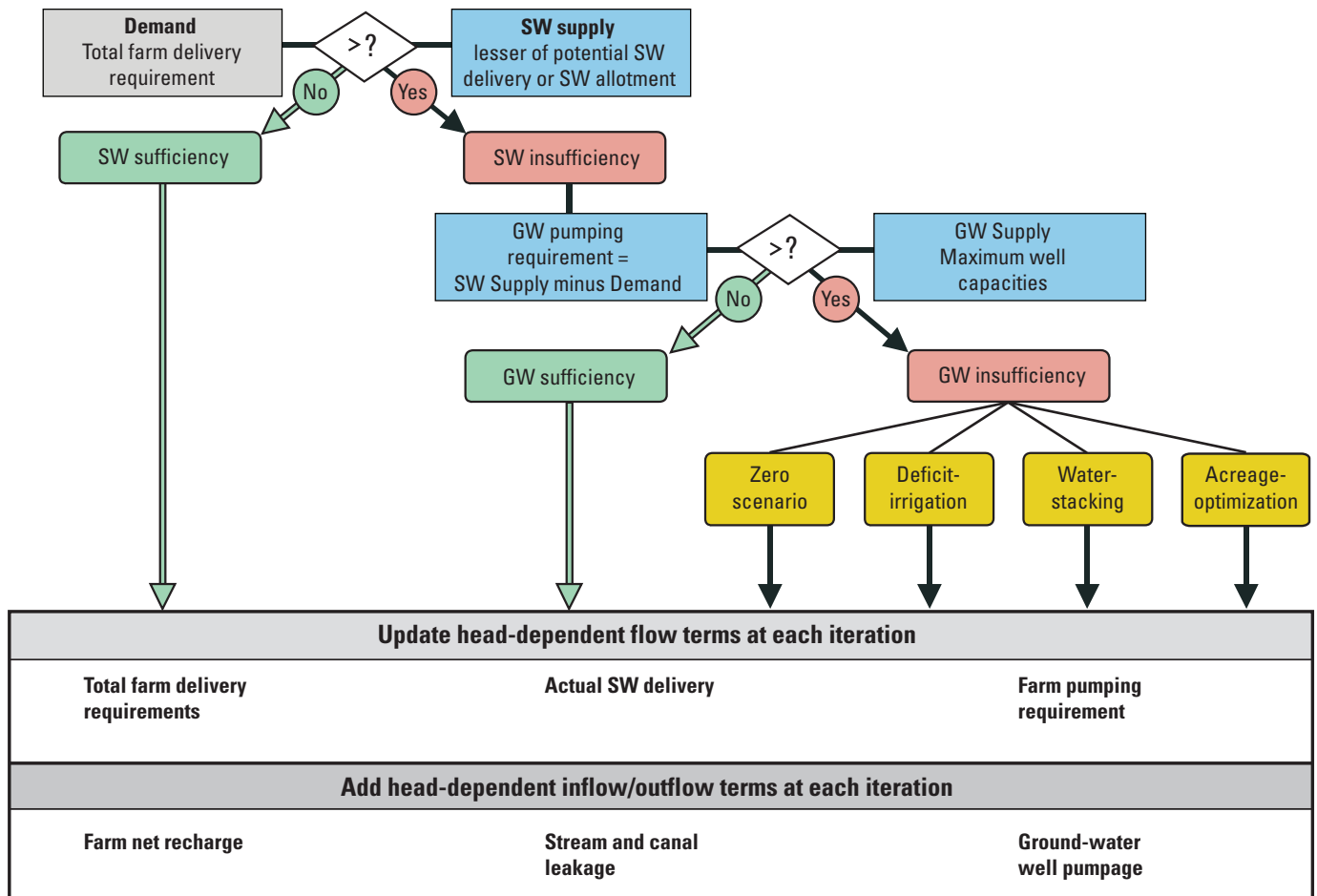


Figure 4. Cases of sufficiency and insufficiency of irrigation water supply in a surface-water dominated irrigation setting.

When using MF2K with the FMP1, this process dynamically integrates the following terms for a farm unit (*fig. 3*):

- Farm irrigation delivery requirement (irrigation demand), which depends on changing climate (evapotranspiration and precipitation) and variable aquifer head;
- Actual surface-water delivery to the farm, which is driven by irrigation demand, but limited to canal stream inflow at the farm's diversion head gate, limited by water-rights allotments, or nonrouted deliveries;
- Supplemental ground-water pumpage, which is the difference between the irrigation demand and the actual surface-water delivery, but limited by a specified maximum capacity for all of the wells associated with a farm; and
- Net recharge to ground water, which is the excess of irrigation and of precipitation minus surface-water runoff and minus evapotranspiration from ground water.

In general, the FMP1 provides four improvements compared to previous approaches of integrated surface-water/ground-water modeling:

- Dynamic dependency of crop water demand on changing climate and variable aquifer head;
- Analytical steady state approximation of unsaturated flow (confirmed with HYDRUS2D simulations for several typical soil types) underlying the derivation of crop water demand and in-excess farm net recharge;
- Allocation of surface-water and ground-water supply driven dynamically by crop water demand, and allowing for the estimation of historic and future ground-water pumping supplemental to surface-water supply; and
- Inclusion of response policies to irrigation insufficiency (drought) to preserve mass balance.

Consumptive Use

Consumptive use is commonly defined as actual evapotranspiration (ET), which includes both plant transpiration and evaporation in an agricultural area (Colorado's Decision Support Systems, 1995; Gelt and others, 1999; European Environment Agency, 2004). The purpose of estimating the consumptive use is to estimate evapotranspiration and its components. Two of its components are the transpiratory irrigation requirement and the evaporation losses from irrigation, which is the major portion of the farm irrigation requirement. In addition, the estimation of farm net recharge requires estimates of both of these irrigation and ground-water components and ET as a whole. In addition, the FMP1 can be used to estimate components of consumptive use for non-farm applications where transpiration accounts for riparian or natural vegetation or for urban vegetation. The FMP1 also can be used for applications with zero transpiration, such as aquifer storage-and-recovery (ASR) systems or urban-land use settings.

The FMP1 establishes the demand for water by estimating the consumptive use as ET from the crop water demand and related bare-soil evaporation of water. At steady state, ET is composed of the transpiratory and evaporative components from three sources: ground water, precipitation, and irrigation (eq. 1), where the CIR represents the components from irrigation. In the FMP, the CIR has been formulated to be head dependent and can vary with changing, ground-water levels within each model cell of each farm. All transpiratory and evaporative outflows are assumed to occur at steady state and, therefore, the soil moisture content (storage) does not change with time.

The irrigation demand (herein referred to as the total farm delivery requirement, TFDR) depends on the head-dependent component CIR. As long as the water supply is sufficient, the surface- or ground-water supply is driven by the irrigation demand. Therefore, the irrigation water supplied by surface water or by ground-water pumping depends indirectly on the head-dependent CIR. In addition, the farm net recharge return flow, as described in the section "Farm Net Recharge," depends directly on consumptive use components of CIR, T_p , E_p , T_{gw-act} , E_{gw-act} , which are partly head-dependent. Hence, farm well discharge and farm net recharge are source/sink terms in the FMP1 that are dynamically dependent on the aquifer head.

In the case where the water table rises above the bottom of the root zone, the actual transpiration is taken to vary proportionally with the active root zone, which can be restricted by anoxia or wilting. Depths corresponding to anoxia- or wilting-related pressure heads within the root zone are found using analytical solutions of a vertical pseudo-steady-state pressure head distribution over the depth of the total root zone (CU Concept 1). Alternatively, a simpler conceptual model is available, which defines how consumptive use components vary with changing head (CU Concept 2).

The variation of transpiration fluxes with changing ground-water level, which includes the actual transpiration from ground water T_{gw-act} as part of the total actual crop transpiration T_{c-act} , is linearly approximated in the FMP1. Transient model runs of variably saturated flow soil column models simulated with HYDRUS2D (Simunek and others, 1999) yielded, for different ground-water levels, transpiration fluxes approaching a steady state. In the FMP1, these approximations of transpiration under variably saturated soil conditions (eq. 2) were derived for three typical soil types: sandy loam, silt, and silty clay.

The variably saturated flow model, HYDRUS2D (Simunek and others, 1999), is based on the nonlinear form of the Richards' equation governing flow in the unsaturated zone, given isothermal Darcian flow of water in a variably saturated rigid porous medium, and assuming that the air phase plays an insignificant role in the liquid flow process. The general nonlinear form of Richards' equation (eq. 2) using Einstein's notation can be described as follows, with the initial condition given by the pressure head distribution:

$$\frac{\partial}{\partial x_i} \left(K_{ij}(\theta) \frac{\partial \psi(\theta)}{\partial x_j} \right) + \frac{\partial K_{iz}(\theta)}{\partial x_i} + S = \frac{\partial \theta}{\partial t} \quad (\text{EQ.2})$$

where

z = 2 for two dimensional and

z = 3 for three dimensional and using indices summation notation.

The solution of the Richards equation (eq. 2) requires the specification of soil-water constitutive functions such as the water-retention function $\psi(\theta)$ or $\theta(\psi)$ and the hydraulic conductivity function $K(\theta)$ or $K(\psi)$. Coefficients of the water retention function can be determined from experimental data of ψ versus θ using nonlinear regression techniques (van Genuchten and others, 1991). Since the measurement of unsaturated hydraulic conductivity for a fixed water content is difficult, $\psi(\theta)$ or $\theta(\psi)$ and the saturated hydraulic conductivity K_s are customarily used in conjunction with theoretical models (for example, Mualem, 1976; van Genuchten, 1980) to obtain $K(\theta)$ (Ravi and Williams, 1998).

The root uptake sink term in HYDRUS2D can be determined by the product $S(\psi)$ of a “Feddes”-type water stress response function $a(\psi)$ and a potential water uptake rate S_p that is assumed to be equally distributed over the root zone (Feddes and others, 1978). The stress response needs to be specified as 0.0 for the wilting point and water-entry pressure heads, and as 1.0 for two values between which the water uptake is considered optimal. The potential water uptake is dependent on the root zone geometry and the potential transpiration rate (Simunek and others, 1999).

Soil-water constitutive functions that can be used in HYDRUS2D are those developed by Brooks and Corey (1964), Mualem (1976), and van Genuchten (1980). The van Genuchten-Mualem approach probably is used most widely. This approach used variably saturated soil column simulations with HYDRUS2D to develop analytical approximations in the FMP1. This approximation simulates the reduction of transpiration proportionally to the reduction of the root zone by changes in the zones of anoxia and wilting. These were incorporated into the FMP1 using the relations given in *table 1*. The parameters α , n , and l are empirical coefficients affecting the shape of the hydraulic functions (Simunek and others, 1999). The selection of a soil type in HYDRUS2D implicitly assumes a set of empirical parameters that define the soil-type-specific hydraulic functions that further define the water-retention and the hydraulic-conductivity function.

The HYDRUS2D simulations of unsaturated flow demonstrate how the resulting fluxes of the actual transpiration from ground water (root uptake from ground water as the only source) and fluxes across the water table merge when approaching steady state (*fig. 5*). These steady state values were plotted for various depths to the ground-water table for sandy loam and silt soils (*fig. 6*) with the corresponding linear approximation (*fig. 7*). In addition, the variation of a maximum possible actual transpiration (with root uptake from sources ground water and irrigation) with changing ‘depths to water’ was determined (*figs. 5 and 6*), along with its linear approximation (*fig. 7*). Since at steady state the output transpiratory flux equals the flux across the water table (plus the irrigation flux, if applied) for the HYDRUS2D models, changes in storage in the unsaturated zone are assumed to be negligible in the FMP1.

Transpiration for Water Levels between Ground Surface and Bottom of Root Zone

In the FMP1, both crop-consumptive-use concepts (Concepts 1 and 2) assume a linear decrease in transpiration as the ground-water level rises above the bottom of the root zone. Hypothetically, the potential ‘maximum possible transpiration’ for ground-water levels between ground surface and the bottom of root zone is taken to vary linearly through the active root zone (dotted line in *fig. 7*), as it is reduced to zero by ground-water levels rising from the bottom of the root zone up to the ground-surface elevation. This hypothesis holds, given the following assumptions:

- (1) The actual transpiration can at maximum be equal to the potential transpiration;
- (2) The potential transpiration is at maximum, if the entire root zone is available for uptake as active root zone; and
- (3) The potential transpiration is distributed equally over the root zone.

Consumptive-Use Concept 1

Consumptive-use concept 1 represents a step-wise linear approximation of transpiration for ground-water levels between the bottom of the root zone and the ground surface. The potential ‘maximum possible transpiration’ is not quite reached by the results from the soil column HYDRUS2D simulations. For a ground-water level equal to the bottom of the root zone (when the transpiration is found to be at maximum), the ‘maximum actual transpiration’ ($T_{c-act-max}$, in *fig. 7* called ‘maximum actual root uptake,’ ARU_{max}) is reduced as the active root zone is restricted by conditions of anoxia or wilting. In the FMP1, the depths within the root zone which correspond to user-specified, crop-specific anoxia- or wilting-related pressure heads (*fig. 8A*), are found using analytical solutions of a vertical steady state pressure head distribution over the depth of the total root zone (*fig. 8B*). This was carried out for ground-water levels located at the bottom of the root zone, where the ‘total actual crop transpiration’ (T_{c-act}) and its component, the ‘actual transpiration from ground water’ (T_{gw-act}), reach a maximum ($T_{c-act-max}$, $T_{gw-act-max}$). As the ground-water level rises above the bottom of the root zone, the anoxia fringe does not change but is shifted upward until it equals the ground-surface elevation. The vertical range over which pressure heads are lower than the wilting-point pressure head, is found by assuming ground water to be the only source for transpiration. Such a “too-dry-zone” in the upper part of the root zone decreases linearly as the ground-water level rises above the bottom of the root zone. This approximation of how transpiration is taken to vary for ground-water levels between the bottom of the root zone and ground surface is the most important feature of what is referred to as CU concept 1 (*fig. 9*) of the consumptive-use approximation in the FMP1.

Table 1. Summary of variably saturated flow equations and soil-water constitutive functions used in HYDRUS2D to develop unsaturated-flow approximations incorporated in the FMP1.

	<p>HYDRUS 2D [from Simunek and others, 1999]</p>
Dimension	2D
Governing equation	$\frac{\partial \theta}{\partial t} = \nabla \cdot (\mathbf{K} \nabla h) - S$ <p>by replacing h with $\psi + z$, and replacing \mathbf{K} with $\mathbf{K}(\mathbf{K}^A)$, where $K = K(\psi, x, z)$ and using Einstein's Notation for 2D, we get:</p> $\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i} \left[K(K_{ij}^A \frac{\partial \psi}{\partial x_j} + K_{iz}^A) \right] - S$ <p>where: $S = a(\psi)S_p$; and $S_p = (L_t T_{pot}) / (L_x L_z)$</p>
Soil-water constitutive functions	<p>HYDRUS2D models using soil-water constitutive functions after van Genuchten (1980) and Mualem (1976):</p> <p>Water retention function:</p> $\theta(\psi) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1 + \alpha\psi ^n)^m} & \psi < \psi_s \\ \theta_s & \psi \geq \psi_s \end{cases}$ <p>Hydraulic conductivity function:</p> $K(\psi) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m \right]^2 \quad \text{with: } m = 1/n, \quad n > 1,$ $S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \begin{cases} \alpha\psi ^{-n} & \psi < -1/\alpha \\ 1 & \psi > -1/\alpha \end{cases} \quad S_e \text{ after Brooks and Corey (1964)}$

List of Parameters and Functions in Table 1:

- | | |
|---|---|
| <ul style="list-style-type: none"> a dimensionless water stress response function [-] K unsaturated hydraulic conductivity [L/T] K hydraulic conductivity tensor [L/T] K_{ij} components of hydraulic conductivity tensor K [L/T] \mathbf{K}^A dimensionless anisotropy tensor for the unsaturated hydraulic conductivity K [-] K_{ij}^A components of dimensionless anisotropy tensor \mathbf{K}^A [-] K_s saturated hydraulic conductivity [L/T] l pore-connectivity parameter [-] L_t width of soil surface associated with transpiration [L] L_x width of root zone [L] L_z depth of root zone [L] | <ul style="list-style-type: none"> n empirical exponent in soil water retention function [-] S sink term – root uptake [1/T] S_e effective water content [-] S_p spatial distribution of the potential transpiration rate [1/T] T_{pot} potential transpiration rate [L/T] α inverse of air-entry value in water retention function [1/L] θ volumetric water content [L^3/L^3] θ_s saturated soil water content [L^3/L^3] θ_r residual soil water content [L^3/L^3] ψ_s air-entry pressure head [L] |
|---|---|

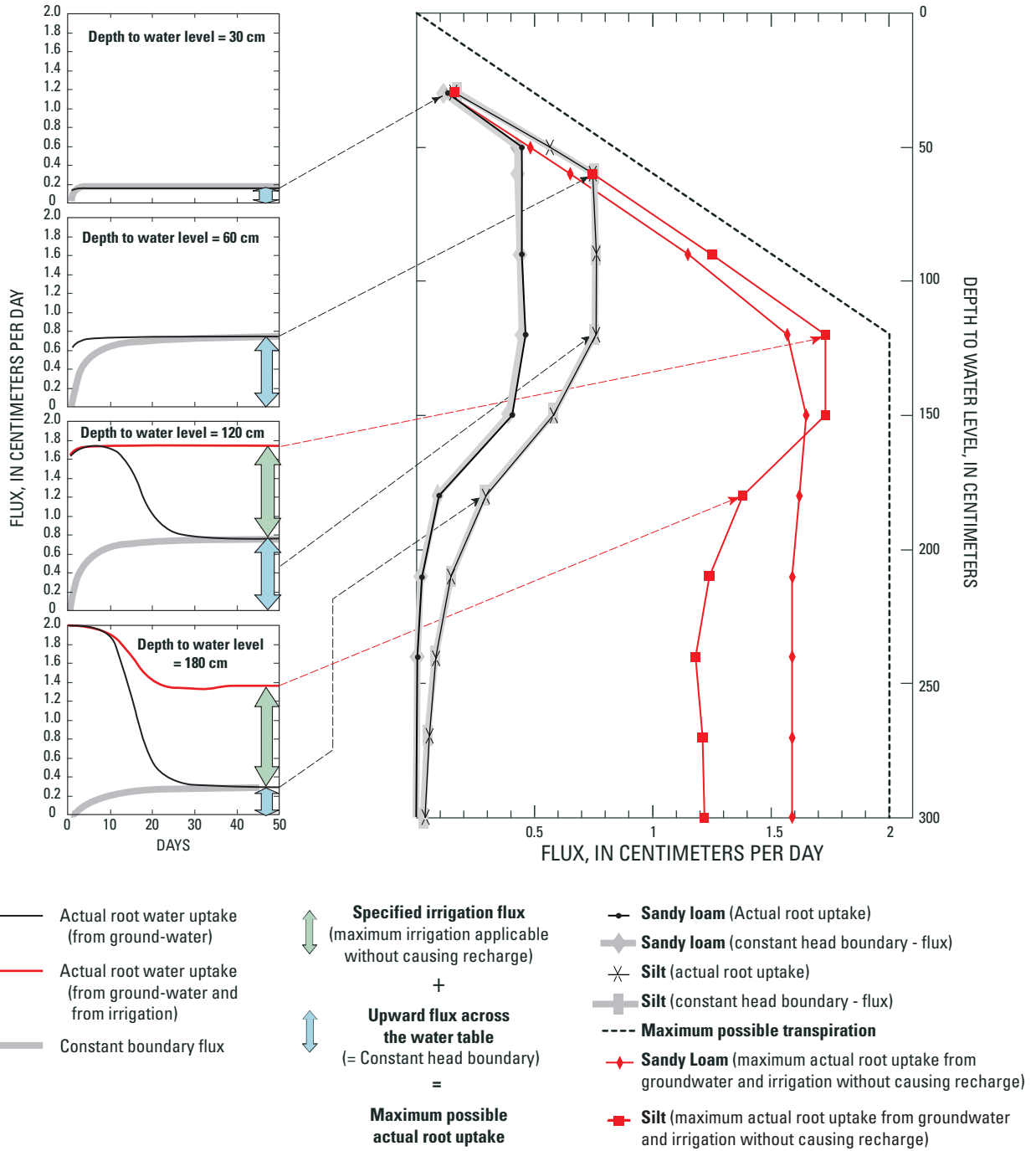


Figure 5 (left). Transient course of root uptake and flux across the water table for different depths to water table. (Soil type: silt; root zone depth = 120 cm; potential crop transpiration $T_{c-pot} = 2$ cm/day)

Figure 6 (right). Variation of actual root uptake from ground water (at steady state), and of maximum actual root uptake from ground water and irrigation (at steady state), with changing water level (root zone depth = 120 cm; potential crop transpiration $T_{c-pot} = 2$ cm/day).

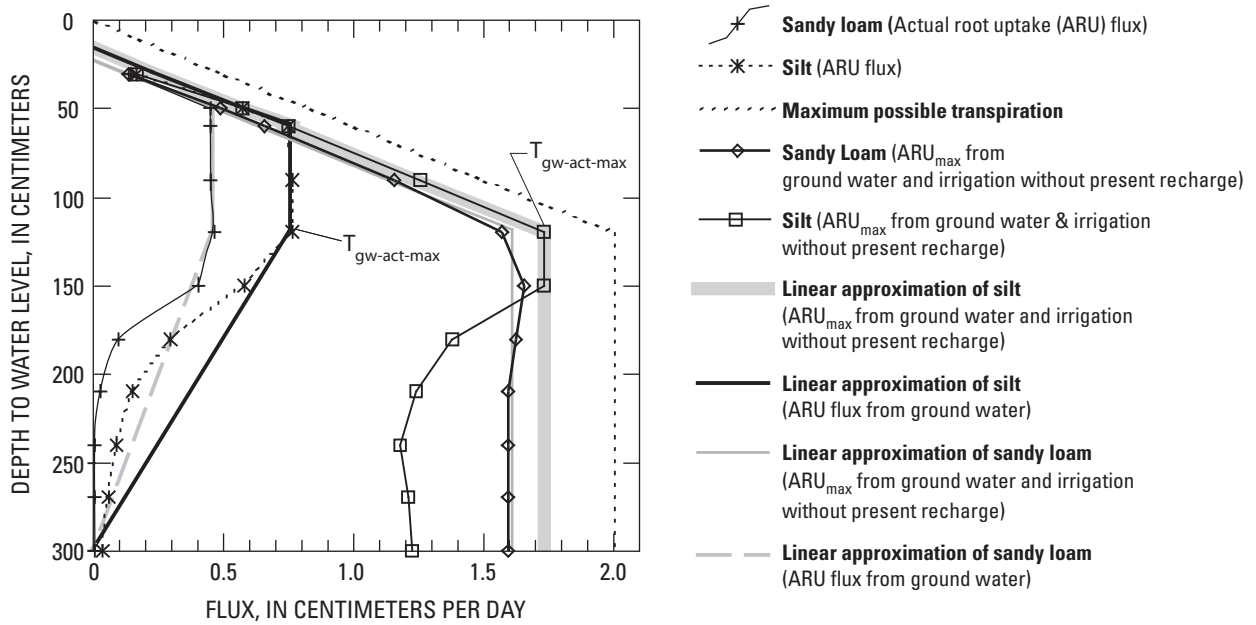


Figure 7. Linear approximation of pseudo-steady-state root uptake from ground water and maximum actual root uptake (ARU) from ground water and irrigation water.

The maximum ‘total actual crop transpiration’ $T_{c-act-max}$ is defined as:

$$T_{c-act-max} = T_{c-pot} \cdot [1 - AZ/TRZ]$$

The maximum ‘actual transpiration from ground water’ $T_{gw-act-max}$ is defined as:

$$T_{gw-act-max} = T_{c-pot} \cdot [1 - (AZ+WZ)/TRZ]$$

where

- T_{c-pot} is the potential crop transpiration,
- $T_{c-act-max}$ is the maximum actual crop transpiration,
- TRZ is the total root zone thickness,
- AZ is the thickness of the anoxia zone, and
- WZ is the thickness of the wilting zone.

Consumptive-Use Concept 2

Alternatively, a simpler, conceptual model, CU concept 2 (*fig. 9*) simply assumes, for a ground-water level equal to the bottom of the root zone, the maximum actual crop transpiration $T_{c-act-max}$ and the maximum actual transpiration from ground water $T_{gw-act-max}$ are equal to the potential crop transpiration T_{c-pot} :

$$T_{c-act-max} = T_{gw-act-max} = T_{c-pot}$$

Transpiration for Water Levels between Bottom of the Root Zone and the Extinction Depth

Transpiration is simulated for ground-water levels between the bottom of the root zone and the extinction depth for both crop CU concepts (fig. 9) and is assumed to decrease linearly with depth. All of the head-dependent variables are specified in red in this section and subsequent sections of this report. As the ground-water level drops below the bottom of root zone, the actual transpiration from ground water T_{gw-act} is assumed to decrease linearly from the respective maximum actual transpiration from ground water, $T_{gw-act-max}$, at the bottom of the root zone to a transpiration-extinction depth (defined to be equal to the capillary fringe) below the bottom of the root zone. For a ground-water level below the bottom of the root zone, the total actual transpiration T_{c-act} is assumed to remain constant at the maximum actual transpiration $T_{c-act-max}$ (fig. 9).

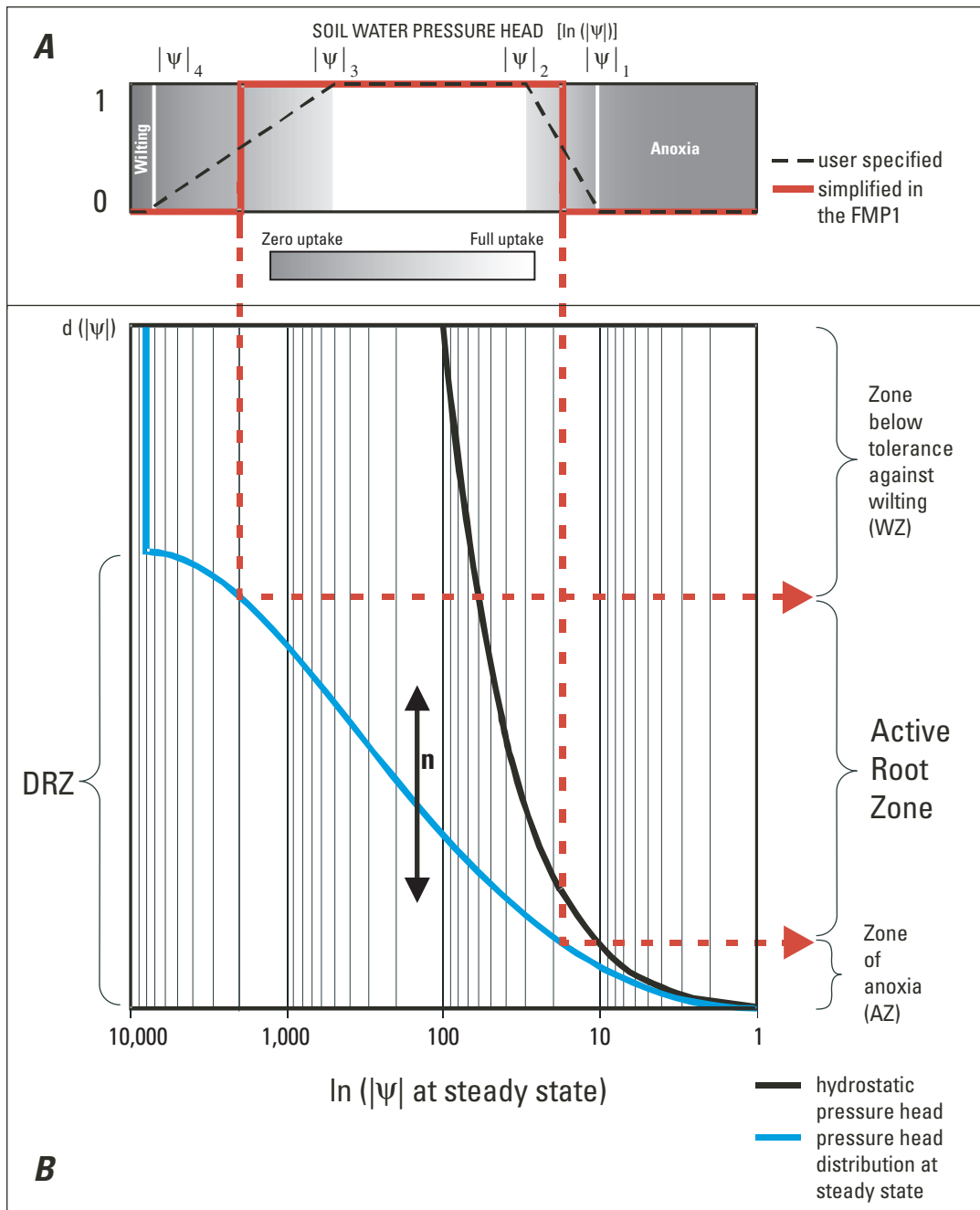


Figure 8. (A) crop specific stress response function $a(|\psi|)$, and (B) analytical function $d(|\psi|)$ fitting the vertical pressure head distribution over depth.

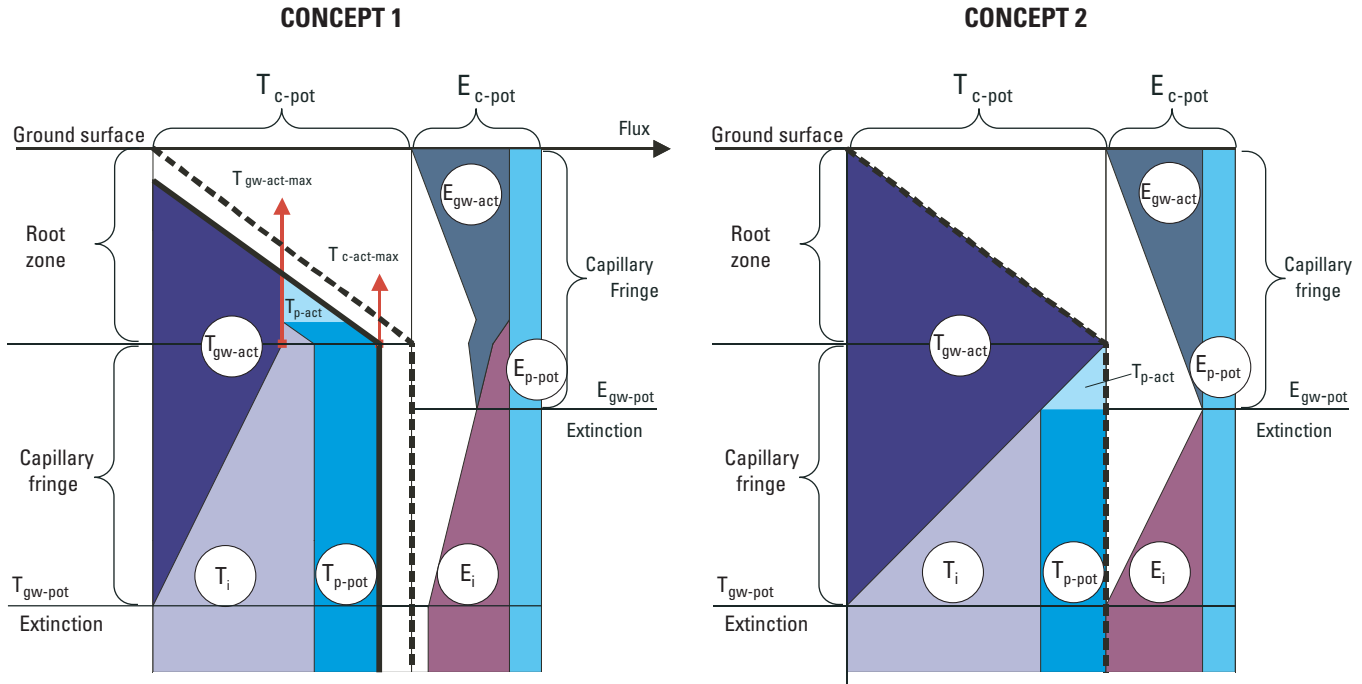


Figure 9. Two conceptual approximations to change of crop consumptive-use components with varying head.

Evaporation for Water Levels between Ground Surface and Extinction Depth

Evaporation from ground water is simulated for ground-water level between the ground surface and the extinction depth (fig. 9). The ‘maximum actual evaporation from ground water’ $E_{gw-act-max}$ is assumed to equal the portion of the saturation water vapor pressure deficit over exposed no crop areas (potential evaporation E_{c-pot}), which is not compensated by evaporating precipitation (E_p), where $E_{gw-act-max} = E_{c-pot} - E_p$. For both crop consumptive use concepts, the extinction of evaporation from ground water is likely to occur when the highest point of the capillary fringe is below the ground surface (Robinson, 1958). Thus, evaporation from ground water E_{gw-act} is assumed to decrease linearly with the ground-water level from the ‘maximum actual evaporation from ground water’ $E_{gw-act-max}$ at the ground surface to an ‘evaporation-from-ground water extinction depth’ (defined to be equal to the capillary fringe) below ground surface.

Head-Dependent Transpiration from Precipitation

Head-dependent transpiration from precipitation (fig. 9) also is simulated by the FMP1. As the transpiration from ground water increases with rising ground-water level, the amount of ‘actual transpiration provided by precipitation’ T_{p-act} ⁴ decreases as long as it is less than the available ‘potential transpiration from precipitation’ that is needed:

$$T_{p-act} = T_{c-act} - T_{gw-act}; \quad \text{if } T_{p-pot} > T_{c-act} - T_{gw-act} \text{ (head-dependent case)}$$

$$T_{p-act} = T_{p-pot}; \quad \text{if } T_{p-pot} \leq T_{c-act} - T_{gw-act} \text{ (nonhead-dependent case)}$$

Head-Dependent Crop Irrigation Requirement

The head-dependent transpiratory irrigation requirement for each model cell (T_i) (fig. 9) is simulated by subtracting the actual transpiration from ground water T_{gw-act} and the actual transpiration from precipitation T_{p-act} from the total transpiration. After adding the evaporative irrigation needs (E_i), which are to compensate surface-evaporative losses from irrigation, this yields the estimate of the crop-irrigation requirement, CIR.

⁴The actual transpiration from precipitation commonly is defined as the so-called crop-‘effective precipitation’ (Doorenbos and Pruitt, 1977; Dastane, 1978; Brouwer and others, 1985; and Brouwer and Heibloem, 1986)

Surface-Water Supply

Surface-water supply as deliveries to a farm or flow of water away from any farm can be simulated for each farm as nonrouted surface water, or simulated as conveyance from diversions or to drainage canals with the SFR1 package (Prudic and others, 2004). The simulation of surface-water conveyance to and from farms can include any combination of nonrouted and routed transfers that, in turn, can represent a variety of conveyance mechanisms from natural rivers to manmade canals and pipelines. Simulation of surface-water deliveries is not required, if the simulated irrigation of a farm is based solely on ground-water pumped from local wells.

Nonrouted surface-water deliveries, herein referred to as water transfers, represent the ability to move water to or from a farm without simulating the actual process of conveyance. Any farm can have any number of separate water transfers from multiple sources. Thus, multiple water transfers can represent deliveries of water from private, county, state, federal, or international sources of water. When water transfers are specified as deliveries, they are the first water-supply components that are used to satisfy the demand representing the total farm delivery requirement (TFDR)(eq. 1). In addition, when a user specifies water transfers, they are assumed to occur during a specified period of time and are not subject to any prior appropriation hierarchy. Water transfers also can be flagged to equate only to the TFDR or can be flagged to allow deliveries in excess of the TFDR. Water transfers can be specified as a positive quantity to represent the delivery of water to the farm (importation). Water transfers also can be specified as a negative quantity to represent the delivery of surface water or ground water away from a farm (exportation). A water export could be an additional water demand that may represent a transfer of water in lieu of farming or could be an addition to any potential TFDR. If, for example, the farm land is fallow then the negative water transfer would be manifested as additional ground-water pumpage or a redirection of surface-water deliveries. This combination of features also allows the simulation of ponds and wells that are part of aquifer-storage-and-recovery (ASR) operations. Thus, excess water transfers could be applied to fallow land that represents infiltration ponds or injection wells where water is returned to the ground-water system. Model cells of infiltration ponds as well as injection wells could be represented by “farm wells.” Alternatively, the excess water transfers also could be returned to the surface water system through the farm canal. Subsequently, later negative transfers can represent additional pump back from the same “farm wells.”

As stated above, each farm may receive nonrouted deliveries from several sources. A farm-specific ranking of these random delivery types is necessary to determine which type of potentially available nonrouted delivery is not used in its entirety if the sum of all types of nonrouted deliveries exceeds the farm’s total delivery requirement (TFDR^f). The ranking scheme assumes a lower number to be of higher priority. The user may specify not only to use the amount sufficient to meet TFDR but to apply the entire amount of an available nonrouted delivery type. In this case, an NRD_{use}-Flag is set to a positive number indicating the target to which the excess or unneeded delivery will be sent. The NRD_{use}-Flag is set to “1” if the surplus from a certain delivery type is to be delivered to a canal. This feature may be useful for simulating the actions of farmers that make local water transfers. Similarly, the NRD_{use}-Flag is set to “2” if the surplus from a certain delivery type is to be injected into the farm’s wells. This feature may be useful if the farm represents an aquifer storage and recovery system (ASR) or where recharge credits are needed. The total of all nonrouted deliveries, TNRD^f, equals the sum of all types of actually used nonrouted deliveries to farm f is determined as follows:

$$TNRD^f = \sum_{t=1}^{t_{act}} NRD_{act}^{f,t} = \sum_{t=1}^{t_{tot}-t_u-1} NRD_{pot}^{f,t} + \sum_{t=t_{tot}-t_u}^{t_{tot}} NRD_{act}^{f,t} \quad (\text{EQ. 3})$$

and:

$$NRD_{act}^{f,t} = \begin{cases} TFDR^f - \sum_{t=1}^{t_{tot}-t_u-1} NRD_{pot}^{f,t} & \forall t = t_{tot} - t_u; \text{ and if } NRD_{use}^{f,t=(t_{tot}-t_u)} = 0 \\ 0 & \forall t > t_{tot} - t_u; \text{ and if } NRD_{use}^{f,t > (t_{tot}-t_u)} = 0 \\ NRD_{pot}^{f,t \geq (t_{tot}-t_u)} & \forall t \geq t_{tot} - t_u; \text{ and if } NRD_{use}^{f,t \geq (t_{tot}-t_u)} = 1 \text{ or } 2 \end{cases}$$

where

- f = 1,2,..., number of farms;
- t = 1,2,..., t_{act} , ... , t_{tot} ; (lower type t = higher priority rank)
- t_{act} = number of actually used ranked types of nonrouted deliveries;
- t_{tot} = total number of available ranked types of nonrouted deliveries;
- t_u = number of types of nonrouted deliveries unnecessary to meet $TFDR^f$;
- $NRD_{pot}^{f,t}$ = potentially available nonrouted delivery of type t to farm f
- $NRD_{act}^{f,t}$ = actually used nonrouted delivery of type t to farm f
- $TNRD^f$ = total of all types of actually used nonrouted deliveries to farm f
- $NRD_{use}^{f,t}$ = binary “ NRD_{use} -Flag” of a nonrouted delivery type t to a farm f :
 if 0: only the amount sufficient is used to meet the farm’s demand,
 if 1: the absolute amount available is used; surplus recharged into canal at farm’s head gate,
 if 2: the absolute amount available is used; surplus injected into farm wells attributed to farm ID.

Routed deliveries can be simulated as fully or semi-routed deliveries. Fully routed streamflow deliveries are linked to the streamflow routing package⁵ (SFR1, Prudic and others, 2004) in MF2K, if the simulation of surface-water supply to farms is desired. The estimation of streamflow at the farm’s head gate⁶, which potentially is available for delivery to the farm, is accomplished by routing streamflow through a network of channels (including streams and canals) to the respective head gate of a farm. To simulate semi-routed deliveries, the user specifies a diversion point from the streamflow-routing network for each farm. The distribution of surface water to the model cells within the farm unit is subject to additional on-farm transmission losses that implicitly are accounted for by the on-farm efficiency. While a simulation with multiple farms can contain a mixture of fully and semi-routed deliveries, each farm only can receive either a fully or semi-routed delivery. However, any farm can receive non-routed deliveries as well as one fully or semi-routed delivery.

The potential surface-water delivery to the farm’s head gate starts with the simulation of routed streamflow using the SFR1 package (Prudic and others, 2004). The stream inflow into the farm’s head-gate reach⁷ (potentially deliverable surface-water supply, DEL_{pot}), is determined by the SFR1 routing scheme moving downstream, which updates each reach’s streamflow by changes in inflows and outflows. The calculation of inflows and outflows is constrained by a mass-balance assumption for each reach (Σ inflows = Σ outflows), assuming no changes in stream-channel storage.

The SFR1 package has four options for simulating water diversions from the last reach of an upstream segment into the first reach of a diversion segments are (with: $Q_{spec-div}$ = user-specified diversion flow; $Q_{spec-max}$ = user-specified maximum streamflow) (Hanson and others, 2003; Prudic and others, 2004):

- (1) if $Q_{spec-div} \leq Q_{stream-inflow}$, then $Q_{diversion} = Q_{spec-div}$
 if $Q_{spec-div} > Q_{stream-inflow}$, then $Q_{diversion} = Q_{stream-inflow}$
- (2) if $Q_{spec-div} \leq Q_{stream-inflow}$, then $Q_{diversion} = Q_{spec-div}$
 if $Q_{spec-div} > Q_{stream-inflow}$, then $Q_{diversion} = 0$
- (3) $Q_{diversion}$ = specified fraction of $Q_{stream-inflow}$ between 0 and 1
- (4) if $Q_{spec-max} < Q_{stream-inflow}$, then $Q_{diversion} = Q_{stream-inflow} - Q_{spec-max}$ } (“Flood Control”
 if $Q_{spec-max} \geq Q_{stream-inflow}$, then $Q_{diversion} = 0$ } type diversion)

⁵The SFR1 package computes leakage rates between the stream and the aquifer as source/sink terms for MF2K.

⁶The farm’s head gate is the point of diversion with respect to the canal or lateral reach where water enters the farm unit.

⁷A stream reach, including head-gate reaches, is a section of a stream that is associated with a particular model cell.

These streamflow-diversion options can be used to specify the method for calculating diversions from a stream or canal to a diversion canal leading to a farm or to a set of farms. Such a ‘canal diversion’ is simulated only by the SFR1. It is different from a ‘farm diversion’ of delivered surface water from any reach along a canal-diversion segment onto a farm that is simulated by a link to the SFR1 from the FMP. The ‘farm diversion’ is established as the ‘actual surface-water delivery’ either from a remote point of diversion (semi-routed delivery) or from the farm’s head gate (fully routed delivery). For fully routed deliveries, the FMP1 automatically determines the most upstream reach along a canal-diversion segment that is adjacent to a farm.

The actual surface-water delivery, DEL_{act}^f , (eq. 4) from a canal to farm f is equal to the portion of the total delivery requirement of farm f , $TFDR^f$, that cannot be supplied by the sum of all types of actually used nonrouted deliveries to farm f , $NRD_{act}^{f,t}$. However, DEL_{act}^f cannot exceed the potentially available stream inflow, $DEL_{pot}^{r,f}$, into the canal reach at the farm’s headgate (for “fully routed deliveries”), or at a point of diversion from the river or from a canal (for “semi-routed deliveries”). In addition, the actual delivery (eq. 4) also cannot exceed a delivery constraint, Q_{constr}^f , associated with a water-rights system:

$$DEL_{act}^f = \min(TFDR^f - \sum_t NRD_{act}^{f,t}, DEL_{pot}^{r,f}, Q_{constr}^f) \quad [L^3/T] \quad (EQ. 4)$$

where

- f = 1,2,..., number of farms;
- r = 1,2,..., number of stream reaches;
- t = 1,2,..., number of ranked types of actually used nonrouted deliveries.

Ground-Water Supply

The ground water supplied to each farm is simulated by a series of user-specified, single-aquifer “farm wells” or through user-specified associations with multi-aquifer wells simulated with the MNW package (Halford and Hanson, 2002). Ground-water pumpage requirements are estimated by the FMP1 after the TFDR is estimated and surface-water imports and exports from routed and nonrouted deliveries have been subtracted from the TFDR. If the TFDR is satisfied by the surface-water deliveries, then no ground-water pumpage will be estimated. Conversely, if no surface-water is available for supply, then ground-water from farm wells will be used to attempt to satisfy the demand estimated as the TFDR.

Ground-water pumping depends indirectly on consumptive use components. The ground-water pumping (eq. 5) of each farm (Q) equals either the farm’s pumping requirement (QREQ), which is reflected as residual farm delivery requirement by farm’s irrigation demand (TFDR) minus the total nonrouted delivery (TNRD) minus the actual surface-water supply (DEL_{act}), or the cumulative maximum pumping capacity, whichever is less (fig. 3):

$$Q = \min(TFDR - TNRD - DEL_{act}, QMAXF) \quad \Rightarrow \quad Q = \min(QREQ, QMAXF) \quad (EQ. 5)$$

The algorithm to calculate the pumping rate for each well in any one farm is as follows:

If $TFDR - TNRD > DEL_{act}$, then

If wells do not exist in farm, apply drought policy scenario (condition 1a).

If wells do exist, then:

(1) If $TFDR - TNRD - DEL_{act} > \sum_i Q_{max}^i$, then

(a) Apply drought policy scenario, so that

$$TFDR \geq TNRD + DEL_{act} + \sum_i Q_{max}^i$$

if $TFDR - TNRD - DEL_{act} < \sum_i Q_{max}^i$, then

update net-recharge, DEL_{act} , and update QREQ by going to (condition 2)

if $TFDR - TNRD - DEL_{act} = \sum_i Q_{max}^i$, then

update net-recharge, and

(b) Pump wells i with $Q^i = Q_{max}^i$

(2) If $TFDR-TNRD-DEL_{act} < \sum_i Q_{max}^i$, then

Pump wells on average with $QAVF = (TFDR-TNRD-DEL_{act})/n$

(a) If $Q_{max}^i \leq QAVF$:

pump well i with $Q^i = Q_{max}^i$

(b) If $Q_{max}^i > QAVF$:

pump well i with $QAVF +$ sum of deficiencies ($QAVF - Q_{max}^j$) of these wells (j) where

$Q_{max}^j < QAVF$, prorated to the wells (k) where $Q_{max}^k < QAVF$

$$Q^i = QAVF + \left[\sum_j (QAVF - Q_{max}^j) \right] * \frac{(Q_{max}^i - QAVF)}{\sum_k (Q_{max}^k - QAVF)}$$

where

$i = 1, 2, \dots, n$ (number of wells per farm)

$j = 1, 2, \dots, l$ (number of wells with $Q_{tot}/n > Q_{max}^j$) and

$k = 1, 2, \dots, m$ (number of wells with $Q_{tot}/n < Q_{max}^k$)

The link between the FMP1 and MNW package can be specified individually for any single- or multi-aquifer well. This link allows the simulation of an actual pumping rate based on (a) the desired ground-water pumping rate, Q^i , as determined by the above algorithm in FMP1, (b) the respective aquifer productivity found by the MNW, and (c) head- or drawdown constraints specified in the MNW data input file. If the actual pumping rate calculated by the MNW is less than Q^i , then the actual pumping rate is used as a simulated QMAX of a well, which replaces the default QMAX (= Q_{max}^i of well i , in the above algorithm) of the FMP1. In this case, the cumulative QMAXF (eq. 5) may be composed of both simulated and non-simulated maximum capacities of wells linked or not linked to the MNW package.

Net Recharge

For each model cell in a farm, net recharge is defined as “(1) inefficiency losses due to excess irrigation and excess precipitation, reduced by (2) the fraction inefficiency losses to surface-water runoff, and reduced by (3) evapotranspiration from ground water.” The following definitions relate to any finite-difference cell in the uppermost active model layer (the model-cell indices (i,j,k) have been omitted):

(1) Inefficiency losses to runoff and deep percolation as a result of excess irrigation and excess precipitation are defined as:

$$(I-CIR) + (P-ET_p),$$

where

- Excess irrigation ($I-CIR$) equal to applied irrigation (I) in excess of the crop irrigation requirement (CIR), plus
- Excess precipitation ($P-ET_p$) equal to precipitation (P) in excess of the evapotranspiration from precipitation (ET_p).

In a sufficiency situation, the applied irrigation (I) is driven by the crop irrigation demand and the demand for compensating inefficient water use ($TDR = CIR/OFE$). In an insufficiency situation, the available irrigation per cell (AVI), depends on the total available supplies and by the reduction scheme or pro-rating scheme of the user-selected deficiency scenario.

(2) The fraction of inefficiency losses to surface-water runoff depends on whether it is related to irrigation (IE_{sw}^I) or to precipitation (IE_{sw}^P). IE_{sw}^I depends on different irrigation methods, which, in turn, often depend on the crop type. For basin-level irrigation, IE_{sw}^I generally is zero. In the FMP1, the user may specify IE_{sw}^I and IE_{sw}^P as estimates between 0.0 and 1.0. Alternatively, the FMP1 can calculate internally the slope as rise-run, and equate both IE_{sw}^I and IE_{sw}^P to the slope. Therefore, in the FMP1, deep percolation can be defined as inefficiency losses to runoff and deep percolation minus the fraction of inefficiency losses to surface-water runoff respectively due to irrigation or precipitation:

$$(I-CIR) (1-IE_{sw}^I) + (P-ET_p) (1-IE_{sw}^P).$$

In the FMP1, deep percolation is taken to be equal to recharge.

(3) Evapotranspiration from ground water (even for irrigated areas) is subtracted from the potential net downward flux to the ground-water system. The net recharge to the uppermost active model cell is therefore equal to ‘recharge’ as defined in (2) minus the evapotranspiration from ground water as:

$$(I-CIR) (1-IE_{sw}^I) + (P-ET_p) (1-IE_{sw}^P).$$

Hence, net recharge to ground-water, R_n (eq. 6), can be defined for each uppermost active model cell in each farm by means of user-specified and head-dependent parameters, which are specified in red as functions of head (h) as:

$$R_n(h) = [I(h) - CIR(h)] (1-IE_{sw}^I) + [P - E_p - T_p(h)](1-IE_{sw}^P) - T_{gw-act}(h) - E_{gw-act}(h), \quad (\text{EQ. 6})$$

where

$I(h)$	= Applied Irrigation (head-dependent) For sufficiency cases: $I(h) = TDR(h)$ For insufficiency cases: $I(h) = AVI(h)$,
$TDR(h)$	= Total Delivery Requirement (head-dependent) = $CIR(h)/OFE(h)$,
$AVI(h)$	= Available Irrigation (head-dependent),
$CIR(h)$	= Crop Irrigation Requirement (head-dependent) = $(T_{c-act} - T_{gw-act} - T_{p-act}) (1 + K_e^i/K_r)$,
$OFE(h)$	= On-Farm Efficiency (optionally head-dependent for IEBFL = 2 and IEBFL = 3),
P	= Precipitation,
E_p	= Evaporation from precipitation,
$T_p(h)$	= Transpiration from precipitation (head-dependent),
IE_{sw}^I	= Fraction of inefficiency losses to surface-water runoff from irrigation,
IE_{sw}^P	= Fraction of inefficiency losses to surface-water runoff from precipitation,
$T_{gw-act}(h)$	= Actual transpiration from ground water, and
$E_{gw-act}(h)$	= Actual evaporation from ground water.

This definition of net recharge is physically valid, given the following assumptions:

- (1) Deep percolation beyond the active root zone is equal to ground-water recharge,
- (2) Recharge is simulated without delay and represents an instantaneous source pulse into ground-water flow, and
- (3) Evapotranspiration from ground water equals an instantaneous sink pulse out of ground-water flow.

Water-Rights Allocation

Allocation constraints representing water-rights hierarchies can be imposed as surface-water allotments. These surface-water allotments may be introduced into a model as a lumped *equal appropriation* allotment height for any stress period in units of [L/T] for all farms within the modeling domain or as water rights calls per stress period in units of [L] for a *prior appropriation* system for individual farms or irrigation regions. Equal appropriation means that all farms receive an equal amount of water from routed or semi-routed surface-water deliveries weighted by the respective area of the farm. The simulation of surface-water deliveries constrained by equal appropriation allotments requires specification of canal diversions in the SFR1 package input file. Simulating surface-water deliveries regulated by a *prior appropriation* system, requires that diversions from a river into canals serving the farms be simulated by the FMP1. Both equal and prior appropriation water rights may constrain the surface-water delivery at a farm's head gate (for fully routed deliveries) or at a specified point of diversion (for semi-routed deliveries). In this report, the phrase "inflow into, or delivery to a farm's head gate" represents either an 'adjacent' head gate for fully routed deliveries or a point of diversion conceived as a 'remote' head gate for semi-routed deliveries. Water-rights allocations that represent the prior appropriation of water can be applied to individual farms or to groups of farms when this group is simulated as a "virtual model farm." Thus, ranked appropriations of entire irrigation districts, or irrigated regions in transboundary settings, can be simulated by MF2K with the FMP1.

Equal Appropriation with Specified Canal Diversions

The potential delivery, $DEL_{pot_f}^{t,k}$ (eq. 7A), of equally appropriated surface water to farms through a 'river to canal' conveyance network is equal to the iteratively updated network inflow into the farm's head gate reach $Q_{in_r,f}^{t,k}$, such that:

$$DEL_{pot_f}^{t,k} = Q_{in_r,f}^{t,k} \quad [L^3/T] \quad \text{(EQ. 7A)}$$

where

- t = time step;
- k = iteration step;
- f = 1,2,..., number of farms; and
- r = 1,2,..., number of stream reaches.

For equally appropriated farms, not only the streamflow but also the farm allotment rate [L^3/T] constrain the actual amount of surface-water delivered. The farm allotment rate, $Q_{allot_f}^t$, is the product of an equal appropriation allotment flux, q_{allot} [L/T], and the respective farm area, A_f (eq.7B). The FMP1 converts the allotment height internally into an allotment flux [L/T] by dividing the height by the duration of the respective stress period [T].

$$Q_{constr_f}^t = q_{allot}^t \cdot A_f = Q_{allot_f}^t \quad [L^3/T] \quad \text{(EQ. 7B)}$$

For an equal appropriation system in the FMP1, the actual delivery (eq. 4) takes on the form:

$$DEL_{act_f}^{t,k} = \min(TFDR_f^{t,k} - TNRD_f^{t,k}, Q_{in_r,f}^{t,k}, Q_{allot_f}^t) \quad \text{(EQ. 7C)}$$

The inflow into the farm's head gate reach, $Q_{in_r,f}^{t,k}$, depends on:

- a specified inflow into a river (for example, release from reservoir);
- a specified diversion from the river into a diversion canal;
- upstream river and canal conveyance losses and gains; and
- upstream diversions from a diversion canal into upstream farms.

Prior Appropriation with Simulated Canal Diversion

Prior appropriation can be simulated with canal diversion as conveyance of surface water to downstream senior water rights in the FMP1. By maintaining a minimum streamflow at any upstream farm with junior rights, the minimum streamflow accounts for the downstream senior demand (senior right) and the conveyance losses to that senior farm. However, satisfying the senior demand also is dependent on the river streamflow, and on maintaining diversions to other even more senior farms that may exist on canals diverting water farther downstream.

For a prior appropriation system, the potential delivery, $DEL_{pot_f}^{t,k}$ (eq. 8A), through a “river to canal” network is equal to the network inflow into the head gate reach of the farm of interest, $Q_{in_r,f}^{t,k}$, minus a minimum streamflow, $Q_{C-min_r,f}^{t,k}$, which accounts for the senior demand of a farm downstream of the same canal and the canal conveyance losses to that farm:

$$DEL_{pot_f}^{t,k} = Q_{in_r,f}^{t,k} - Q_{C-min_r,f}^{t,k} \quad [L^3/T] \quad (\text{EQ. 8A})$$

where

t = time step;

k = iteration step;

f = 1,2,..., number of farms; and

r = 1,2,..., number of stream reaches.

For a ranked prior appropriation water-rights system, each farm is assigned a certain water right or water-rights call, which the respective farm can receive as a maximum:

$$Q'_{constr_f} = Q'_{call_f} \quad [L^3/T]. \quad (\text{EQ. 8B})$$

Other approaches to simulate farm diversions in the recent past have implemented prior appropriation water rights systems into conjunctive surface-water and ground-water modeling programs. The main concept of a water-rights package, called MODRIGHT for MODFLOW-96 (McCurry, 2000), was to satisfy a farm's water rights call as an irrigation demand exists, and, if so, then to send the entire call in a model to a point of main diversion from the river. This addresses a situation, where a farm or an irrigation setting would use its entire right. In some states or regions, this procedure might apply to common practices. In general, however, it could lead to oversupply. Thus, the FMP1's concept is to deliver only the simulated demand, but not more than a specified water rights call.

For the implementation of the prior appropriation system in the FMP1, the actual delivery (eq. 4) takes on the following form:

$$DEL_{act_f}^{t,k} = \min(TFDR_f^{t,k} - TNRD_f^{t,k}, Q_{in_r,f}^{t,k} - Q_{C-min_r,f}^{t,k}, Q'_{call_f}) \quad (\text{EQ. 8C})$$

Both the inflow into a respective farm's head gate reach, $Q_{in_r,f}^{t,k}$, and the required minimum streamflow to preserve the delivery to a downstream senior farm, $Q_{C-min_r,f}^{t,k}$, depend on:

- A specified inflow into a river (for example, release from reservoir);
- Upstream river conveyance losses and gains;
- A potential diversion from the river into a diversion canal, which accounts for the
 - o Irrigation water demand of all farms on a canal sequentially according to their water rights rank;
 - o Canal conveyance losses and gains from the point of canal diversion from the river to these farms; and
- An actual diversion from the river into a diversion canal, which might be equal to a potential diversion accounting for all the deliveries on one main diversion canal or be restricted by the river streamflow.

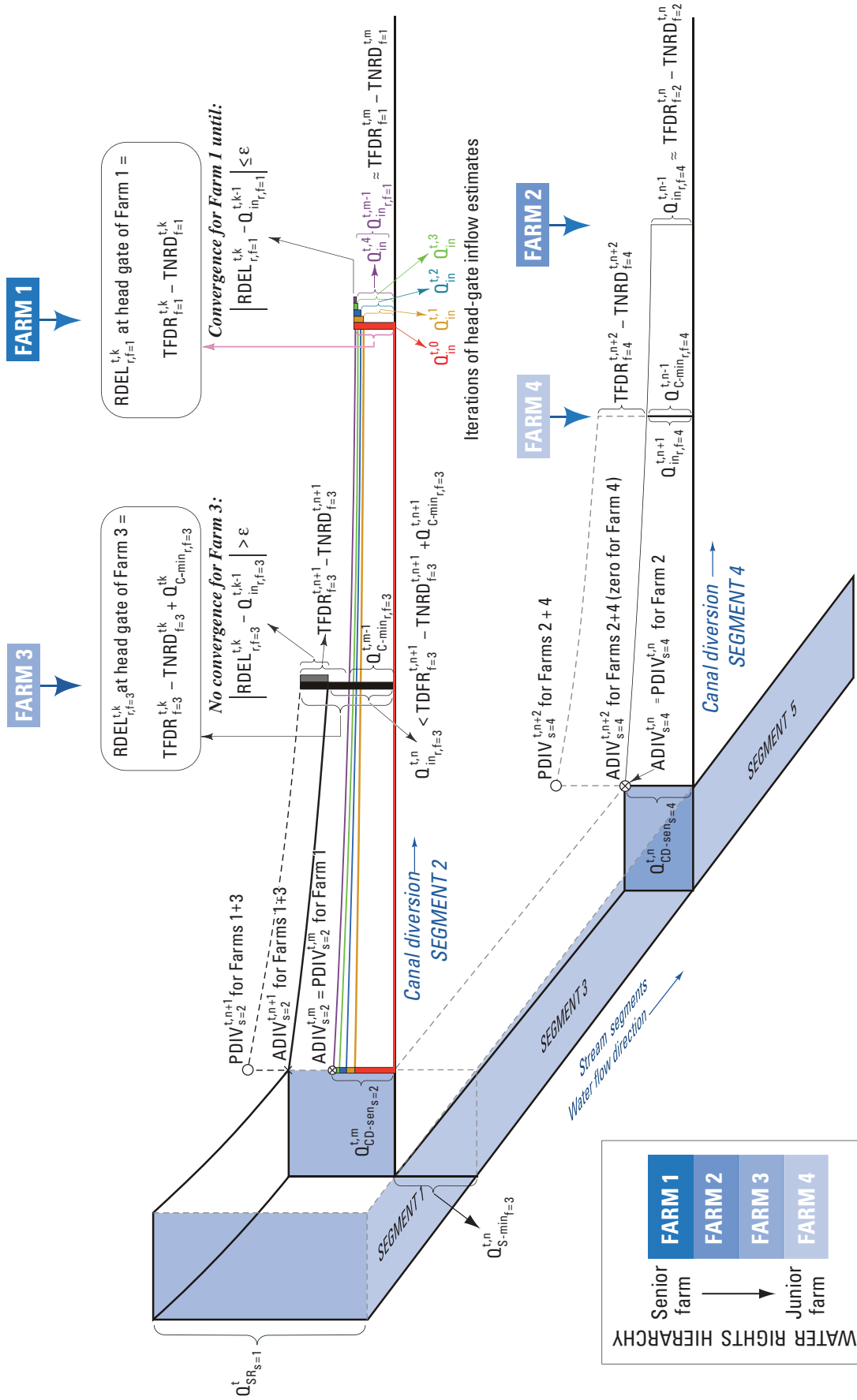
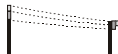


Figure 10. Numerical procedure for determining the diversion rate to a canal for farms subject to a water-rights allocation hierarchy.

EXPLANATION (figure 10)

- $PDIV_s^{t,k}$ potential diversion from river into canal segment s at time step t, and at iteration step k
- × $ADIV_s^{t,k}$ actual diversion from river into canal segment s at time step t, and at iteration step k
- ⊗ Actual diversion = potential diversion
- $Q_{SR_s}^t$ Stream release into river segment s (specified per stress period and constant over time step t)
- $Q_{S-min_f}^{t,k}$ Minimum river streamflow that is not available for diversion to farm f, necessary to account for the demand and for related conveyance losses to a downstream senior farm located at a downstream diverting canal
- $Q_{CD-sen_s}^{t,k}$ Diversion into canal for senior farm on canal
- $Q_{C-min_{r,f}}^{t,k}$ Minimum canal streamflow not available for farm f at its head gate, necessary to account for senior farm on same canal
-  $RDEL_{r,f}^{t,k}$ Iterative approach of determining the canal diversion for a farm (here: starting with an initial $Q_{CD-sen_s}^{t,0}=0$)
- - - - - Simulation of a potential diversion for a junior farm exceeding the actual diversion
- $TFDR_f^{t,k}$ Total farm delivery requirement of farm f, at time step t, and at iteration step k
- $TNDR_f^{t,k}$ Total non-routed delivery to farm f, at time step t, and at iteration step k =

$$TNDR_f^{t,k} = \left(\sum_{types} (NRD_{act})^{type} \right)_f^{t,k} = \text{sum of all types of actually used non-routed deliveries}$$
- $RDEL_{r,f}^{t,k}$ Delivery requirement into head gate reach of farm f, at reach r, at time step t, and at iteration step k
- $Q_{in_{r,f}}^{t,k}$ Inflow into head gate reach of farm f, at reach r, at time step t, and at iteration step k
- ϵ Error tolerance (convergence criterion)
- s Stream segment (group of reaches specified in streamflow routing package SFR1)
- r Reach number: reach = section of stream segment associated with finite-difference cell
- f Farm identifier (farm number): lower farm ID = higher water rights ranking
- t Time step (diagram displayed within one particular time step)
- k Iteration step
- m Number of iterations to reach a “convergence solution” for farm 1:
 - solving for actual diversion from river into canal to satisfy the delivery requirement for farm 1, and
 - determination of minimum canal stream flow at farm 3 to account for demand of downstream farm 1.
- n Number of iterations to reach a “convergence solution” for farm 1 (m iterations) + number of iterations to reach a “convergence solution” for farm 2:
 - solving for actual diversion from river into canal to satisfy the delivery requirement for farm 2, and
 - determination of minimum river stream flow at upstream canal to account for demand of farm 2, and
 - determination of minimum canal stream flow at farm 4 to account for demand of downstream farm 2.
- n+1 Number of iterations to reach an “exceedance solution” for farm 3:
 - potentially necessary diversion (PDIV) exceeds ADIV at first iteration after convergence solution for farm 2:
 (delivery to head gate reach is less than RDEL and equal to: $Q_{C-min_{r,f=3}}^{t,n} - Q_{C-min_{r,f=3}}^{t,m-1}$)
- n+2 Number of iterations to reach an “exceedance solution” for farm 4:
 (delivery to head gate reach is zero, since: $Q_{in_{r,f=4}}^{t,m+1} = Q_{C-min_{r,f=4}}^{t,n-1}$)
 - potentially necessary diversion (PDIV) exceeds ADIV at first iteration after exceedance solution for farm 3:

The numerical objective is to satisfy a farm's residual irrigation delivery requirement that is not yet supplied by nonrouted deliveries (TFDR-TNRD) by sufficiently diverting water from a river into a canal to account for the canal's conveyance losses to that farm, and for the surface-water inflow into the farm's head gate reach to meet the farm's delivery requirement. Depending on an estimated diversion from the river into the canal and the conveyance losses or gains, the inflow into the farm's head gate reach will be either sufficient or insufficient to satisfy the residual delivery requirement, TFDR-TNRD. Although canals generally will be 'losing channels,' the algorithms also hold for canals that are 'gaining channels.' A schematic (*fig. 10*) illustrates how the diversion rate for a canal is determined. The farm identification numbering scheme is inversely proportional to its rank (water-right seniority).

No Senior Farm Downstream of the Farm of Interest on the Same Canal

For the hypothetical example farm 1 (*fig. 10*) is the most senior water-right farm in the model, and is not constrained by more senior water rights of any downstream farms. "Downstream farms" in this context stands for farms downstream on the same canal where the farm of interest is located and for farms on canals diverting from the river on downstream locations. If no senior farm exists downstream on the same canal, the delivery requirement (eq. 9) to the head gate reach of farm 1, $RDEL_{rf}$, simply equates to the total farm delivery requirement, minus the total nonrouted delivery, $TFDR_f - TNRD_f$:

$$RDEL_{rf} = TFDR_f - TNRD_f \tag{EQ. 9}$$

where

$f = 1, 2, \dots$, number of farms;
 $r = 1, 2, \dots$, number of stream reaches; and
 $s = 1, 2, \dots$, number of segments (in text).

The iterative algorithm determines the 'unsatisfied increment' between the reach delivery requirement, $RDEL_{r,f}^{t,k}$, at a current iteration (k) and the actual inflow into the farm's head gate reach, $Q_{in,r,f}^{t,k-1}$, resulting from a diversion rate specified or estimated at the previous iteration (k-1).

The initial potential diversion rate $PDIV_s^{t,0}$, into a certain canal segment (s) is specified by the user in the SFR1 input file and can be any arbitrary number (for example, zero). The 'unsatisfied increment', $RDEL_{r,f}^{t,1} - Q_{in,r,f}^{t,0}$, then is added to the initial potential diversion rate, $PDIV_s^{t,0}$, and is applied as the new potential diversion rate, $PDIV_s^{t,1}$. The program passes on this temporary potential diversion rate to SFR1, where it is used as an actual diversion rate. Before solving the ground-water-flow equation in MF2K, SFR1 generates the resulting canal streamflow and streambed leakage rates. Due to these conveyance losses or gains, the inflow at the farm's head gate, $Q_{in,r,f}^{t,1}$, again might not be sufficient to satisfy the delivery requirement exactly. During the following iteration, the algorithm then recomputes again the 'unsatisfied increment, $RDEL_{r,f}^{t,2} - Q_{in,r,f}^{t,1}$, and adds it to the previous potential diversion rate, $PDIV_s^{t,1}$.

The algorithm repeats (eq. 10, *fig. 10*) the computation of the "unsatisfied increment," $RDEL_{r,f}^{t,k} - Q_{in,r,f}^{t,k-1}$, until convergence is reached within a user-specified tolerance ($|RDEL_{r,f}^{t,k} - Q_{in,r,f}^{t,k-1}| \leq \epsilon$).

$$PDIV_s^{t,k} = PDIV_s^{t,k-1} + (RDEL_{r,f}^{t,k} - Q_{in,r,f}^{t,k-1}) \tag{EQ. 10}$$

(indices t, k, s, r, f, *fig. 10*)

Senior Farm Exists Downstream of the Farm of Interest on the Same Canal

As long as the potential diversion is less than the available river streamflow, the same procedure (eq. 9) is repeated for the next more junior water-right farm along the same canal, starting with the PDIV value from the previously processed senior water-right farm. If the junior water-right farm is further upstream along the canal (see farm 3, *fig. 10*), then it has to guarantee a minimum canal streamflow, $Q_{C-min,r,f}$, which accounts for the conveyance losses and the downstream senior-right demand. The delivery requirement into the farm's head gate reach, RDEL is, therefore, equal to the $TFDR_f$ of farm 3 minus the total nonrouted delivery, $TNRD_f$, plus the minimum streamflow, $Q_{C-min,r,f}$, required to sustain the delivery to farm 1 and not available for farm 3. If a senior farm exists downstream on the canal, the delivery requirement (eq. 11) is estimated as:

$$RDEL_{rf} = TFDR_f - TNRD_f + Q_{C-min,r,f} \tag{EQ. 11}$$

After having determined a cumulative potential diversion, PDIV, from the river for a certain farm and all farms senior to that farm along a canal (farm 3 + farm 1 in *fig. 10*), the FMP1 passes PDIV on to the SFR1 and to the MF2K main program. PDIV is compared with the current value of the actual river streamflow at the point of diversion into the canal before the ground-water-flow equation is solved. If PDIV (\pm in *fig. 10*), exceeds the actual possible diversion, then ADIV (\times in *fig. 10*), as indicated by the dashed line in *figure 10*, only an insufficient stream inflow can be used for the demanded delivery of the current farm.

No Senior Farms Exist on Downstream Diverting Canal (Case A)

If no senior farms exist on a diverting canal located downstream of the canal under consideration (not shown in *fig. 10*), then the farms along the canal are supplied sequentially, according to their rank, until the diversion into the canal is restricted or ceases owing to limited available streamflow. At that point, a farm junior to the already sufficiently supplied farms will not receive enough water. In this case, the actual diversion from the river reach into the canal segment, $ADIV_s$, is constrained by the stream inflow, Q_{S-in_r} , into the river stream reach, r . ADIV needs to have already provided the diversion necessary for the delivery to senior farms along the same canal segment, s , and the canal conveyance losses to such senior farms (Q_{CD-sen_s}). The only amount of a limited river streamflow that is available for the supply to a junior farm and the related conveyance losses, is the outflow, Q_{S-out_r} , out of the reach from which the canal diverts (eq. 12):

Case A: No senior farms exist on downstream diverting canal (not shown in *fig. 10*).

$$\begin{aligned} ADIV_s &= PDIV_s, & \text{when } PDIV_s < Q_{S-in_r} \\ ADIV_s &= Q_{S-in_r} = Q_{CD-sen_s} + Q_{S-out_r}, & \text{when } PDIV_s \leq Q_{S-in_r} \end{aligned} \quad (\text{EQ. 12})$$

Senior Farms Exist on Downstream Diversion Canal (Case B)

If higher-ranking farms divert from downstream canals, then a minimum river streamflow, Q_{S-min_f} , is maintained at the point of diversion into an upstream canal. This minimum streamflow is not available for diversion to farm f , which is served by the upstream diverting canal. Q_{S-min_f} must include downstream canal diversions from the river to downstream senior farms and for downstream river and canal conveyance losses (*fig. 10*). Therefore, as apposed to Case A, the actual diversion into the upstream diversion canal is limited not only by the river streamflow, but also by a limiting minimum streamflow. The minimum streamflow, Q_{S-min} , is the difference between the river streamflow downstream from the point of the upstream diversion canal and streamflow from the point of the downstream diversion canal. This difference accounts for the conveyance losses and the downstream diversion necessary to supply the downstream senior farm located on the downstream diverting canal.

In this case (Case B), the actual diversion from the river reach into the canal segment, ADIV, is equal to the inflow into the river stream reach minus the minimum streamflow that is not available for diversion to farm f , Q_{S-min_f} . As before in Case A, ADIV needs to have already provided the diversion necessary for the delivery to senior farms along the same canal and the canal conveyance losses to such senior farms (Q_{CD-sen_s}). The only amount of a limited river streamflow available for an insufficiently supplied junior farm is:

- The outflow from the river reach from which the canal diverts, Q_{S-out_r} ,
- *minus*
- The minimum streamflow, Q_{S-min_f} , that is not available for diversion to farm f , necessary to guarantee downstream canal diversions from the river to downstream senior farms and to compensate for downstream conveyance losses (eq. 13):

Case B: Senior farms exist on downstream diversion canal (farm 2, *fig. 10*).

$$\begin{aligned} ADIV_s &= PDIV_s & \text{when } PDIV_s < Q_{S-in_r} - Q_{S-min_f} \\ ADIV_s &= Q_{S-in_r} - Q_{S-min_f} = Q_{CD-sen_s} + Q_{S-out_r} - Q_{S-min_f} & \text{when } PDIV_s \geq Q_{S-in_r} - Q_{S-min_f} \end{aligned} \quad (\text{EQ. 13})$$

The lesser of the residual farm delivery requirement that is not yet supplied by nonrouted deliveries, TFDR - TNRD, or the available streamflow from the farm's head gate reach, $Q_{in} - Q_{C-min}$, or of a water rights constrained maximum allowable flow rate (commonly called a "call," Q_{call}), will be diverted from the farm's head gate reach into the farm (eq. 8C). Supplying the residual farm delivery requirement to the most junior farm would require that the cumulative potential delivery from the river into the canal be less than the river streamflow (Case A), or less than the river streamflow minus a minimum required streamflow to account for downstream senior-rights-driven canal diversions (Case B). If those canal diversions are restricted, as formulated by equations (12) and (13), then the junior rights farm will receive a reduced stream inflow at the farm's head gate. The surface water available to the junior farm equals this stream inflow minus further streamflow restrictions for downstream senior farms along the same canal.

A flow rate in the amount of a water rights call will be diverted only if the available streamflow exceeds the call. Again, that available streamflow could be either sufficient or insufficient to satisfy the farm's residual delivery requirement. The FMP1 uses only water rights calls to stipulate a limitation on the farm. Other approaches may result in an oversupply to any farm (for example, McCurry, 2000).

Modification of Prior Appropriation System for Surface-Water Surplus

Surplus deliveries owing to the (1) absolute use of nonrouted deliveries, or to (2) a reduced TFDR after invoking a drought response policy, may modify the rules of a prior appropriation system as follows:

(1) Nonrouted deliveries that exceed the farm's delivery requirement of an upstream farm may be specified to supply surplus water into the conveyance system (NRDuse-Flag = 1) to benefit downstream users through a local water transfer. The downstream farm's diversion requirement from the river accordingly can be replaced in part or fully by supplying surplus water into the canal at an upstream farm. This concept assumes a replacement of the rate of surface-water delivery, which a downstream farm would have received to satisfy its demand and the according conveyance losses.

(2) After invoking a drought response policy (for example, water-stacking or acreage-optimization), the farm's delivery requirement may be reduced to be less than the limited surface-water supply. This could be the result of a reduced demand from priority crops (in the case of water-stacking), or owing to a reduction of the cropped acreage that would force the demand to be even smaller than the limited supply. The latter may occur in situations where surface-water irrigation is unprofitable for a particular cropping pattern.

There are several important assumptions in the FMP1 regarding surplus delivery cases 1 and 2:

Assumptions for case 1:

Surplus due to excess nonrouted deliveries supplied to the canal at a certain junior upstream farm can increase the available supply to a senior downstream farm. Under such conditions, the junior farm, formerly restricted by the demand of senior farms under the prior appropriation system, now has the potential to supply water to senior downstream farms. Such a scenario might occur if water is traded between farms along the same canal. However, the concept of a prior appropriation water rights system would not be strictly maintained. The FMP1's farm budget would account for these additional credited deliveries.

The flow-rate portion of the diversion from the river is potentially necessary to account for the demand of the senior farm and the conveyance losses to that farm.

- Assumption 1a: When the surplus is smaller than the minimum streamflow requirement, the delivery of surface water is reduced by the rate gained by the surplus supplied at the upstream farm and is additionally reduced by any potential canal losses for the upstream farm. That is, the remaining diversion from the river plus the surplus supplied at an upstream farm compensate fully for the downstream farm's demand. No water will remain in the canal downstream of the downstream farm.

- Assumption 1b: When the surplus is greater than the minimum streamflow requirement, the delivery of surface water is reduced to zero. That is, the downstream farm's demand and the conveyance losses between the upstream and downstream farm is compensated fully by supplying the surplus at the upstream farm into the canal. The excess surplus (that is, surplus in excess of minimum streamflow requirement) also is supplied to the canal. Therefore, more water will arrive at the downstream farm than what is needed to satisfy this farm's demand.

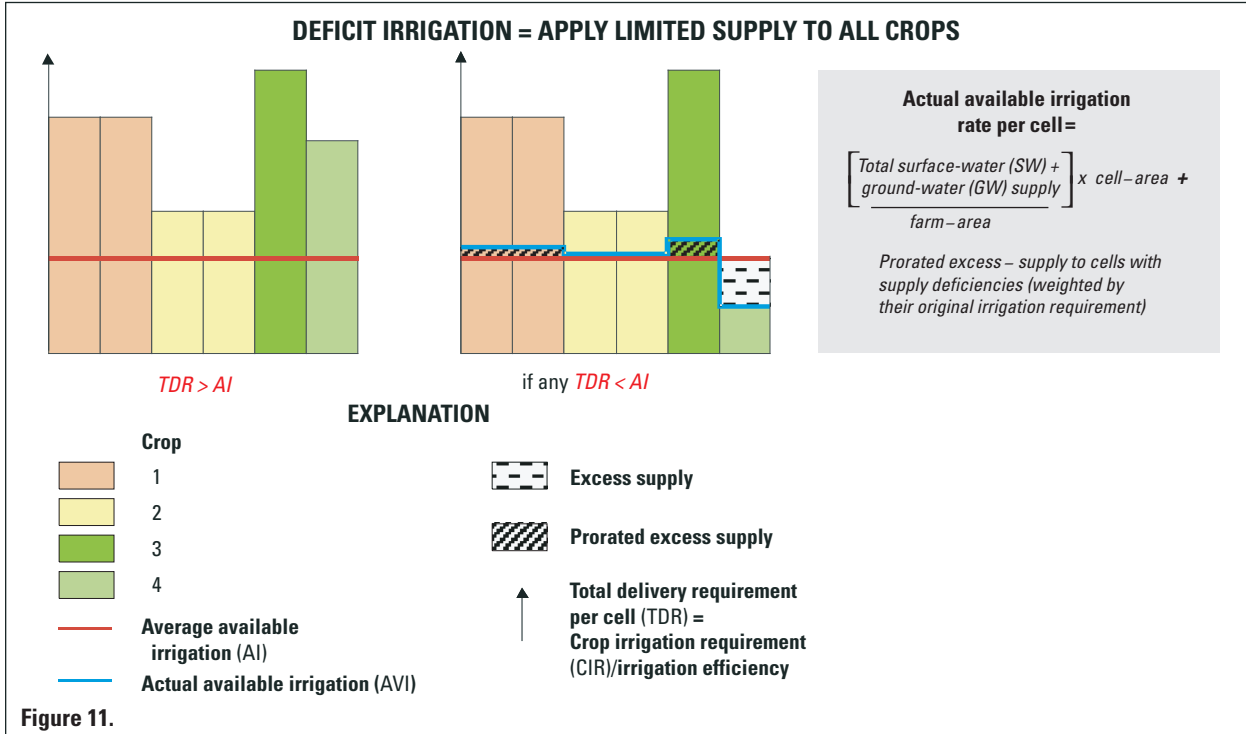


Figure 11.

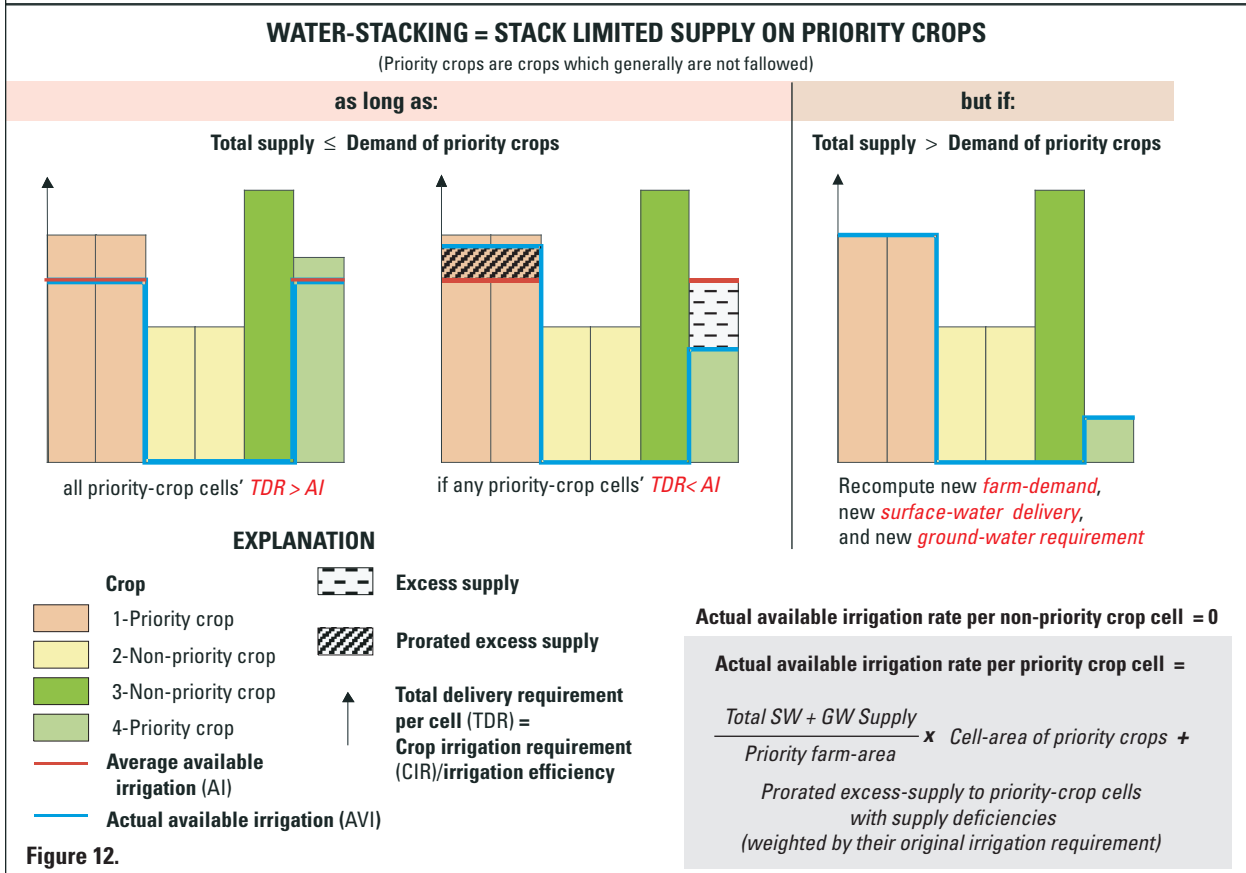


Figure 12.

Figure 11. Concept of Deficit Irrigation Policy.

Figure 12. Concept of Water-Stacking Policy (Legend see figure 11).

Assumption for case 2:

Using less routed surface-water than what was formerly available as limited supply also implies that a lesser flow rate is needed for diversion from the river into the canal to account for this new demand and associated conveyance losses. Such a lesser diversion consequently leads to excess streamflow in the river downstream of the diversion, which is in contrast to invoking the drought scenario where the downstream junior farm(s) located along a downstream diverting canal will benefit from the reduced diversion. If this benefit exceeds the demand of the downstream junior farm then such a farm will not need to reduce its demand anymore and the drought-policy scenario may not be invoked for the downstream junior farm(s).

Drought Scenario Alternatives

If the potential supply of surface water and ground water is insufficient to meet the crop demand, three options of economic and noneconomic drought response policies can be applied: acreage-optimization (eq. 14), deficit irrigation (fig. 11), or deficit irrigation with water-stacking (fig. 12).

If the desired response to insufficient irrigation supplies is to reduce crop acreage through an optimization routine, then the optimized total farm irrigation demand must be equal to or less than the available supply of nonrouted, and (semi-)routed surface water as well as ground water ($TFDR \leq TNRD + DEL_{act} + QMAXF$). The objective function describes a linear optimization scheme, where the objective is to maximize the farm's overall profit associated with the surface water irrigated acreage and with the ground-water-irrigated acreage of all farm cells.

The optimization of surface- and ground-water irrigated cell acreages (equals the optimization variables) is subject to resource and area constraints: the farm's irrigation demand from nonrouted surface water, (semi-) routed surface water, and ground water should not be greater than the respective available water resources ($TNRD$, DEL_{act} , $QMAXF$). The area of each cell's acreage should be bound by an initial maximum acreage and a minimum allowed acreage, which usually is zero. The ratio between the optimum cell acreage and the initial maximum cell acreage is applied as a reduction factor to the cell's net recharge calculation before the net-recharge term is added to the left-hand side and right-hand side of the finite-difference flow equation.

The economic value or net profit per unit area associated with the irrigation of a specific water type and with a certain crop type can be determined for each cell by subtracting the respective costs of applying either irrigation of a certain water type to a unit area of the model cell from the crop benefit per unit area. As opposed to the *crop benefit per unit area* (b), which enters the objective function directly as user-specified parameters, the water costs per unit area irrigated with a certain water type are calculated by the FMP1 in the objective function (eq. 14) as the product of *water costs per unit water volume* (c^{gw} , c^{sw}) associated with a user-specified water-type multiplied by the required *model-cell specific crop irrigation flux* (q).

Update of Source Term Flow Rates

After a drought policy has been applied, the source-term flow rates are updated regardless of whether the supplies are (A) greater than or equal to or (B) less than the adjusted irrigation demand (fig. 13).

(A) If after applying a drought policy scenario, the total irrigation demand is still greater than or equal to the total supply, that is,

If $TFDR \geq TNRD + DEL_{act} + QMAXF \Rightarrow$ then for the following drought policies

- deficit irrigation (in general),
- water stacking (if reduced farm delivery requirement of priority crops > total supply),
- acreage-optimization (if demand was forced to equal the total supply), then the flow rates are updated as follows:
 - (1) For all scenarios: apply "pre-policy" surface-water supply $TNRD + DEL_{act}$ and ground-water pumping at maximum capacity $QMAXF$.
 - (2) For all scenarios: apply reduced available irrigation (AVI) to cells, which do not receive the originally required total delivery requirement $TDR = CIR/OFE$ (for $AVI > CIR$); irrigation related losses are: $(AVI - CIR)$ instead of $(TDR - CIR)$.

(B) If, after applying a drought policy scenario, the total irrigation demand is less than the total supply, that is,

If $TFDR < TNRD + DEL_{act} + QMAXF \Rightarrow$ then for the following drought policies:

- water stacking (reduced farm delivery requirement of priority crops < total supply)
- acreage-optimization (demand of low profitable crops even < total supply) flow rates are updated as follows:

Objective Function:
$$\max Z = \sum_i \sum_t (b_i - c_i^t \times q_i) x_i^t \quad (\text{EQ. 14})$$

subject to:

$$\sum_i q_i \times x_i^t \leq WR^t \times OFE$$

$$\sum_t x_i^t \leq x_{i-max}$$

$$\sum_t x_i^t \geq x_{i-min} (= 0)$$

notations:

- q_i - crop irrigation flux required for a cell (CIR) _{i} ;
 x_i^t - acreage per cell irrigated with water type t ;
 x_{i-max} - initial / maximum possible acreage of cell;
 x_{i-min} - minimum possible acreage of cell (taken to be zero);
 i = 1,2,..., number of cells in a farm;
 t = nrd, rsw, gw;
 nrd = nonrouted delivery,
 rsw = routed surface water,
 gw = ground water.

notations (cont.):

WR^t - water supply resource of type t :

WR^{nrd} = total nonrouted delivery to a farm ($TNRD$);

WR^{rsw} = actual surface-water delivery to a farm (DEL_{act});

WR^{gw} = cumulative maximum capacity of all wells in a farm ($QMAXF$)

OFE - on-farm irrigation efficiency.

b_i – crop benefit from expected yield and crop market price : $y \left[\frac{W}{A} \right] p \left[\frac{\$}{W} \right] = b \left[\frac{\$}{A} \right]$;

with : $y = a \times ET_c + b$ (water production function).

c_i^t – costs of water type t .

c_i^{nrd} – nonrouted-delivery costs $\left[\frac{\$}{L^3} \right]$

c_i^{rsw} – surface-water costs:

$$c_i^{rsw} = c^{rsw-FP} + c_i^{rsw-SHL} + c_i^{rsw-DEL}$$

with : c^{rsw-FP} = fixed price of surface water $\left[\frac{\$}{L^3} \right]$

$$c_i^{rsw-SHL} = \text{unit pumping costs} \left[\frac{\$}{L^3 \times L} \right] \times \text{surface head lift from nearest canal reach to cell} [L]$$

$$c_i^{rsw-DEL} = \text{unit delivery costs} \left[\frac{\$}{L^3 \times L} \right] \times \text{distance of cell to nearest reach} [L]$$

c_i^{gw} – ground-water costs:

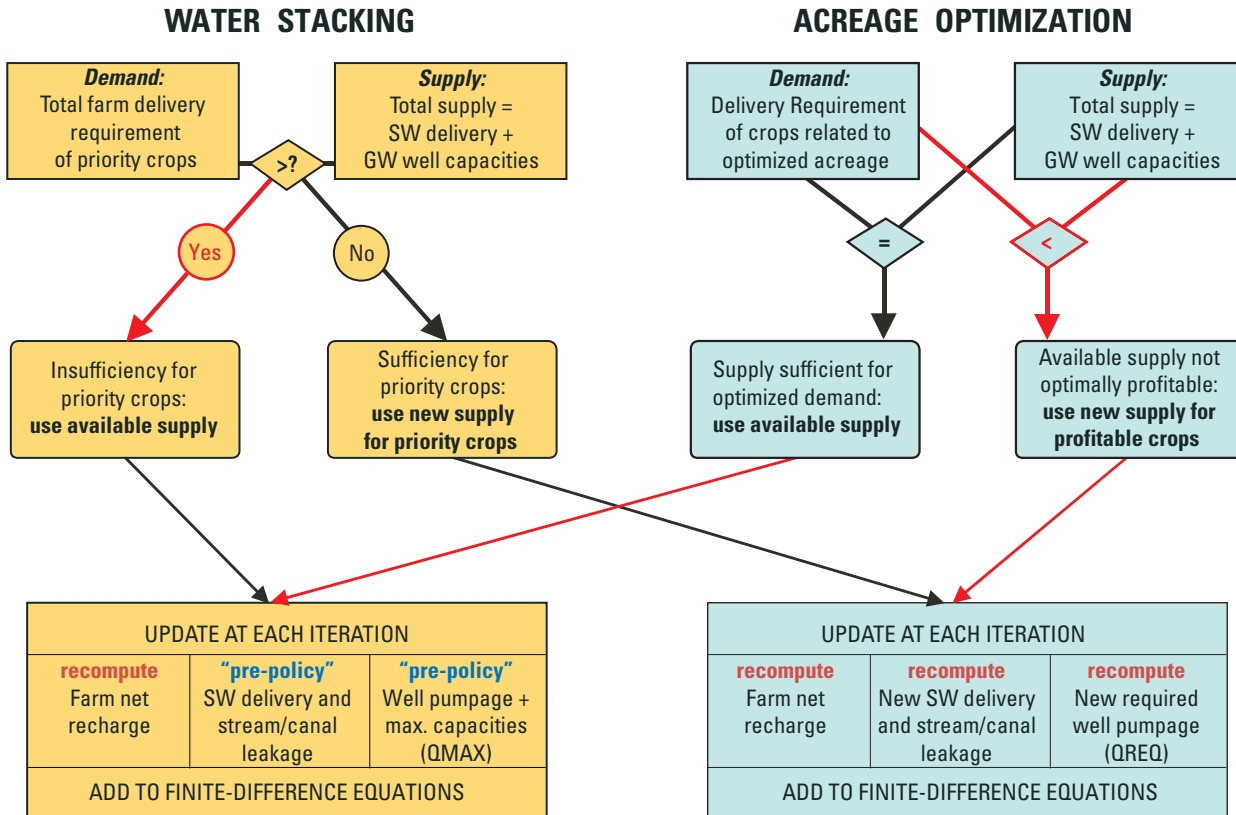
$$c_i^{gw} = c^{gw-BASE} + c_F^{gw-WHL} + c_i^{gw-SHL} + c_i^{gw-DEL}$$

with : $c^{gw-BASE}$ = pumping base maintenance costs $\left[\frac{\$}{L^3} \right]$

$$c_F^{gw-WHL} = \text{unit pumping costs} \left[\frac{\$}{L^3 \times L} \right] \times \text{effective well head lift of all farm wells} [L]$$

$$c_i^{gw-SHL} = \text{unit pumping costs} \left[\frac{\$}{L^3 \times L} \right] \times \text{surface head lift from "effective well" to cell} [L]$$

$$c_i^{gw-DEL} = \text{unit delivery costs} \left[\frac{\$}{L^3 \times L} \right] \times \text{effective distance from cell to well} [L]$$



EXPLANATION

- >? Test for sufficiency, demand > supply?
- < Less than
- SW Surface water
- GW Ground water

Figure 13. Updating of source-term flow-rates depending on the drought-response policy chosen.

- (1) For water stacking: recompute TNRD, DEL_{act} for priority crops, and supplemental QREQ (here < QMAXF) for priority crops.
- (2) For acreage optimization: apply resulting profitable amount of nonrouted delivery (\leq initial TNRD), surface-water (\leq initial DEL_{act}) and ground-water pumping (\leq QMAXF).
- (3) For both scenarios: apply reduced available irrigation (AVI) to cells, which do not receive the originally required total delivery requirement $TDR = CIR/OFE$ (for $AVI > CIR$); irrigation related losses are: $(AVI - CIR)$ instead of $(TDR - CIR)$.

For cases (A) and (B), if in any cell the available irrigation is smaller than the CIR ($AVI < CIR$), then all available irrigation is used, and no irrigation related losses occur.

Applicability and Limitations

The FMP1 facilitates the estimation of water consumption from irrigated agriculture from precipitation, surface water, and ground water. The types of approximations made by the FMP1 can be used to simulate a wide variety of irrigation settings that span the spectrum from flooded fields, to drip irrigation of truck crops and orchards. In addition, this process can be used for a wide variety of applications that include consumption of water by vegetation in nonirrigated agriculture, fallow fields, natural vegetation, and urban landscape settings.

While the FMP1 can simulate a wide variety of settings for consumption of water by vegetation and evaporation, a number of basic assumptions are required to facilitate these simulations. These approximations represent limitations that may preclude the application of the process to certain types of problems. The limitations include:

- (1) The steady-state analytical approximation for changes in flow in the unsaturated part of the root zone does not include any changes in storage in the unsaturated zone;
- (2) The potential transpiration is assumed to be equally distributed over the entire active root zone;
- (3) There is no delay in the infiltration of irrigation and precipitation. Therefore, runoff from the soil surface is subtracted after infiltration and evapotranspiration are estimated;
- (4) Deep percolation beyond the active root zone is taken to be recharge;
- (5) Recharge is assumed to be an instantaneous source pulse into ground water;
- (6) Evapotranspiration from ground water is taken to be an instantaneous sink pulse out of ground water;
- (7) The farm wells are assumed to be single-aquifer wells. However, multi-aquifer wells entered through Multi-Node Well package also can be linked to FMP1;
- (8) The nonrouted surface-water deliveries are assumed to be exempt from water-rights allocations and are accounted for first with respect to satisfying the TFDR; and
- (9) With respect to satisfying the TFDR during sufficiency, nonrouted deliveries are accounted for by first priority, semi- or fully routed surface-water deliveries by second priority, and ground-water pumpage by third priority.

General Data Requirements

A review of general data requirements will assist the user with the compilation of the data required to use the FMP1 with MF2K. The items reviewed in this section generally follow the sequence of the data input items as described in the “Data Input Instructions” section of this report. In particular, the data requirements described in the “Data Input Instructions” section of this report discuss data requirements for the entire simulation and then data requirements for each stress period. To facilitate understanding of these data requirements, two-dimensional data arrays and multi-dimensional data lists, which could be retrieved from Geographic Information System (GIS) coverages, are summarized.

Input parameters, or parameters from which input parameters are derived, generally are kept in *italic*. Some parameters, parameter arrays, or parameter lists are read only once when related option flags are specified by the user. The flags are capitalized and in parentheses. These flags are defined in detail in the following section of this report (Data Input Instructions in the “Explanation of Fields used in the Input Instructions” subsection of this report).

Arrays and Lists of Spatially Distributed Data

Two-dimensional arrays of spatially continuous features (for example, polygons) and multi-dimensional lists for line or point features are required mostly for the entire simulation, but in some cases also are required for every stress period. The compilation of these data may be supported through the use of a GIS. Two-dimensional arrays of farm, soil-type, or crop-type identifiers relate only to a single identifier (ID) variable and, therefore, are not discussed again in the following sections. Multi-dimensional attribute lists contain several parameters attributed to one multi-dimensional variable. They, therefore, are, discussed in more detail in the following sections of this report: “Data requirements for the entire simulation” and “Data requirements for each stress period.”

Two-Dimensional Arrays

In MODFLOW, the model domain is discretized into a mesh of blocks called cells, the locations of which are described in terms of rows, column, and layers with an i,j,k indexing system (Harbaugh and others, 2000). A two-dimensional (2D) array refers to a 2D-matrix of a model variable, $x(i,j)$, that contains a value for each cell, that is applied at the center of the cell. Each value of the model variables, $x(i,j)$, is held constant during either each stress period or for the entire period of simulation. Spatially distributed model variables, such as 2D-arrays of real or integer variables, can be generated by a GIS preprocessor using the same boundaries and discretization as specified in the input file for the Basic Package (BAS6) or in the Discretization File (DIS) (Harbaugh and others, 2000).

Ground-Surface Elevation

A two-dimensional (2D) real array of ground-surface elevation is required for the entire simulation. This array may be obtained optionally by converting Digital Elevation Model (DEM) data into a GIS raster data grid of different resolution, or from a point feature class or polygon feature class that is sampled at the cell centers (where it may represent the mean, median, or minimum land-surface elevation).

Identification Arrays

Every farm, soil type, and crop type must have an integer number identifier (ID). Each respective ID grid array can be obtained optionally by converting the ID attribute of a GIS polygon feature class into a GIS raster grid coverage. Alternatively, a point feature class with MF2K cell center coordinates and an attributed ID can be created by overlaying the ID attribute of a polygon feature class onto a point feature class, which contains coordinates of the MF2K model cell centers. If these features are at a smaller resolution or more detailed than the user-specified model-grid discretization, these features may need to be simplified to average values for each model cell. Other farm, soil type, or crop type attributes are not represented as a 2D-array, but as data lists related to their respective IDs. While the ID arrays are mostly required only for the entire simulation, the Crop-Type Identification also may be read for each stress period, if crop rotation is desired. The sequence of each respective farm, soil type, or crop type must run from 1 to the total number of farms, soil types, or crop types.

- **Farm Identification**—A 2-D integer array of Farm Identification (*Farm-ID*) is required for the entire simulation. The spatial distribution of the *Farm-ID* may be random as long as there is no water-rights allocation ranking associated with the *Farm-ID* ($IALLOT < 2$). Non farm-active mode cells must be given an identifier of zero. If the prior appropriation option is selected ($IALLOT \geq 2$), then the sequence of the *Farm-ID* numbering scheme has to follow the farms' water-rights ranking (water-right seniority). That is, the *Farm-ID* equal to one is the farm with the most senior water rights and the larger *Farm-ID* numbers indicate a lower (that is, more junior) water-rights ranking.
- **Soil-Type Identification**—A 2-D integer array of Soil-Type Identification (*Soil-ID*) is required for the entire simulation. The spatial distribution of the *Soil-ID* may be random. Soil types outside the farms can be given a zero identifier. Soil types within farms must have an identifier greater than zero. Spatial estimates of soils can be simplified from sources such as the State Soil Geographic Database STATSGO (U.S. Department of Agriculture, 2005a) or the more detailed Soil Survey Geographic Database (SSURGO) (U.S. Department of Agriculture, 2005b).
- **Crop-Type Identification**—A 2-D integer array of Crop-Type Identification (*Crop-ID*) is required for the entire simulation if the distribution of crop types is considered permanent throughout the simulation ($IROTFL \geq 0$). If the spatial distribution of crop types changes temporally (that is, crop rotation; $IROTFL = -1$), then the *Crop-ID* array must be read for each stress period. The sequence and spatial distribution of the *Crop-ID* may be random. Crop types outside the farms can be given a zero identifier. Crop types within farms must have an identifier greater than zero. Polygons of fallowed areas are identified by a *Crop-ID* of -1 . In addition, fallowed areas combined with nonrouted deliveries can be used to simulate Aquifer-Storage and Recovery (ASR) infiltration ponds.

Multi-Dimensional Attribute Lists

Multiple attributes that relate to the same identification (ID) of a multi-dimensional variable can be represented in form of a “multi-dimensional attribute list,” $x(m,n)$. The list contains a value for each variable number, n , and attribute number, m . The variable ID is equal to the variable number, n . An attribute list also may contain layer, row, and column number associated with the variable ID. For instance, layer, row, and column number could be represented as $x(1,n)$, $x(2,n)$, and $x(3,n)$. Other integer or real parameters attributed to each variable number, n , then would be represented as $x(m,n)$, where $m = 4, 5, \dots$, total number of attributes. GIS coverages can display the delineation of features associated with an ID and other attributed parameters. Such a coverage can provide the data input variables needed for an attribute list such as GIS point-feature coverages representing farm wells or GIS-arcs representing stream segments. In addition, GIS polygon-feature coverages or GIS grids can provide the location of a variable ID such as model cells representing stream reaches or farm wells.

Farm Wells

Farm well attributes of “parameter” farm wells must be defined for the entire simulation if “parameter” farm wells exist ($MXL > 0$) that can be used to scale maximum well capacities with a multiplier. For FMP1, the word “parameter” stands for this “multiplier-parameter.” These simple multipliers are not part of the MF2K parameter-estimation process that requires observations. The list of attributes for “parameter” farm wells is described fully in a later section (“Data Requirements for the Entire Simulation”). A parameter name is given for each such list that contains a scaled parameter-factor assigned to a certain attribute, which, for farm wells, is the maximum capacity of farm wells.

Farm well attributes of “nonparameter” farm wells can also be defined for each stress period if “nonparameter” farm wells exist during a stress period ($ITMP > 0$). They are described in the “Data Requirements for Each Stress Period” section of this report as data input variables of the attributes list for “nonparameter” farm wells. A GIS point- or polygon-feature coverage of *Farm-Well IDs* and other farm-well attributes can provide the input variables needed for the attributes list for farm wells. The list of attributes associated with each farm well includes the layer number of the screened aquifer, horizontal location coordinates, the farm well ID, the farm ID and the maximum capacity. This list also may include wells whose discharge rates are simulated by the Multi-Node Well (MNW) Package (Halford and Hanson, 2002).

The pumping requirement of a farm well in the FMP1 can be limited to maximum well capacity, that is, to a ‘volumetric rate’ constraint. A farm well alternately can be designated in the FMP1 attributes list to be a multiple-aquifer well that straddles several model layers and the pumpage is simulated as an MNW farm well. For MNW farm wells, the pumping requirement also can be constrained indirectly by a defined aquifer head elevation or by a specified maximum drawdown through the optional constraints of the MNW package.

For “multi-layer” wells, an additional advantage of linking an FMP1 well to the MNW package is that the lesser of the simulated pumping requirement or the initially specified maximum capacity of the well can be reapportioned to several productive aquifer layers. Depending on the aquifer productivity of each respective aquifer, the total actual pumping rate simulated in the MNW package may be equal to or less than the originally desired pumping requirement and the distribution of pumpage between model layers may change as heads change between aquifer layers. This actual pumping rate acts as a simulated ‘maximum capacity.’ It replaces the initially specified ‘maximum capacity’ during the second and following iterations when compared to the iteratively changing well pumping requirement.

Stream Segments and Reaches

The definition of stream segments and reaches is needed only if routed surface-water deliveries to a farm and drain return flows away from a farm are simulated by using the SFR1 package (Prudic and others, 2004) jointly with the FMP1. Surface-water deliveries can be semi-routed or fully routed to farms by selecting FMP1 options $ISRDFL=1$ or $IRDFL=1$. In this case, the FMP1 needs information to be entered as SFR1 data input about the stream segments and reaches that represent the conveyance network that transports water to a specified point of diversion (for semi-routed deliveries), or directly to a farm’s head gate (for fully routed deliveries). In addition, the FMP1 needs information to be entered as SFR1 data input about the drains that deliver excess water away from the farm. In the SFR1 package, the numbering scheme and sequence of segments and reaches remain the same throughout the simulation. Additional attributes of stream segments are defined as SFR1 input data for each stress period.

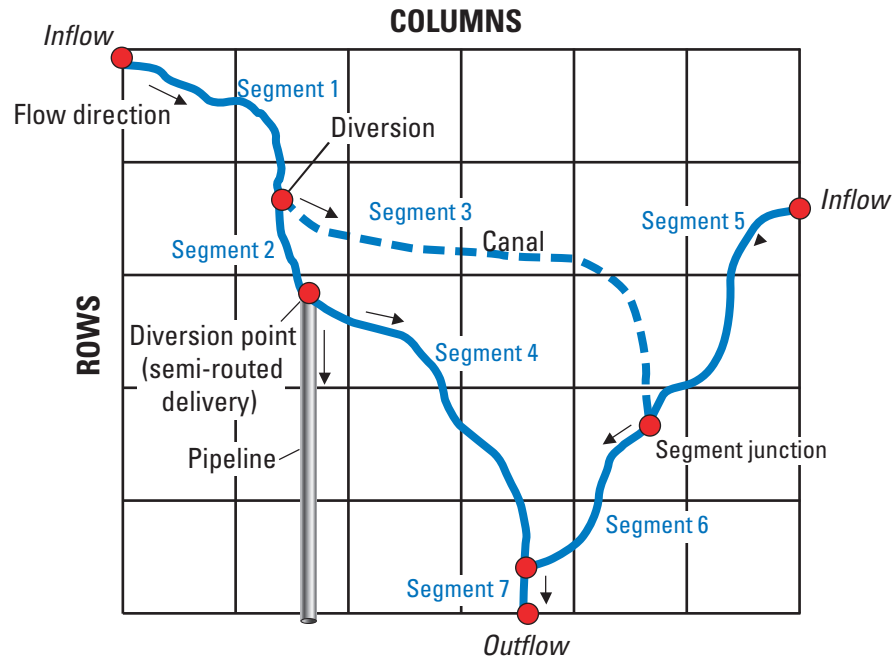


Figure 14. Streamflow-routing segment-numbering scheme in relation to direction of flow and model grid (Prudic and others, 2004).

- Stream Segments**—Every segment requires an integer identification number (*Stream-Segment ID*). The ID sequence is not random but must maintain a downstream order similar to the rest of the streamflow network (fig. 14). The segment number increases sequentially from upstream to downstream. For instance, diversion segments have a higher segment number than the upstream stream segment, from which water is diverted. Tributary segments merge into a downstream stream segment with a higher segment number. In general, stream segment parameters are defined for each stress period. They are input variables of the attributes list for stream segments. The only stream segment-related attribute that does not change throughout the simulation is the *Stream-Segment ID*. A GIS arcs coverage of *Stream-Segment IDs* and other stream segment attributes can provide the input variables needed for the attributes list for stream segments. The conversion of a GIS arc coverage of Stream Segments into a grid yields a segment ID and reach length associated with a stream reach in a finite-difference cell. Both stream reach attributes enter the attributes list for stream reaches among other reach-specific parameters (see “Data Input Instructions” section of this report). The discretization of segments into reaches and the resulting respective reach length depends, in part, on the discretization of the model domain as defined in the Discretization File (DIS) of MF2K.
- Stream Reaches**—Attributes of stream reaches are defined for the entire simulation. They are data input variables of the stream reaches-related data attribute. A GIS grid coverage of *Stream-Reach IDs* and other stream reach attributes can provide the input variables needed for the stream reaches data list. These attributes can be derived from various GIS sources.

Data Requirements for Entire Simulation

The data requirement items in this section generally follow the sequence of the data input items for the entire simulation in the section “Data Input Instructions.” However, for better understanding, 2-D data arrays, which could be retrieved from GIS coverages (for example, *Farm-ID*, *Soil-ID*, *Crop-ID*), are explained separately in a section called “Arrays and Lists of Spatially Distributed Data” prior to this section. Note that at the beginning, the FMP1 input file can contain text comments that start with #.

Farm-Wells Data

Farm wells can be specified as either parameter or nonparameter wells. Farm well attributes of “parameter” farm wells must be defined for the entire simulation if “parameter” farm wells exist ($MXL > 0$). Attributes of “nonparameter” farm wells are only defined for each stress period and are described in section “Data Requirements for each Stress Period.”

The following data input is required only for the entire simulation, if farm-well parameters exist ($NPFWL > 0$). The only parameters that are estimated as multipliers with the FMP1 farm wells are used to change the Maximum Capacity of farm wells (QMAXfact).

General Information

- *Number of farm-well parameters* (that is, multipliers to QMAXfact).
- *Maximum number of parameter farm wells*.

Data entry block for the QMAX-multiplier parameter

- *Parameter name* for list of parameter-farm wells related to the current multiplier parameter. This can be invoked at any stress period.
- *Parameter type*: QMAXfact is the only allowed parameter type in the FMP1.
- *Parameter value*: multiplier applied to QMAXfact of parameter farm wells.
- *Number of parameter farm wells* specific for the current parameter.

Read Parameter-Farm Wells List

- Read list from external file, if cross-referenced to file name containing the list, or
- Read list directly from FMP-input file.

Repeat the above data entry block for all other multiplier parameters with a specific parameter name and the attribute list of farm wells, for which QMAXfact the respective multiplier is to be applied. Lists of parameter-farm-wells specific for certain QMAX-fact-multiplier parameters can be invoked at any stress period by reading the respective ‘parameter name.’

List of Farm-Wells Related Attributes—All attributes of farm-irrigation wells are taken to be constant with time. Note that time series of actual well discharge and water-level hydrographs are potentially important information for model calibration. However, they are not included in the data input, since the ‘unknown’ farm-well discharge is the main estimation parameter of the program. Input variables that represent attributes of a farm well are as follows:

–*Layer*

–*Location (Row, Column)*

–*Farm-Well ID*

–*Farm ID associated with Farm Well*

–*Maximum Well Capacity, which can be varied by changing the parameter value*

–*[Auxiliary Attribute QMAXRESET or other Auxiliary Attributes]*.

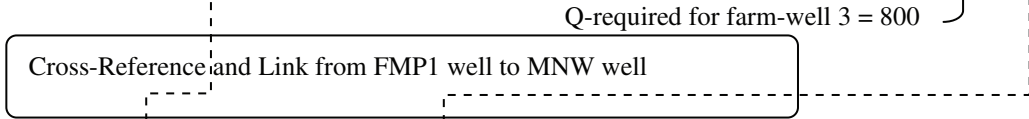
- **Layer**—In many cases, farm wells are pumping from an uppermost unconfined alluvial aquifer. However, since some wells may pump from deeper aquifers, it is necessary to assign to each well the model layers that coincide with the well screens. In the attributes list of farm wells that is read for the entire simulation, only one layer can be attributed uniquely to a farm-well ID. Alternatively, the FMP1 may be linked to the multi-node well package (MNW) (Halford and Hanson, 2002), where pumpage across multi-aquifer screen intervals can be reapportioned and estimated by the MNW package. Layers of wells that contain screens in multiple aquifer model layers are defined in the MNW package input file. When MNW farm wells are linked to the MNW Package by specifying a “negative” farm-well ID in the farm-well attributes list of the FMP1 input file, the specification of layers is defined externally in the MNW data input file. Thus, for multi-layer MNW farm wells, the layer number is specified as zero as a flag within the FMP1 to specify that the well is a MNW well with its range of model layers specified in the MNW package. In addition, the list of farm-well attributes may also contain single-layer wells, whose discharge rate and maximum capacities are simulated by the MNW package. For single-layer MNW farm wells, the user may specify the respective layer number in both the list of farm-well attributes in the FMP1 and in the MNW data input file.

- Location**—The location of a farm well is designated with the model cell row and column coordinates. Farm wells associated with a specific farm do not necessarily have to be located within the model cells that coincide with that farm. Thus, farm wells for any farm also can be located beyond the farm's boundary. The FMP1 may require a relatively finer resolution to account for crop distribution and well locations associated with each farm if cost optimization features are used. For example, this is important especially if the user takes into account that the distance of each farm well to a model cell has an impact on the costs of the applied ground water, which is specified in the acreage-optimization case deficiency scenario. In the FMP1, each well is associated with a certain *Farm ID*. Thus, different wells that are associated with different farms can be located within the same model cell (that is, same row and column coordinates). However, this is not the case for wells that are designated as MNW wells (negative *Farm-well ID*). Since the MNW package does not recognize *Farm IDs* associated with wells, the identification of MNW farm wells is established between the FMP1 and MNW package through the same row and column coordinates. Therefore, only the horizontal location of one farm well can be identified uniquely through row and column coordinates for MNW farm wells.
- Farm-Well ID**—The FMP1 simulates pumping from or injection into a well as a point sink or source term associated with the center node of a finite-difference cell that is defined by layer, row, and column. In the FMP1, each such point sink or source is considered an individual "well." In reality, such "wells" may represent well intervals screened over one aquifer layer. In the attributes list each such "well" has to be attributed uniquely to a *Farm-well ID*. For a well, which produces for different farms, the predominantly receiving farm has to be identified or, alternatively, it needs to be split into several 'virtual' wells located in the same model cell. Because of the association with the *Farm-ID*, the farm wells that are associated with a specific farm do not need to be located within that farm, but may be located anywhere in the active model-cell domain (that is, beyond the farm's boundary). While the sequence of the *Farm-ID* must run from 1 to the total number of farms, the *Farm-well ID* can be random. Farm wells that are screened over multiple aquifer layers are designated in the FMP1 by a "negative" *Farm-well ID* which is used by the FMP1 to establish a link to the MNW package.
- Farm ID**—Each farm-irrigation well is associated with a certain farm and, therefore, uniquely attributed to a specific farm identification (*Farm ID*). Multiple "single-layer" farm wells that possess equal row and column coordinates can be related to different wells and, therefore, must be attributed to different *Farm-well IDs*. They can be attributed to the same *Farm ID* or to different *Farm IDs*, as long as they are located horizontally next to each other. This may be especially important for coarse-resolution models with large cell sizes. Multiple screened well intervals that relate to the exact same multi-layer well cannot be associated in the FMP1 input file with the same *Farm-well ID* and, therefore, not with the same *Farm ID*. As opposed to "single-layer" farm wells, multiple "multi-layer" MNW farm wells cannot possess equal row and column coordinates. Therefore, only one multi-layer well can be simulated by the MNW package for one row and column coordinate regardless of *Farm IDs*. For models that contain many multi-layer wells, the model resolution should be fine enough to facilitate MNW package farm wells in separate model cells. To simulate a well that produces for more than one farm, the predominantly receiving farm has to be identified. Alternatively, a "single-layer" well can be split into several 'virtual' wells that have equal row and column coordinate but are attributed to different *Farm IDs*. Each such virtual well must be assigned a unique maximum well capacity that is a portion of the overall maximum well capacity of the real farm well.
- Maximum Well Capacity**—Even though the Maximum Well Capacity (QMAX) [L^3/T] may be a difficult input parameter to estimate, it is very important to assign a good estimate. Even if a value for QMAX may not be readily available, drilling records or pumping tests may allow the estimation of such data. For example, a step-drawdown test (SDT) or constant-discharge test (CDT) may have been carried out to test the well or aquifer performance, respectively. If so, then those tests easily could give evidence about a maximum well capacity. In addition, wells of similar construction screened over similar parts of the aquifer also may have similar hydraulic properties. So, even if not all wells are associated with an individually determined QMAX, wells without an individually determined QMAX still may be assigned a value extrapolated from other wells. Aside from physically or technically defined maximum capacity, alternatively, allotment rules may provide policy constraints, which may serve as a limitation of the well discharge to a maximum flow rate as well. For parameter farm wells, QMAX is calculated as the product of a maximum capacity factor, QMAXfact and a specific-parameter multiplier, which are read for the entire simulation. Using this method, various sets of QMAX rates can be saved for the same or for different wells under a "parameter name" that can be selected at any stress period. Thus the determined "default" QMAX rate may be replaced by a rate simulated by a well-specific link between the FMP1 and the Mult-Node Well package (MNW). The QMAX simulated by the MNW can only be equal or less than the desired pumping rate, which, in turn, can only be less than the default QMAX rate of the FMP1. This could lead to a "self-limiting process," where the simulated QMAX of a new time step could only be equal or less than the simulated QMAX of a previous time step. Hence, in the FMP1, the MNW1-simulated QMAX rate is reset to the FMP1-determined QMAX rate

by default at the beginning of each stress period. However, in the FMP1, an optional flag can be set to reset the simulated QMAX to the default QMAX rate at the beginning of each time step (see below in “Auxiliary Attribute QMAXRESET” and see section “Data Input Instructions/Explanations and fields Used in the Input Instructions/Dimensions and Flags/Optional Flags”). By resetting the simulated QMAX at each time step, the MNW package can calculate the hydraulically maximum possible rate not limited to a simulated QMAX of a previous time step, but bounded only by the FMP1-determined rates of the desired pumping rate and the default QMAX rate of the FMP1.

Example of a Farm-Well List for the FMP1:

Layer	Row	Column	Farm Well ID	Farm ID	QMAXfact [L ³ /T]
			1	1	
			2	1	
0	5	6	-3	1	1000
			4	2	
			5	2	



Example of a Well List for the Multi-Node Well Package:

Layer	Row	Column	Q-desired [L ³ /T]	Other nonfarm-related data	Hlim = limiting water level, or limiting drawdown [L]	Other nonfarm related data
1	5	6	Q-req. or QMAX passed on from FMP1 and re-apportioned to each layer		50	
2	5	6			50	
4	5	6			50	

(The well list for the MNW package is read for each simulation)

- Auxiliary Attribute QMAXRESET**—The specification of the option flag “AUX QMAXREST” as an auxiliary attribute will prompt the FMP1 to reset QMAX as simulated by the MNW package to the default QMAX as defined by FMP1 at the beginning of each time step. The optional flag “AUX QMAXRESET” tells FMP1 to read an auxiliary integer variable in column 7 of the farm wells list after the QMAXfact of QMAX variable. If a “1” is read in column 7 of the farm wells list, then the MNW-simulated QMAX is reset to the default QMAX in the first iteration of each time-step.
- Auxiliary Attribute (in general)**—As many as five auxiliary attributes optionally can be specified to the right of the mandatory farm-well attributes. These values will be read after the QMAXfact or QMAX variable. The auxiliary attribute variables will be printed together with the simulated farm well pumping rate to the listing file or to a binary file, where they then could be used to facilitate post processing or future linkages to the FMP1.
- Model Calibration Data**—Observed discharge rates along with water-level measurements or water-level hydrographs of some of the farm wells are necessary and valuable to calibrate the simulated farm well discharge rates. Therefore, while known discharge rates of farm well are not needed as data input, these data can be used to calibrate the simulated farm-well pumpage. Layer, location, and discharge rates of nonfarm-related wells, such as municipal or industrial use within the study area, also may be necessary data input that would be specified separately with the WELL package of MODFLOW-2000 (Harbaugh and others, 2000) or the MNW package (Halford and Hanson, 2002).

Farm Data

Farm data consist of farm identifiers and on-farm-irrigation efficiencies. The farm identifiers are a 2-D integer array of Farm Identification numbers (*Farm ID*) that is required for the entire simulation with a nonzero integer number identifier for every farm. Nonfarm-active model cells must be given an identifier of zero, similar to the IBOUND arrays for MF2K. The sequence and spatial distribution of the *Farm ID* may have any order as long as no water-rights ranking is associated with the *Farm ID* (IALLOT < 2). However, if the prior appropriation option is selected (IALLOT ≥ 2), then the sequence of the *Farm ID* numbering scheme has to follow the farms' water-rights ranking (water right seniority). That is, the larger *Farm ID* numbers indicate a lower water-rights ranking.

Farm Irrigation Efficiency

The On-Farm-Efficiency (OFE) is related to each farm through association with every *Farm ID* and is represented as a fractional real number between 0 and 1 ($0 < OFE \leq 1$). This user-specified irrigation efficiency is either constant for each farm for the entire simulation period (IEFFL = 1) or user-specified for each stress period (IEFFL = 2). In addition, the user also can specify head-dependent irrigation efficiencies that are coupled to the simulated ground-water levels on a cell-by-cell basis. The user can distinguish between two conservative irrigation practices (herein referred to as "efficiency behavior") where an additional flag IEBFL is set. The user can specify two forms of conservative behavior that represent a constant irrigation efficiency over each time step (IEBFL = 1) or a constant delivery over each time step (IEBFL = 2 and 3). For conservative management practices that seek to maintain a certain constant delivery, a varying on-farm efficiency still could occur owing to natural conditions, such as a fluctuating shallow ground-water level, along with which the beneficially used CIR changes. For IEBFL = 2 and 3, the FMP1 uses the user-specified on-farm efficiency, OFE_{spec} , to calculate an initially demanded TFDR at the beginning of each stress period (IEBFL = 2) or at the beginning of each time step (IEBFL = 3) and calculates subsequently an on-farm efficiency, OFE, for the current time step prior to enacting any deficiency scenario as a head-dependent parameter.

Indices and parameters used in the sections below (summations follow Einstein notation if not indicated otherwise):

- t = time step;
- k = iteration step;
- f = number of farm (farm-ID);
- n = number of finite-difference cells in a farm;
- r = reach of canal segment;
- h = aquifer head;
- OFE = on-farm efficiency (OFE_{spec} = specified on-farm efficiency);
- CIR = crop irrigation requirement per cell n ;
- TDR = total delivery requirement per cell n ; and
- $TFDR$ = total farm delivery requirement per farm f .

The On-Farm Efficiency (OFE_{spec}) for each farm can be specified for either the entire simulation (IEFFL = 1) or for each stress period (IEFFL = 2). Every *Farm ID* is associated with a real number fraction of on-farm efficiency between 0 and 1 ($0 < OFE_{spec} \leq 1$) as follows:

Farm ID	OFE_{spec}
1	
2	
3	

The FMP1 simulates for each model cell in a farm a CIR that dynamically depends on an iteratively changing aquifer head. Conservative assumptions may imply either farm-specific on-farm efficiencies to be constant during a model time step (IEBFL = 1) or the total applied delivery to be constant (IEBFL = 2,3). In both cases, the parameter assumed constant acts as a proportionality factor for CIR when simulating the other one (IEBFL = 1, 2, 3):

- **Constant Efficiency Over Time Step (Case 1, IEBFL = 1)**—An iteratively changing, head-dependent total cell delivery requirement is calculated by:
 - o an iteratively changing, head-dependent CIR; and
 - o an on-farm efficiency constant during time step ‘t’, acting as proportionality factor for CIR.

The on-farm efficiency is specified as a constant value for the entire simulation or for each stress period and, therefore, is constant during all time steps, t, for the given stress period. This case applies to the assumption that the farmer knows by experience how efficient or inefficient he can operate. To compensate for inefficient use, the CIR must be increased to the total delivery requirement by a proportionality factor equal to the inverse of the predefined efficiency. For each model cell, n, in a farm, f, the total delivery requirement (TDR) (eq. 15) is estimated as:

$$TDR_{f,n}^{t,k}(h_n^{k-1}) = CIR_{f,n}^{t,k}(h_n^{t,k-1}) / OFE_{spec,f}^t \quad (\text{EQ. 15})$$

The total for the entire farm, f, is summed:

$$TFDR_f^{t,k} = \sum_n TDR_{f,n}^{t,k}$$

Accumulating the TDR of all model cells in a farm yields the total farm delivery requirement, TFDR, reflected in the Farm Budget output file. In contrast with cases 2.1 and 2.2, this option (case 1) does not cause any model output of ‘computed’ efficiencies, since on-farm efficiency is considered to remain equal to its input value. However, for reference, the specified values of on-farm efficiencies are reflected in the Farm Budget output file “FDS.OUT” in column 5, labeled “OFE.”

- **Constant Delivery Over Time Step (Case 2, IEBFL = 2, 3)** — An iteratively changing, head-dependent on-farm efficiency is calculated by:
 - o an iteratively changing, head-dependent CIR; and
 - o a total applied delivery, constant over time step ‘t,’ acting as proportionality factor for CIR.

The total delivery requirement is assumed to be equal to the total applied delivery and to remain constant over a time step ‘t.’ By taking the TDR to be equal to the actual applied delivery implies that the demand can be supplied fully and that there is no existing deficiency for the model cell. Thus, case 2 (IEBFL = 2, 3) cannot be used in conjunction with deficiency scenarios (that is, IDEFFL ≠ 0 when IEBFL = 2, or 3). Since TDR is assumed to be constant throughout a time step, its initially determined value does not change iteratively as a function of changing aquifer head. However, the initial value of TDR evaluated during the first iteration (k = 1) of time step ‘t’ depends on the aquifer head of the solution of the previous time step (t-1). This case represents a conservative behavior of a farmer who chooses to maintain an initially determined rate of delivery, regardless of whether a changing ground-water level influences the CIR. For instance, a rising ground-water level could cause uptake from ground water to contribute to the crop water demand, which, in turn, would lower the CIR. To maintain the same rate of water application while CIR decreases would mean that the on-farm efficiency decreases. For each finite-difference cell in a farm, the head-dependent efficiency (eq. 16) is estimated as:

$$OFE_{f,n}^{t,k}(h_n^{t,k-1}) = CIR_{f,n}^{t,k}(h_n^{t,k-1}) / TDR_{f,n}^{t,k=1}(h_n^{t-1}), \text{ for } k > 1 \text{ and } t > 1 \quad (\text{EQ. 16})$$

for any farm:

$$OFE_f^{t,k} = \sum_n CIR_{f,n}^{t,k} / \sum_n TDR_{f,n}^{t,k=1}$$

with evaluation of TDR at first iteration of first time step of stress period (IEBFL=2), or evaluation of TDR at first iteration of each time step (IEBFL=3) as:

$$TDR_{f,n}^{t,k=1}(h_n^{t-1}) = CIR_{f,n}^{t,k=1}(h_n^{t-1}) / OFE_{spec,f}^t, \text{ for } k = 1, t = 1 \text{ (IEBFL=2)}$$

for k = - 1, for all t (IEBFL=3)

and evaluation of TDR at first iteration of second and following time steps as:

$$TDR_{f,n}^{t,k=1}(h_n^{t-1}) = CIR_{f,n}^{t,k=1}(h_n^{t-1}) / OFE_f^{t-1}(h_n^{t-1}), \text{ for } k = 1, t > 1 \text{ (IEBFL=2)}$$

The initial value of TDR is a function of CIR, which depends on the aquifer-head of the last iteration of the previous time step. In addition, the initial TDR may be either a function of a specified efficiency (for $k = 1, t = 1$ when $IEBFL = 2$, or for $k = 1$ of all time steps when $IEBFL = 3$) or a head-dependent efficiency evaluated during the last iteration of a previous time step (for $k = 1, t > 1$ when $IEBFL = 2$).

The user can specify, whether efficiency is reset to the specified efficiency only at the beginning of the first time step of each stress period (case 2.1; $IEBFL = 2$), or at the beginning of the each time step (case 2.2; $IEBFL = 3$). The latter option is especially useful when the CIR changes rapidly within a stress period from time step to time step (for $ICUFL = 3$, or $IRTFL = 3$, or $IPFL = 3$). In this case, a constant TDR over a time step may be evaluated solely based on the time step-specific CIR and user-specified efficiency. The use of the head-dependent efficiency of a previous time step may not be appropriate for the calculation of an initial TDR value of a current time step. For instance, if a very high consumptive use in a certain time step causes the water level to drop heavily, then the CIR may increase and approach a TDR constant over that time step, that is, the efficiency could reach 100 percent. Then, if in a following time step, the water level recovers and the CIR decreases, accordingly, then the initial TDR would be equal to CIR based on 100-percent efficiency calculated at the end of the previous time step.

Within each time step, the head-dependent efficiency needs to approach beyond a preset 1 percent closure criterion between the value of the solution iteration and the value of the second last iteration. Closure, however, is determined by head convergence. Therefore, if head convergence is achieved without sufficient efficiency convergence, the program will output the following message to the screen, asking the user to lower the head closure criterion:

“HCLOSE MUST BE SMALLER FOR HEAD-DEP. EFFICIENCY OF FARM ?? TO CONVERGE!”

For Cases 2.1 and 2.2, the FMP1 will yield a time series of head-dependent efficiencies, which is included in the Farm Budget output file, “FDS.OUT” in column 5, labeled “OFE.”

Soil-Type Data

Soil-type data consisting of a 2-D integer array of Soil Type Identification (*Soil-Type ID*) and of soil type-related attributes is read once and used for the entire simulation. The *Soil-Type ID* can have any user-specified distribution and sequence that is independent of the farms IDs. A data list of soil-type attributes related to each soil type is associated with the *Soil-Type ID* (table 2). Capillary fringe and/or coefficients for an analytical solution that approximates transpiration uptake (Concept 1) are variables attributed to each *Soil-Type ID* for the entire simulation as:

- *Capillary Fringe*,
- *Coefficients for Analytical Solution* (a, b, c, d, e), *Soil-Type ‘Word’* (*SANDYLOAM, SILT, or SILTYCLAY*) (if Consumptive-Use Concept 1 is chosen with $ICCFL = 1$).

Table 2. Example of soil-type attributes associated with the *Soil-Type ID*.

Soil-Type ID	if $ICCFL = 1$						
	if $ICCFL = 2$						
	Capillary Fringe [L]	Coefficients for $DRZ = f(T_{pot}, TRZ)$			Coefficients for $n = f(DRZ)$		Soil Type in Words ¹
a		b	c	d	e		
1		0.201	-0.195	3.083	3.201	-3.903	SANDY LOAM
2		0.320	-0.329	2.852	1.303	-2.042	SILT
3		0.348	-0.327	1.731	0.530	-0.377	SILTY CLAY

¹ The user either specifies numeric coefficients or the word for the soil types for these predefined soil types.

The soil-type specific capillary fringe is needed along with root zone depths for each crop type (table 2) to linearly approximate transpiration uptake (fig. 7). The user-specified capillary fringe values must be greater than zero. Coefficients $a, b, c, d,$ and e are used to define parameters DRZ and n of an analytical solution, which describes a vertical pressure head distribution (eq. 17) that is reached at steady state in soils with root uptake from ground water as the only source (fig. 8B) (absolute value of the pressure head $|\psi|$ over the depth d of the total root zone):

$$|\psi| = DRZ \cdot \left(\frac{|\psi_4|}{DRZ} \right)^{\left[\frac{d(|\psi|)-1}{DRZ-1} \right]^n} + d(|\psi|) - DRZ \tag{EQ. 17}$$

Since this analytical function cannot be solved explicitly, it can be solved iteratively for depth $d(|\psi|)$ by the *Bisection Method* in the FMP1. A reduction of the linearly-approximated transpiration by conditions of anoxia or wilting is proportional to a reduction of the total root zone by ranges of pressure heads within the vertical pressure head distribution that are typical for anoxia or wilting. Such ranges of pressure heads, at which uptake is zero due to anoxia or wilting, are described below as “Root Uptake Coefficients” for specific crop type (fig. 8A). Therefore, the parameters “DRZ” and “n” allow the fitting of a vertical, pseudo, steady-state pressure head distribution.

Parameters DRZ and n in equation 17 are defined as follows:

- (1) The Depleted Root Zone (DRZ) (eq. 17A) is a function of the potential Transpiration and the Total Root Zone. It is defined as the lower part of the root zone at which the pressure head increases with depth from the minimum (negative) pressure head (defined as ψ_4 in stress response function, see below) to zero at the bottom of the root zone (fig. 8B) as:

$$DRZ = e^{[a \cdot \ln(T_{pot}) + b \cdot \ln(TRZ) + c]} \tag{EQ. 17A}$$

- (2) The Sinuosity Coefficient (n) (eq. 17B) expresses the curvature of the vertical pressure head configuration over depth (fig. 8B), which increases with increasing DRZ as:

$$n = d \cdot \ln(DRZ) + e \tag{EQ. 17B}$$

Coefficients a to e for three different soil types (Schmid, 2004) are predefined in the FMP1 for three soil types. The user has the option to either enter key words for the predefined soil types or the numeric values for user-defined approximations of the DRZ and sinuosity coefficient, n.

Example for using Concept 1 along with Soil Type ‘Words’

Soil-type ID	Capillary fringe [L]	if ICCFL = 1, and if using Soil Type ‘Word’
1		SANDYLOAM
2		SILT
3		SILTYCLAY

Predefined Coefficients a,b,c,d,e that are used FMP1 internally, when using Soil Type ‘Words’

Coefficients for DRZ = f(T _{c-pot} , TRZ)			Coefficients for n = f(DRZ)		Soil Type in Words
a	b	c	d	e	
0.201	-0.195	3.083	3.201	-3.903	SANDYLOAM
0.320	-0.329	2.852	1.303	-2.042	SILT
0.348	-0.327	1.731	0.530	-0.377	SILTYCLAY

Example for using Concept 1 along with user-defined approximations of DRZ and n.

Soil-type ID	Capillary fringe [L]	if ICCFL = 1				
		Coefficients for DRZ = f(T _{c-pot} , TRZ)			Coefficients for n = f(DRZ)	
		a	b	c	d	e
1						
2						
3						

Crop-Type Data (Natural)

Crop-type data consist of a 2-D array of Crop-Type Identifications (*Crop-Type ID*) and related attributes, which are constant throughout the entire simulation. If no crop rotation is specified ($IROTFL \geq 0$), then there is no change in the spatial distribution of the crop type with time and only one set of *Crop-Type IDs* are needed for the entire simulation. However, if rotating crops are being simulated ($IROTFL = -1$), then the crop distribution (*Crop-Type IDs*) is specified for each stress period. The *Crop-Type ID* is an integer number with any user-specified distribution. Model cells representing fallowed areas are identified by a *Crop-Type ID* of -1 . Crop-type attributes that are grouped as “natural” crop variables (as opposed “agro-economic,”) and related to each *Crop-Type ID* are:

- *Root zone depths* (constant throughout the entire simulation);
- *Fractions of transpiration and evaporation of consumptive use*⁸ (constant throughout the entire simulation);
- *Fractions of inefficiency losses to surface-water runoff* (constant throughout the entire simulation);
- *Root Uptake Coefficients for Stress Response Function* (constant throughout the entire simulation);
- *Coefficients* to calculate time series of cumulative growing degree day values (CGDD), crop coefficients (K_c), potential crop evapotranspiration (ET_{c-pot}), and root-zone depth.

Root-Zone Depth

The root-zone depth can be specified for each crop for the entire simulation ($IRTF1 = 1$) or specified for each stress period ($IRTF1 = 2$), or calculated for time-step averages ($IRTF1 = 3$) from climate-data time series and a list of crop-specific coefficients. The root-zone depths always must be greater than zero.

For $IRTF1 = 1$, the user specifies the root-zone depth (ROOT in data input instructions), as a lumped parameter that is constant during the entire simulation as:

Crop ID	Root depth [L]
1	
2	
3	

Fraction of Transpiration and Evaporation of Consumptive Use

The transpiratory and evaporative fractions are defined as fractions of consumptive use for the entire simulation ($IFTEFL = 1$) or for each stress period ($IFTEFL = 2$). Consumptive use is specified by the user as constant potential crop-evapotranspiration, ET_{c-pot} during a stress period ($ICUFL = 2$), or it is derived internally by the FMP1 as time series, based on crop coefficients, K_c , and reference evapotranspiration, ET_o ($ICUFL = 3$). The ET_{c-pot} is defined as:

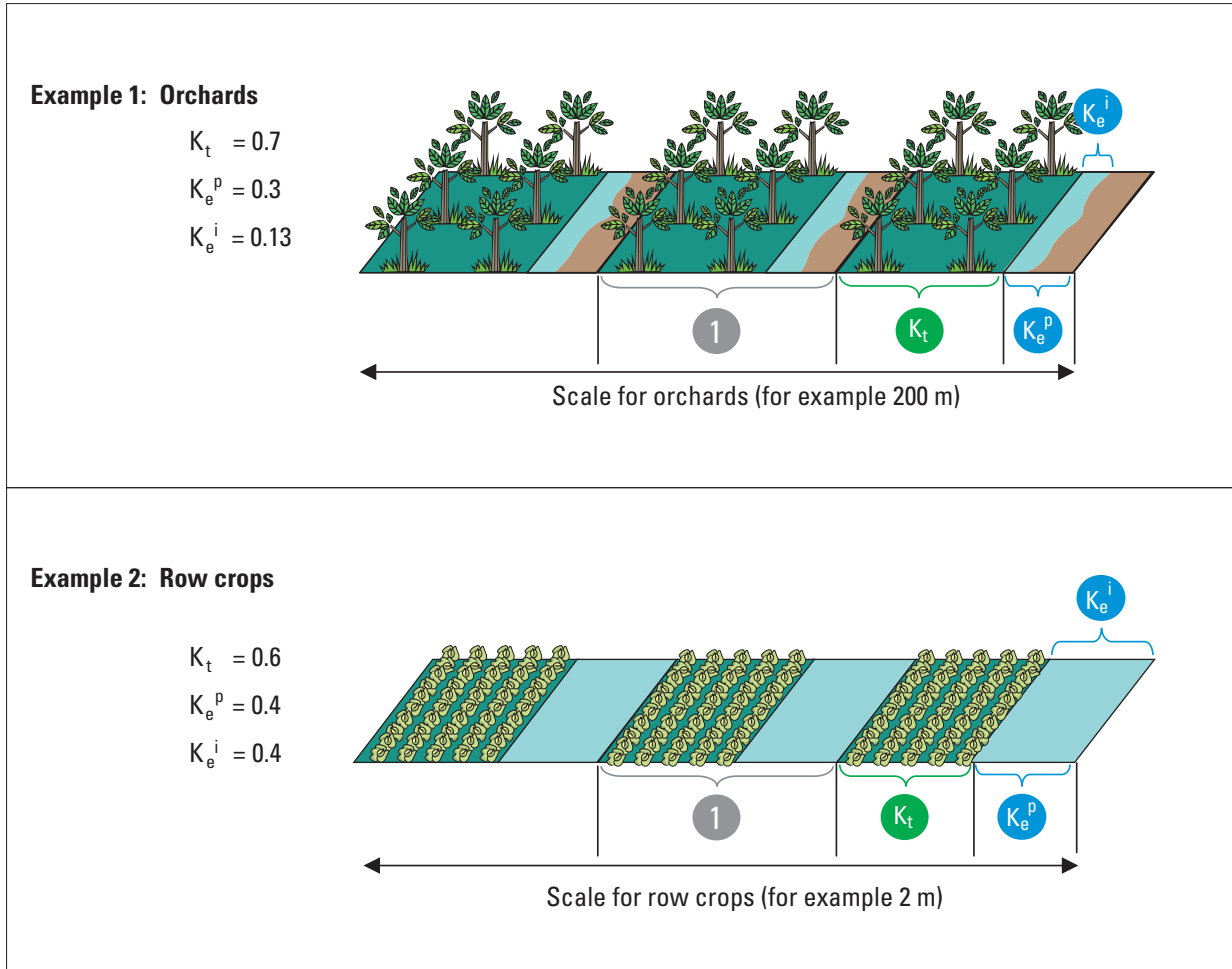
$$ET_{c-pot} = (K_t + K_e) \cdot ET_{c-pot} = (K_t + K_e) \cdot K_c \cdot ET_o$$

The transpiratory and evaporative fractions of consumptive use are taken to vary linearly with the respective area occupied by crops and the respective area open to soil-evaporation (*fig. 15*). If the cropped area and the exposed, wetted area amount to the entire area, then $K_t + K_e = 1$, and $K_e = 1 - K_t$, therefore:

$$T_{c-pot} = K_t \cdot ET_{c-pot}$$

$$E_{c-pot} = (1 - K_t) \cdot ET_{c-pot}$$

⁸Consumptive use is defined commonly as crop evapotranspiration, which includes transpiration and evaporation in a cropped agricultural area (Colorado's Decision Support System, 1995; Gelt and others, 1999; European Environment Agency, 2004).



EXPLANATION








- | | | | |
|---|-----------------------------------|---|---|
|  | Wetted area (crop-covered) |  | Total area |
|  | Wetted area (exposed) | Fraction of area available for: | |
|  | Non wetted area (exposed) |  | Transpiration |
| | |  | Evaporation related to irrigation |
| | |  | Evaporation related to precipitation |

Figure 15. Transpiratory (K_t) and Evaporative (K_e) Fractions of Consumptive Use.

The transpiratory fraction of consumptive use, K_t (FTR in data input instructions), is assumed to be independent of whether the transpiratory consumptive use is satisfied by irrigation, precipitation, or ground-water uptake.

The FMP1 assumes that evaporation from precipitation occurs over the entire exposed area because all noncrop-covered area will be wetted such that the fraction of evaporation from precipitation (FEP) is $K_e^p = 1 - K_t$, or $K_t + K_e^p = 1$. If the wetted portion of the exposed area does not extend to the entire exposed area—as is possible for irrigation—then K_e can be restricted such that the fraction of evaporation from irrigation (FEI in data input instructions) is $K_e^i < 1 - K_t$. Different irrigation methods can lead to different lateral extent of the wetted area, with $K_e^i \leq 1 - K_t$, or $K_t + K_e^i \leq 1$. For basin flood irrigation, however, a complete inundation of the noncovered area is expected and, thus: $K_e^i = 1 - K_t$, or $K_t + K_e^i = 1$.

For precipitation as source for evaporation:
$$E_{c-pot} = K_e^p \cdot ET_{c-pot} = (1 - K_t) \cdot ET_{c-pot}$$

For irrigation as source for evaporation:
$$E_{c-pot} = K_e^i \cdot ET_{c-pot}$$

Which fraction of the consumptive use is transpiratory (FTR) or evaporative (FEP and FEI) also depends highly on type of crop and growth stage, which is why K_t and K_e can also be specified for each stress period. If the vegetation cover reaches close to a 100 percent, then $K_t = 1$ and $K_e = 0$.

Each crop may be associated with lumped or constant values of a transpiratory (K_t) and evaporative fraction of consumptive use (K_e^p - related to precipitation, K_e^i - related to irrigation) during the entire simulation (changes during the growing season from stress period to stress period would be ignored). Thus, for IFTEFL = 1, $K_t + K_e^p = 1$ and $K_t + K_e^i \leq 1$, and these are listed for each crop type as follows:

Crop ID	K_t ($0 < K_t \leq 1$)	K_e^p ($0 \leq K_e^p \leq 1$)	K_e^i ($0 \leq K_e^i < 1$)
1			
2			
3			

In the FMP1, the evaporation losses from irrigation, E_i , are defined to vary proportionally to T_i , and it is assumed that there is equality between E_i/T_i and K_e^i/K_t . Therefore, $E_i = T_i \times (K_e^i/K_t)$ and K_t must not be zero.

Fraction of Inefficiency Losses to Surface-Water Runoff

The fraction of inefficiency losses to surface-water runoff can be specified for the entire simulation (IIESWFL = 1), for each stress period (IIEWSFL = 2), or related to slope calculated internally as rise-run (IIESWFL = 0). For IIESWFL = 1, each crop may be associated with lumped and constant values of fractions of inefficiency losses to surface-water runoff that are related to precipitation or irrigation during the entire simulation, as follows:

Crop ID	IE_{sw}^p ($0 \leq IE_{sw}^p \leq 1$)	IE_{sw}^i ($0 \leq IE_{sw}^i \leq 1$)
1		
2		
3		

Root-Uptake Coefficients for Stress Response Function

The root-uptake coefficients for the stress response function are specified when Consumptive Use Concept 1 is chosen (ICCFL = 1) and Concept 2 (ICCFL = 2) is not chosen. Each crop is associated with root uptake parameters equal to the absolute values of four different negative pressure heads at which uptake is zero (ψ_1 -Anoxia, ψ_4 -Wilting Point) and optimal (ψ_2, ψ_3) as follows:

Crop ID	$ \psi_1 $ [L]	$ \psi_2 $ [L]	$ \psi_3 $ [L]	$ \psi_4 $ [L]
1				
2				
3				

Specific Crop Coefficients

Coefficients to calculate Growing Degree Days (GDD), Cumulative Growing Degree Days (CGDD), Crop Coefficients (K_c), Crop Evapotranspiration (ET_c), and Root Depths are user-specified if Consumptive Use (ET_c) or Root Depth of each crop are to be calculated as time-step averages (ICUFL = 3 or IRTFL = 3). The calculation of growing degree days (GDD), and other time-variable parameters that depend on GDD rests on empiric equations, which take into account daily minimum and maximum temperatures and crop-specific minimum and maximum cutoffs and base temperatures. For using the option to calculate time series of crop evapotranspiration (ICUFL = 3) and root depths (IRTFL = 3) FMP-internally, the time-series steps must be entered in 'days'. To select daily time-series steps, the time unit of all model data must be 'days' in the Discretization File (ITMUNI = 3) (Harbaugh and others, 2000). The program considers it a conceptual mistake if the user specifies ICUFL = 3 or IRTFL = 3 and, at the same time, a time unit different from days. In that case, the program will stop and the user will be informed about the problem on the screen.

- Growing Degree Days (*GDD*) and Cumulative Growing Degree Days (*CGDD*) for a specific crop and a certain day d of the time series are calculated by the program in conjunction with climate time series of daily minimum and maximum temperature (T_{min} , T_{max}), using the following crop-specific parameters specified by the user:

- *Base-Temperature* = T_{base}
- *Minimum-Cutoff-Temperature* = $T_{min-cut}$
- *Maximum-Cutoff-Temperature* = $T_{max-cut}$

$$GDD(d) = \begin{cases} (T_{max-cut} + T_{min-cut})/2 - T_{base} & \forall T_{max} \geq T_{max-cut}; \forall T_{min} \leq T_{min-cut} \\ (T_{max-cut} + T_{min})/2 - T_{base} & \forall T_{max} \geq T_{max-cut}; \forall T_{min} > T_{min-cut} \\ (T_{max} + T_{min-cut})/2 - T_{base} & \forall T_{max} < T_{max-cut}; \forall T_{min} \leq T_{min-cut} \\ (T_{max} + T_{min})/2 - T_{base} & \forall T_{max} < T_{max-cut}; \forall T_{min} > T_{min-cut} \end{cases}$$

$$CGDD(d) = \sum_{t=1}^d CDD(t) \quad \text{with: } t = 1, 2, \dots, d; \quad \forall 1 \leq d \leq D,$$

where D = total number of days in time series.

- Crop Coefficient (K_c) and potential Crop-Evapotranspiration (ET_{c-pot}): The calculation of a crop coefficient K_c as a third-degree polynomial of a cumulative growing degree day value for a day d requires four polynomial coefficients specified by the user:

- *Polynomial Coefficients to describe a CGDD- K_c functionality*

$$K_c(d) = C_0 + C_1 \cdot CGDD(d) + C_2 \cdot CGDD(d)^2 + C_3 \cdot CGDD(d)^3$$

The potential crop-evapotranspiration (ET_c) is calculated by the program as:

$$ET_c(d) = K_c(d) \cdot ET_o(d);$$

with: $ET_o(d)$ = Reference-ET at day d of climate-data time series.

- Root Depths: The root depth for a specific crop and a certain day d is calculated as a linear function of a cumulative growing degree day, using the following crop specific parameters specified by the user:

- *Beginning Root Depth* = RD_{beg}
- *Maximum Root Depth* = RD_{max}
- *Root Growth Coefficient* = RGC

$$RD(d) = \begin{cases} RD_{beg} & \forall RGC \cdot CGDD(d) < RD_{beg} \\ RGC \cdot CGDD(d) & \forall RD_{beg} \leq RGC \cdot CGDD(d) \leq RD_{max} \\ RD_{max} & \forall RGC \cdot CGDD(d) > RD_{max} \end{cases}$$

Specific crop coefficient are entered by the user for the entire simulation, if ICUFL = 3 or if IRTFL = 3, as follows:

Crop ID	Coefficients for GDD calculation			Polynomial coefficients for CGDD-Kc-function				Coefficients for root-depth calculation		
	Base-temperature	Minimum cutoff-temperature	Maximum cutoff-temperature	C ₀	C ₁	C ₂	C ₃	Maximum root depth	Root growth coefficient	Beginning root depth
1										
2										
3										

As long as the temperature units are used consistently, either °C or °F can be used in the FMP1 to calculate the Crop Coefficient K_c. If, however, the polynomial coefficients retrieved from the literature (for example, Sammis and others, 1985) were derived from a CGDD-K_c functionality with GDDs in °F, but the GDD calculation in MODFLOW-FMP1 is based on read-in temperatures, in °C, then the polynomial coefficients need to be converted ahead of reading them into the FMP-input file, as follows:

$$\begin{aligned}
 C_1^{°C} &= (9/5) \cdot C_1^{°F}, \\
 C_2^{°C} &= (9/5)^2 \cdot C_2^{°F}, \\
 C_3^{°C} &= (9/5)^3 \cdot C_3^{°F},
 \end{aligned}$$

In general, a Crop Factor K_c calculated with CGDD based on °C, and with polynomial coefficients based on °F, can be formulated as follows:

$$K_c = C_0 + (9/5) \cdot C_1^{°F} \cdot CGDD^{°C} + (9/5)^2 \cdot C_2^{°F} \cdot (CGDD^{°C})^2 + (9/5)^3 \cdot C_3^{°F} \cdot (CGDD^{°C})^3$$

Also, if Root Growth Coefficients (RCG) are available only in inch/°F, but the program is run in metric units, and then a conversion from inch/°F to m/°C has to be carried out in the following way:

$$RGC^{m/°C} = 9 \left/ \left(5 \cdot \left(\frac{1}{RGC^{in/°F} \cdot 0.0254} - 32 \right) \right) \right.$$

Climate Data

Climate data can be read as constants for each stress period or can be read as time series throughout the duration of the entire simulation. The attributes that are read for the entire simulation for each time-series step (for example, day) include time series of daily *minimum- and maximum-temperature, precipitation, and reference evapotranspiration*. These climate data are necessary only if one of the following three parameters is to be calculated as averages during each time step (for example, weekly) (ICUFL = 3, or IRTFL = 3, or IPFL = 3):

- Consumptive Use (potential crop evapotranspiration)
- Root Depth
- Precipitation

When the precipitation data are used directly to build time-step averages, the reference evapotranspiration and the minimum- and maximum-temperature data are used in conjunction with crop-specific coefficients, to calculate the potential crop ET and the crop specific depth of the root zone. Most commonly, the Penman-Monteith estimate of potential evapotranspiration is used as a reference evapotranspiration. For more information on the calculation of the Penman-Monteith reference evapotranspiration, the reader is referred to the FAO publications 24 and 56 (Doorenbos and Pruitt, 1977; Allen and others, 1998) or to Hoffman and others (1992).

Time-Series Steps	Max-Temperature	Min-Temperature	Precipitation	Reference ET
1				
2				
3				

The calculation of growing degree days is based on empiric equations, which take into account daily minimum and maximum temperatures and crop-specific minimum-cutoff, maximum-cutoff and base temperatures. For using the option to calculate time series of crop evapotranspiration and root depths FMP-internally, the time-series steps must be specified in days. To select daily time-series steps, the time unit of all model data must be 'days' in the Discretization File (ITMUNI = 3) (Harbaugh and others, 2000). The total number of days in a time series then is equal to the length of the simulation LENSIM. Hence, for a period of a 1-year simulation, a data record with 365 time-series steps will be read, if the climate data are available in daily time-series steps.

However, if the option to build averages during each time step is chosen only for time series of precipitation, then other time units are possible (in this case: columns of T_{max} , T_{min} , and ET_o are zero or remain empty). For instance, if the simulation encompasses 100 years, and precipitation is available only as yearly means, then averages can be built for 5 yearly time steps. In this case, the time unit must be chosen to be years in the Discretization file (ITMUNI = 4) of MF2K, and the FMP1 would read a record with 100 time-series steps. Another example would be that if the duration of the simulation is 1 year, and the precipitation comes in hourly values, then averages could be built for weekly time steps. In this case, the time unit must be hours in the Discretization file (ITMUNI = 2), and the FMP1 would read a record with 8,760 time-series steps.

The option to build averages from preexisting time series over MF2K time steps should be handled with care as memory insufficiency might occur. As described above, for precipitation only, the user could use units that are consistent with the MF2K time units of yearly, daily, and hourly time-series steps. Theoretically, one also could use minutes (ITMUNI = 2) or seconds (ITMUNI = 1) as time units. However, the allocation of memory for very short time units and long periods of simulation could exceed computer memory (for example, seconds and 1-year simulation would cause the allocation of 31,536,000 elements). In addition, precipitation recorded at every second or minute is very unlikely. For that reason, the program always will issue a warning on the screen, as soon as IPFL = 3 and ITMUNI = 1 or = 2.

Crop-Type Data (Agro-Economic)

A crop-type related data list is a list of attributes related to each crop type. The fallow flag and crop benefit attributes are “agro-economic” crop variables (as opposed “natural” crop-type data) that are attributed to each crop-type identifier.

Crop-Type-Related Fallow Flags

The fallow flag attribute is required if stacking water on priority or nonfallowable crops (“water-stacking”) is desired as a deficiency scenario (IDEFFL = -2). Input parameter of the Fallow List for the entire simulation:

- *Fallow-Flag:*
 - 1 = Crop type fallowed (for example, onions)
 - 0 = Crop type not fallowed (for example, pecan trees)

Crop ID	Fallow flag
1	
2	
3	

Crop-Type Benefits Data

Crop benefits are derived from crop specific water production functions and from the crop’s market price if Acreage-Optimization is chosen as the deficiency scenario (IDEFFL > 0). The crop benefit minus the irrigation costs associated with irrigated areas assigns an economic value (profit) to the optimization variables “ground water- and surface-water irrigation area” for each model cell. Water production functions and a crop’s market price may be specified for each crop type either for the entire simulation (IBEN = 1) or for each stress period (IBEN = 2).

A water-production function is a linear relation between the 'water beneficially used for crop production' [length] and the 'expected yield' [weight/area]. For a linear relation between the water used and the yield, the 'water beneficially used' is taken to be equal to the crop evapotranspiration. The FMP1 allows the user to apply selected water production functions from the literature (for example, Doorenbos and Kassam, 1979; New Mexico State University Climate Center, 1996). These water production functions do not take into account micro-scale conditions other than evapotranspiration and yield. For instance, a ground-water elevation close to ground surface can cause local anoxia and a reduction of yield. Therefore, yield, as derived by means of a water production function, is independent of head. As a result, acreage optimization simulations with the FMP1 generally are limited to conditions in which the ground-water elevation is such that the yield and, consequently, the benefit are not affected. The crop evapotranspiration entering the water production function either is specified by the user or calculated by the program. The user has the option to either specify crop evapotranspiration (ET_c) as a constant consumptive use for each stress period or to simulate time series of ET_c . The monetary crop benefit per unit area can be obtained by multiplying yield with the crop's market price [value/weight]. Slope and intercept of the water production function and the market-price per crop are required data input parameters.

Input Parameters of the Crop Benefits Data

Each crop type may be associated with the following parameters constant during the entire simulation (only if IDEFFL > 0, and for the entire simulation if IBEN = 1):

- *Coefficients of crop-specific Water-Production Function (Yield vs. ET_c):*
 - Slope
 - Intercept
- *Market-price per crop*

Crop ID	Calculation of crop benefit		
	Water production function		Crop market price
	Slope (a)	Intercept (b)	
	YIELD = a × ET + b, where: YIELD in [weight/area], and ET in [length]		[value/weight]
1			
2			
3			

The FMP1 computes a crop-yield from a water-production-function specified in consistent units. The length units are the units specified in the discretization file (*.DIS) of MF2K, that is, feet for LENUNI = 1, centimeter for LENUNI = 2, and meter for LENUNI = 3. Generally, the weight units will be pounds for English length units (the only possible English length unit in discretization file is feet), and kilograms for International units (centimeters or meters). However, the choice of the weight unit depends on the user's preference. It is the user's responsibility to keep consistently the same weight unit for the output-yield of the water-production-function and for the crop-market-price. In many cases, the user will be able to retrieve water-production-functions from the literature, available in form A or form B:

$$(A) \text{ Yield [lb/acre]} = a_{lit} \cdot ET_c \text{ [inch]} + b_{lit}$$

$$(B) \text{ Yield [kg/hectar]} = a_{lit} \cdot ET_c \text{ [cm]} + b_{lit}$$

where a_{lit} , b_{lit} = coefficients of water production function as retrieved from the literature

This report provides assistance in converting water-production-functions of form A into a form using pound and feet or kilograms and centimeters or meters, and of form B into a form using kilograms and meters or centimeters.

Converting form A into pounds and feet:

$$\text{Yield [lb/ft}^2\text{]} = (a_{lit} \cdot 12/43560) \cdot ET_c \text{ [ft]} + (b_{lit} / 43560)$$

the coefficients a and b entering the water production function are:

$$a = a_{lit} \cdot 12/43560$$

$$b = b_{lit} / 43560$$

Converting form A into kilogram and centimeter or meter:

$$\text{Yield [kg/cm}^2] = [a_{lit} \cdot 2.47/(2.54 \cdot 2.2 \cdot 10^9)] \cdot \text{ET}_c \text{ [cm]} + [b_{lit} \cdot 2.47/(2.2 \cdot 10^9)]$$

the coefficients a and b entering the water production function are:

$$a = a_{lit} \cdot 2.47/(2.54 \cdot 2.2 \cdot 10^9)$$

$$b = b_{lit} \cdot 2.47/(2.2 \cdot 10^9)$$

$$\text{Yield [kg/m}^2] = [a_{lit} \cdot 2.47/(2.54 \cdot 2.2 \cdot 10^2)] \cdot \text{ET}_c \text{ [cm]} + [b_{lit} \cdot 2.47/(2.2 \cdot 10^4)]$$

the coefficients a and b entering the water production function are:

$$a = a_{lit} \cdot 2.47/(2.54 \cdot 2.2 \cdot 10^2)$$

$$b = b_{lit} \cdot 2.47/(2.2 \cdot 10^4)$$

Converting form B into kilogram and centimeter or meter:

$$\text{Yield [kg/cm}^2] = (a_{lit}/10^9) \cdot \text{ET}_c \text{ [cm]} + (b_{lit}/10^9)$$

the coefficients a and b entering the water production function are:

$$a = a_{lit} / 10^9$$

$$b = b_{lit} / 10^9$$

$$\text{Yield [kg/m}^2] = (a_{lit}/10^2) \cdot \text{ET}_c \text{ [m]} + (b_{lit}/10^4)$$

the coefficients a and b entering the water production function are:

$$a = a_{lit} / 10^2$$

$$b = b_{lit} / 10^4$$

Converting form B into pounds and feet:

$$\text{Yield [lb/ft}^2] = [a_{lit} \cdot 2.54 \cdot 12 \cdot 2.2/(2.47 \cdot 43560)] \cdot \text{ET}_c \text{ [ft]} + [b_{lit} \cdot 2.2/(2.47 \cdot 43560)]$$

the coefficients a and b entering the water production function are:

$$a = a_{lit} \cdot 2.54 \cdot 12 \cdot 2.2/(2.47 \cdot 43560)$$

$$b = b_{lit} \cdot 2.2/(2.47 \cdot 43560)$$

Water-Cost Coefficients

Water-cost coefficients are implemented if acreage-optimization as deficiency scenario is chosen (IDEFFL > 0). As opposed to the *crop benefit per unit area*, which enters the objective function directly, the water costs per unit of ground-water or surface-water irrigated area are calculated implicitly in the objective function as the product of *ground-water- or surface-water-specific water costs, per unit water volume*, multiplied by the required *model-cell specific crop irrigation flux*.

For ground water and surface water, the respective water costs, per unit volume, can be expressed by different cost coefficients that are independent or dependent of head or distance. Base maintenance costs for ground-water pumping, a fixed price for (semi-) routed surface water⁹, and a fixed price for nonrouted surface-water deliveries are specified directly by the user as costs per unit volume. Head- or distance-dependent costs are calculated by the FMP1 by multiplying user-specified costs *per unit volume and unit head lift or unit distance* multiplied by the respective actual vertical head lift or horizontal distance to the cell. Note that distance-dependent costs only occur, if the increasing distance is proportional to increasing costs, caused, for example, by pipe-friction.

⁹ **Routed surface-water delivery:** Surface water routed through a 'river to canal' network to a farm head-gate directly adjacent to the farm. **Semirouted surface-water delivery:** Surface water routed through a 'river-to-canal' network to a point of diversion from where water is delivered in a nonrouted form (for example, by way of pipeline) to a remote farm that is not adjacent to the canal.

Ground-water and surface-water cost coefficients determine the cost of ground water or surface water per unit water volume. Multiplied with a model-cell specific irrigation flux, we get the cost of applying ground water or surface water to the area of a model cell. By subtracting this number from the crop-benefit of a model cell, the net profit of ground-water or surface-water irrigation of a certain crop can be computed in that model cell. Four ground-water cost coefficients and four surface-water cost coefficients are required as data input. They may be specified for the entire simulation either as lumped coefficients for all farms, or for each farm. The latter requires the input of a farm-related list of coefficients that, alternatively, can be specified for each stress period.

- *Ground water base maintenance costs* per unit volume [$$/L^3$]

- *Ground water costs for pumping in well* per unit volume per unit of lift [$$(L^3 \cdot L)$]

Pumping costs are dependent on the head-lift per farm well. The FMP1 calculates an effective head lift per farm, weighted by the maximum capacities of the respective farm wells. Multiplying the pumping costs per unit volume and unit lift by the 'effective head lift' in a farm results in the effective well-pumping costs per unit applied volume specific for a certain farm.

- *Ground-water costs for vertical lift from well to cell* per unit volume per unit of lift [$$(L^3 \cdot L)$]

For nonhorizontal surfaces, an additional head-lift from the well to the respective model cell may occur. The FMP1 calculates an effective elevation of a 'virtual well location' as average of all farm well elevation, weighted by their maximum capacities. If the ground elevation of a respective (irrigated) model cell is higher than the effective elevation, then the difference represents the additional surface-head-lift needed to be overcome to pump the ground water uphill. Multiplying the Well-to-Cell-Lift Costs per unit volume and unit lift by the 'surface head lift' yields Effective Well-to-Cell Pumping costs per unit applied volume.

- *Ground-water delivery costs* per unit volume, per unit distance [$$(L^3 \cdot L)$]

The FMP1 calculates an effective distance of each model cell in a farm to a virtual location of a ground water source by weighting the distances of each well to the model cell by their respective maximum capacities. Multiplying the ground water delivery costs by that 'effective distance' yields Effective Ground water Delivery Costs per unit volume to each model cell.

- *Fixed Price of (Semi-) Routed Surface Water* per unit volume [$$/L^3$]

- *Costs for Vertical Lift of (Semi-) Routed Surface Water from Canal to Cell*, per unit volume per unit lift [$$(L^3 \cdot L)$]

For nonhorizontal surfaces, an additional head lift from the nearest canal reach to the respective model cell also may occur. The FMP1 determines the elevation of stream head in the nearest reach (for routed deliveries) or in the reach specified (for semi-routed deliveries), and calculates the difference between the elevation of the stream-head and the elevation of the model cell if the latter is higher than the former. This difference represents the actual surface-water lift. Multiplying the surface-water lift costs per unit volume and unit lift by the actual lift yields the Surface-Water Lift Costs per unit-applied volume.

- *Delivery Costs of (Semi-) Routed Surface Water* per unit volume, per unit distance [$$(L^3 \cdot L)$]

The FMP1 calculates the distance of each model cell in a farm to the nearest canal-reach (for routed deliveries) or in the reach specified (for semi-routed deliveries). Multiplying the surface-water delivery costs by that nearest distance yields Surface Water Delivery Costs per unit volume to each model cell from its respective nearest reach.

- *Fixed Price of Nonrouted Surface Water* per unit volume [$$/L^3$]

Lumped Water Cost Coefficients for all Farms

The data input of lumped Water Cost Coefficients does not require a data list but simply eight lumped real constants for the entire simulation and for all farms of the entire model area (if IDEFFL > 0, and ICOST = 0) as follows:

Ground water pumping base costs	[\$/L ³]	Value
Well-Pumping costs	[\$/(L ³ ·L)]	Value
Well-to-Cell lift costs	[\$/(L ³ ·L)]	Value
Ground-water delivery costs	[\$/(L ³ ·L)]	Value
Fixed price of (Semi-)Routed Surface Water	[\$/L ³]	Value
Reach to Cell lift costs of (Semi-)Routed Surface Water	[\$/(L ³ ·L)]	Value
Reach to Cell delivery costs of (Semi-)Routed Surface Water	[\$/(L ³ ·L)]	Value
Fixed price of Nonrouted Surface Water	[\$/L ³]	Value

Farm-Related Water Cost Coefficients

Each farm may be associated with ground-water and surface-water cost coefficients constant during the entire simulation (if IDEFFL > 0, and ICOST = 1) as follows:

Farm ID	Ground-water pumping base costs	Well Pumping costs	Well-to-Cell lift costs	Ground-water delivery costs	Fixed Price of (semi-) routed surface water	Reach to Cell lift costs of (semi-) routed surface water	Reach to Cell delivery costs of (semi-) routed surface water	Fixed Price of nonrouted surface water
	[\$/L ³]	[\$/(L ³ ·L)]	[\$/(L ³ ·L)]	[\$/(L ³ ·L)]	[\$/L ³]	[\$/(L ³ ·L)]	[\$/(L ³ ·L)]	[\$/L ³]
1								
2								
3								

Surface-Water Data

Surface-water data are required if surface water is allocated as either “nonrouted,” as “semi-routed,” or as “fully routed” delivery to a farm

Nonrouted Deliveries

Nonrouted deliveries or extractions are volumes of water allocated to or extracted from a farm that are independent of any simulated delivery or conveyance mechanism (if nonrouted surface-water delivery flag INRDFL = 1). In the FMP1, nonrouted deliveries are assumed to change from stress period to stress period and, therefore, can not be specified for the entire simulation.

Routed Deliveries

The streamflow routing is facilitated by a link of the FMP1 to the SFR1 package for routing surface water through a conveyance network either to a specified, remote point of diversion (if “semi-routed” is selected), or directly to a head gate adjacent to a farm (if “fully routed” is selected).’

Semi-Routed Deliveries

Semi-routed surface water is defined as surface water routed through a “river-to-canal” network to a point of diversion from where water is delivered in a nonrouted form (for example, by pipeline) to a remote farm not adjacent to the canal (for the entire simulation if semi-routed surface-water delivery flag ISRDFL = 1). Such a farm only can receive “semi-routed” but not “fully routed” deliveries. Each farm may be associated with a point of diversion for the entire simulation as:

- Farm ID
- Row
- Column
- Segment number
- Reach number

Example for specifying farm specific points of diversion for semi-routed deliveries:

Farm ID	Row	Column	Segment number	Reach number
1				
2				
3				

The user may optionally specify the diversion point by (1) a full set of information consisting of model cell coordinates, stream segment number, and reach number (row, column, segment, reach), or (2) by just the model cell coordinates and a stream segment number (row, column, segment), or (3) by just the model cell coordinates (row, column), or alternatively (4) by the number of a stream segment and the number of a reach, or (5) simply by the reach number, which, in any case is uniquely associated with a segment number. Option (3) does not require any data information from the SFR1 package but is possible only if a unique identification of a reach is not necessary. Such a unique identification is important if more than several stream segments pass through one model cell. If a farm is adjacent to a canal and can divert “routed” deliveries from a head-gate, then this farm cannot receive “semi-routed” deliveries at the same time. If coordinates of a point of diversion are entered mistakenly for a semi-routed delivery, then the program exits and prints an error message that asks the user to set the coordinates for that farm to zero.

Fully-Routed Deliveries

Fully routed deliveries can be described as surface water routed to a farm by a “river-to-canal” conveyance network (if routed delivery flag IRDFL = 1). For this option, the farm has to be adjacent to the canal/lateral. Such a farm only can receive “fully routed” but not “semi-routed” deliveries. “Adjacent” in this context means that there must be no model cell in between at least one cell containing a canal reach and at least one cell of a particular farm. By setting IRDFL=1, the user has the option to let the FMP1 automatically generate head gates at the most upstream located canal reach for a farm, where canal reach cells are adjacent to a section of the farm boundary. Clearly, the setup of the Farm ID array and the specification of stream reach locations (row, column) in the SFR1 (see “Stream-Reach Data” below) decides whether fully routed deliveries to farms can be simulated or not. For farms, where canal reach cells are separated from farm cells by one or more model cells, the user may specify remote points of diversion for farms for semi-routed deliveries (ISRDFL > 0).

Stream-Reach Data

A list that specifies stream reach data is required for the entire simulation (as defined by the SFR1 package input instructions), if the semi-routed delivery flag ISRDFL = 1 or if the fully routed delivery flag IRDFL = 1. The user should refer to the input instructions for the SFR1 package (Prudic and others, 2004) if the SFR1 package and the FMP1 are used jointly. Attributes of stream reaches are defined as data SFR1 data input for the entire simulation and described below. The reaches in the list must be sorted sequentially by segment numbers.

Attributes of stream segments (in other words, inflow, roughness, vertical hydraulic conductivity, thickness, and elevation of top of streambed) are defined for each stress period in section “Data Requirements for Each Stress Period”

Stream reach related data:

- Layer number of the cell containing the stream reach.
- Row number of the cell containing the stream reach.
- Column number of the cell containing the stream reach.
- Number of Stream Segment in which the stream is located (sequentially ordered).
- Sequential number of this reach within a stream segment.
- Length of channel of the stream within this model cell.

Data Requirements for each Stress-Period

The data-requirement items used for each stress period that are briefly described in this section of the report generally follow the sequence of the data-input items for each stress period described in the subsequent section of this report “Data Input Instructions.” The data items reviewed here represent the additional or different specifications for the entire simulation that was described in the previous section of this report.

Farm-Wells Data

Farm well attributes of “nonparameter” farm wells must be defined for each stress period if “nonparameter” farm wells exist during a stress period ($ITMP > 0$). In FMP1, the word “parameter” stands for a “multiplier-parameter” (herein referred to as “parameter wells”). This term is used during a stress period to modify a parameter factor assigned to certain attributes for the entire simulation. The maximum capacity of farm wells is the only attribute that currently is available in the FMP1 for parameter scaling and this feature does not currently include parameter estimation.

Nonparameter or Parameter Farm-Wells Lists

A Flag ($ITMP$) is read at the beginning of each stress period that is either equal to the number of nonparameter farm wells, or—if such a nonparameter farm wells list was used in one stress period—that specifies to reuse the list. If only parameter farm wells are used, and their list already was read for the entire simulation, then that flag always is zero. Another flag is read in the same line indicating the number of parameters in use during the current stress period (NP).

If parameter farm wells exist for the current stress period ($NP \geq 1$) a lists of parameter farm wells that are specific for a certain QMAX-fact multiplier parameter can be invoked simply by reading the respective “parameter name,” which was predefined for the entire simulation. The FMP1 will read NP parameter names NP times during one stress period. That is, the user has several choices, depending on whether one or several multiplier parameters were prespecified, which apply either to a selection or all of the farm wells. For instance, one parameter name representing a group of farm wells could be repeated for every stress period, whereas, by choosing different parameter names for other groups of farm wells, the wells could experience a change in their maximum capacities from stress period to stress period, representing respectively changing QMAX-fact multipliers. To apply changing multipliers to a group of farm wells most effectively would require to cross-reference to a file name containing that respective list, so the list doesn’t need to be repeated in the input file.

The simplest advantage of using parameter farm wells versus nonparameter farm wells seems to be the following: If the list of farm-well variables, including the maximum capacities, does not change during the entire simulation, then the same parameter name representing that list simply can be reread at any stress period. It may be preferable to specify for the entire simulation a list of farm-well variables that have been constant during the entire simulation than to put that list into the section for the first stress period as a nonparameter farm-wells list, and to repeat it by setting $ITMP = -1$.

If nonparameter farm-wells exist for the current stress period (if $ITMP > 0$), then a similar list of farm-well attributes as outlined for the entire simulation (for parameter farm wells) can be specified and read for nonparameter farm wells at each stress period either directly from the FMP1 input file or from an external file containing the list. Nonparameter maximum well capacity values that are read for each stress period remain constant for the entire stress period. In contrast, maximum well capacity parameters that are specified for the entire simulation can be modified by stress period-specific multipliers. The reuse of Nonparameter Farm-Well List from the previous stress period is specified by $ITMP$ of current stress period = -1 , and if $ITMP$ of previous stress period > 0 . Input variables, that represent attributes of a farm well, are as follows:

- *Layer*
- *Row*
- *Column*
- *Farm Well ID*
- *Farm ID associated with Farm Well*
- *Maximum Well Capacity*
- *[Auxiliary Attributes]*

Similarly to parameter farm-wells, an attributes list of nonparameter farm wells can, as well, include attributes of farm wells that are simulated by the MNW Package. A “negative” farm-well ID designates that a link to the MNW package is established. A “zero” layer number indicates that the well linked to the MNW package is a “multi-layer” well, and that the layers associated with the respective screened aquifers are defined in the MNW package input file. A detailed explanation of input variables for nonparameter farm wells and how to establish a link of an FMP1 well to a MNW package well can be obtained from the section describing the input variables of parameter farm wells. The only difference between a parameter farm-wells list and a nonparameter farm-wells list is that the maximum capacity factor, QMAXfact, is replaced by the maximum capacity, QMAX.

Example of Farm-Well List for the FMP1:

Layer	Row	Column	Farm Well ID	Farm ID	QMAXfact [L ³ /T]
			1	1	
			2	1	
0	5	6	-3	1	1000
			4	2	
			5	2	

Q-required for farm-well 3 = 800

Cross-Reference and Link from FMP1 well to MNW well

Example of a Well List for the Multi-Node Well Package:

Layer	Row	Column	Q-desired [L ³ /T]	Other nonfarm-related data	Hlim = limiting water level, or limiting drawdown [L]	Other nonfarm-related data
1	5	6	Q-req. or QMAX passed on from FMP1 and re-apportioned to each layer		50	
2	5	6			50	
4	5	6			50	

(The well list for the MNW package is read for each simulation)

Farm Irrigation Efficiencies

On-farm efficiency can be specified as a constant or on a farm-by-farm basis either for the entire simulation or for each stress period. Variable efficiencies in FMP1 can be chosen to depend on the aquifer head (IEBFL = 2 or 3). The user-specified values, OFE_{spec} are either held constant (IEBFL = 1) or employed as initial guess at the beginning of each time step when calculating variable efficiency for each time step (IEBFL = 2 or 3).

Example list of farm irrigation efficiencies:

Farm ID	OFE _{spec}
1	
2	
3	

Crop-Type Arrays and Data (Natural Attributes)

An array of *Crop-Type IDs* only is required for each stress period if a change of the spatial distribution of crops throughout time is desired. These changes could represent crop rotation, urbanization, or other changes in agricultural land use. Crop-type-related data lists specified for each stress period contain attributes, which are constant throughout each stress period.

Crop-Type Identification Array

If changes in crop distribution are specified for each stress period (IROTFL = -1), then the new set of *Crop-Type IDs* are specified for that stress period. Fallowed areas are identified by a *Crop-Type-ID* of -1.

Crop-Type Data

Crop-type-related data lists specified for each stress period contain attributes that are constant throughout each stress period, such as:

- (1) *Root-zone depths* constant throughout each stress period;
- (2) *Consumptive-use* constant throughout each stress period;
- (3) *Fractions of transpiration and evaporation of consumptive-use* constant throughout each stress period;
- (4) *Fractions of inefficiency losses to surface-water runoff* constant throughout each stress period.

- *Root Depth [L]* :

The root depth for each crop is user-specified for each stress period (IRTFI = 2) or calculated as time-step averages (IRTFI = 3) from Climate-Data Time Series and a List of Crop-Specific Coefficients. If root depth is specified for each stress period (IRTFI = 2), then

- (1) Root depth may be read optionally as a constant throughout a stress period for all crops.
- (2) Each crop may be associated optionally with a spatially lumped Root Depth value constant for each Stress Period (S-PER) as follows:

Example for a specific stress period:

Crop ID	Root Depth [L] per S-PER
1	
2	
3	

- *Consumptive-Use Flux [L/T]* :

The consumptive-use flux for each crop is user-specified for each stress period (ICUFI = 2) or calculated as time-step averages (ICUFI = 3) from Climate Data Time Series and a List of Crop-Specific Coefficients. Consumptive use is defined commonly as crop evapotranspiration, which includes transpiration and evaporation in a cropped agricultural area (Colorado’s Decision Support Systems, 1995; Gelt and others, 1999; European Environment Agency, 2004). Each crop may be associated with a spatially lumped consumptive use value constant for each Stress Period (S-PER) as follows:

Example for a specific stress period:

Crop ID	Consumptive Use [L/T] per S-PER
1	
2	
3	

- *Fractions of Transpiration and Evaporation of Crop Consumptive Use:*

The fractions of transpiration and evaporation for each crop are user-specified for each stress period (IFTEFI = 2). Each crop may be associated with spatially lumped values of a transpiratory (K_t) and evaporative fraction of consumptive use (K_e^p - related to precipitation, K_e^i - related to irrigation), which is constant throughout each stress period (allowing changes throughout the growing season between stress periods) as follows:

Example for a specific stress period:

Crop ID	K_t ($0 < K_t \leq 1$)	K_e^p ($0 \leq K_e^p \leq 1$)	K_e^i ($0 \leq K_e^i < 1$)
1			
2			
3			

In the FMP1, the evaporation losses from irrigation, E_i , are defined to vary proportionally to T_i . Equality between E_i/T_i and K_e^i/K_t , therefore, evaporation is assumed to be:

$$E_i = T_i \times (K_e^i/K_t)$$

This is why K_t must not be zero.

- *Fractions of Inefficiency Losses to Surface-Water Runoff:*

Fractions of inefficiency losses to surface-water runoff for each crop are user-specified for each stress period (IIESWFL = 2) or, if related to slope, calculated internally as “rise-over-run” (delta-elevation/delta-lateral distance) (IIESWFL = 0). For IIESWFL = 2, each crop may be associated with spatially lumped values of fractions of in-efficient losses to surface-water runoff related to precipitation or irrigation, which is constant throughout each stress period as follows:

Example for a specific stress period:

Crop ID	IE_{sw}^p ($0 \leq IE_{sw}^p \leq 1$)	IE_{sw}^i ($0 \leq IE_{sw}^i \leq 1$)
1		
2		
3		

Climate Data

Climate-related data may be specified as constants for each stress period, as opposed to climate data that are read as time series throughout the duration of the entire simulation. The only climate variable that may be specified for each stress period is precipitation. Although consumptive use depends on climate (among other factors), it is considered a crop-specific parameter and, therefore, is listed in the “Crop-Type Arrays and Data” section of this report.

Precipitation Array

Changed precipitation distributions can be user-specified for each stress period (IPFL = 2) as a lumped average value or a spatially distributed array of values, if not specified as daily time series for the entire simulation (IPFL = 3), which would allow the calculation of time-step averages.

- *Lumped Average Precipitation Value [L] :*

A spatially lumped precipitation value for entire domain averaged throughout a stress period.

- *Distributed Average Precipitation Values [L] :*

Precipitation is user-specified as a 2D-array of spatially distributed precipitation averaged throughout a stress period. Depending on whether the temporal or spatial variability of precipitation is greater, the user should decide if daily time series are read in (IPFL = 3) while accepting that the data are lumped spatially or if a spatially distributed 2D array is read in while averaging the temporal data for each polygon or cell throughout the duration of one stress period (IPFL = 2; with cross-reference to file containing the 2D array). However, minimal impact of precipitation on the overall water budget would be expected in (semi-) arid areas such as the southwestern United States. In this type of climatic setting a spatially lumped precipitation value averaged throughout a stress period usually should be sufficient (IPFL = 2; with value read in as constant for entire domain).

Crop-Type Data (Agro-Economic)

Crop benefits are derived from crop-specific water production functions and from the crop’s market price if Acreage-Optimization is chosen as deficiency scenario (IDEFFL > 0). Water production functions and a crop’s market price also can be user-specified for each crop type for each stress period (IBEN = 2).

Crop-Type Benefits Data

Crop benefits can be user-specified for each stress period if IDEFFL > 0 and IBEN = 2. Each crop type may be associated with the following parameters constant over each stress period:

- *Coefficients of crop-specific Water-Production Function (Yield vs. ETc):*
 - o Slope
 - o Intercept
- *Market-price per crop:*

Crop ID	Calculation of Crop Benefit		
	Water Production Function		Crop Market Price
	Slope (<i>a</i>)	Intercept (<i>b</i>)	
	YIELD = $a \times ET + b$, where: YIELD in [weight/area], and ET in [length]		[value/weight]
1			
2			
3			

Water-Cost Coefficients

Four ground-water cost coefficients and four surface-water cost coefficients are user-specified for each farm for each stress period (ICOST = 2) if Acreage-Optimization is desired as a deficiency scenario (if IDEFFL > 0). These cost coefficients are user-specified for each farm and may be associated with ground-water and surface-water cost coefficients that remain constant over each stress period as follows:

Farm ID	Ground-water pumping base costs	Well-pumping costs	Well-to-cell lift costs	Ground-water delivery costs	Fixed price of (semi-) routed surface water	Reach to cell lift costs of (semi-) routed surface water	Reach to cell delivery costs of (semi-) routed surface water	Fixed price of nonrouted surface water
	[\$/L ³]	[\$/(L ³ ·L)]	[\$/(L ³ ·L)]	[\$/(L ³ ·L)]	[\$/L ³]	[\$/(L ³ ·L)]	[\$/(L ³ ·L)]	[\$/L ³]
1								
2								
3								

Surface-Water Data

Surface-water data are required if surface water is allocated as either “nonrouted,” as “semi-routed,” or as “fully routed” delivery to a farm.

Nonrouted Surface-Water Deliveries

Nonrouted surface-water deliveries are user-specified for each stress period if surface-water delivery flag INRDFL = 1. Importation schemes for surface-water delivery from outside the modeling domain such as water transfers or complex deliveries can be simulated as nonrouted deliveries independent of a river or canal network from the SFR1 package. The scheme for simulation of nonrouted deliveries is presented in the section ‘Surface-water Delivery’ (eq. 3).

Although there are no data required for the entire simulation, a list containing rates, ranks, NRD_{use} -flags of random, unranked types of nonrouted surface-water deliveries (t_u) may be associated with each farm and is read for each stress period:

- Farm ID
- Farm specific Nonrouted Delivery
- Farm specific Rank of Nonrouted Delivery
- Farm specific Binary NRD_{use} -flag, which (if 0) tells to use only the amount sufficient to meet the farm’s demand, or (if 1) tells to use the absolute amount available, and to recharge surplus from a certain delivery type back into the canal at a farm’s head gate, or (if 2) tells to use the absolute amount available, and to inject surplus from a certain delivery type into the farm wells attributed to a certain farm ID.

Example of a list of nonrouted deliveries for each farm for a specific stress period.

Farm ID	Unranked Nonrouted Delivery Type 1			Unranked Nonrouted Delivery Type 2			Unranked NRD Type t_u
	Nonrouted Delivery [L ³]	Priority Rank of NRD	NRD _{use} -Flag of 'sufficient' or 'absolute' use of NRD	Nonrouted Delivery [L ³]	Priority Rank of NRD	NRD _{use} -Flag of 'sufficient' or 'absolute' use of NRD	...
1							
2							
3							

The following two examples show for one specific stress period and one specific farm, how particular settings of the NRD_{use} -flags for four water transfer types t (NRD_{use} ^{$t=1,2,3,4$}) can influence, what the total nonrouted delivery the example farm amounts to, whether only the sufficient or the absolute amount of a nonrouted delivery in excess of the TFDR is used, and whether excess nonrouted delivery is recharged back into the canal or injected into farm-wells.

Example 1–Potential Oversupply by Non-Routed Deliveries (4 different scenarios):

Input data set for four scenarios of NRD use-flag settings for example farm 1 and for a specific stress period (here: Rank No. = Type No.)

Farm ID	NRD Type 1			NRD Type 2			NRD Type 3			NRD Type 4		
	Volume	Rank	Use-flag	Volume	Rank	Use-flag	Volume	Rank	Use-flag	Volume	Rank	Use-flag
Scenario 1:												
1	5	1	0 or 1 or 2	3	2	0 or 1 or 2	3	3	0	4	4	0
Scenario 2:												
1	5	1	0 or 1 or 2	3	2	0 or 1 or 2	3	3	1 or 2	4	4	0
Scenario 3:												
1	5	1	0 or 1 or 2	3	2	0 or 1 or 2	3	3	0	4	4	1 or 2
Scenario 4:												
1	5	1	0 or 1 or 2	3	2	0 or 1 or 2	3	3	1 or 2	4	4	1 or 2

Scenario	TFDR = 10 units				NRD _{pot} ¹	NRD _{pot} ²	NRD _{pot} ³	NRD _{pot} ⁴	Results	
	NRD _{use} ¹	NRD _{use} ²	NRD _{use} ³	NRD _{use} ⁴	5	3	3	4	$\sum_{t=1}^4 NRD_{act}^t$	Insufficiency (I) Sufficiency (S) Oversupply (O)
					NRD _{act} ¹	NRD _{act} ²	NRD _{act} ³	NRD _{act} ⁴		
1	0 or 1 or 2	0 or 1 or 2	0	0	5	3	2	0	10 units used = TFDR (S)	Sufficiency
2a	0 or 1 or 2	0 or 1 or 2	1	0	5	3	3	0	11 units used > TFDR (O)	1 to canal
2b	0 or 1 or 2	0 or 1 or 2	2	0						1 to wells
3a	0 or 1 or 2	0 or 1 or 2	0	1	5	3	2	4	14 units used > TFDR (O)	4 to canal
3b	0 or 1 or 2	0 or 1 or 2	0	2						4 to wells
4a	0 or 1 or 2	0 or 1 or 2	1	1	5	3	3	4	15 units used > TFDR (O)	5 to canal
4b	0 or 1 or 2	0 or 1 or 2	2	1						1 to well, 4 to canal
4c	0 or 1 or 2	0 or 1 or 2	1	2						1 to canal, 4 to well
4d	0 or 1 or 2	0 or 1 or 2	2	2						5 to wells

Example 2 – Insufficiency of Nonrouted Deliveries:

Input data set for any scenarios of NRD use-flag settings for example farm 1 and for a specific stress period

Farm ID	NRD type 1			NRD type 2			NRD type 3			NRD type 4		
	Volume	Rank	Use-flag	Volume	Rank	Use-flag	Volume	Rank	Use-flag	Volume	Rank	Use-flag
1	3	Any	Any	1	Any	Any	3	Any	Any	2	Any	Any

Scenario	TFDR = 10 units				NRD _{pot} ¹	NRD _{pot} ²	NRD _{pot} ³	NRD _{pot} ⁴	Results	
	NRD _{use} ¹	NRD _{use} ²	NRD _{use} ³	NRD _{use} ⁴	3	1	3	2	$\sum_{t=1}^4 NRD_{act}^t$	Insufficiency (I) Sufficiency (S) Oversupply (O)
	NRD _{act} ¹	NRD _{act} ²	NRD _{act} ³	NRD _{act} ⁴						
All	For all NRD _{use} -flags settings				3	1	3	2	9 units used < TFDR (I)	Insufficiency case

If supply through nonrouted deliveries is found to be insufficient, as demonstrated in Example 2, then the FMP1 checks on whether the remaining demand can be supplemented by (semi-) routed deliveries, or by farm well pumping.

Routed Surface-Water Deliveries

The streamflow routing is facilitated by a link of the FMP1 to the SFR1 package for routing surface water through a conveyance network either to a specified, remote point of diversion (if “semi-routed” is selected), or directly to a head gate adjacent to a farm (in “fully routed” is selected).

‘Semi-Routed’ Delivery

If semi-routed deliveries are user specified for each stress period, the surface-water delivery flag ISRDFL = 2. Routing surface-water along a river or major canal, and diverting nonrouted deliveries from a point of diversion along such a river or major canal is defined in the FMP1 as ‘semi-routed’ surface-water delivery. In this case, the SFR1 package is used only to rout streamflow along a river or major canal. Aside from the attributes list for stream segments, a list of farms-related data has to be specified for each stress period containing the respective coordinates (row, column) from which location along a river or major canal the delivery is diverted:

- Farm ID
- Row
- Column
- Segment number
- Reach number

Farm ID	Row	Column	Segment number	Reach number
1				
2				
3				

The user may optionally specify the diversion point by (1) a full set of information consisting of model cell coordinates, stream segment number, and reach number (row, column, segment, reach), or (2) by just the model cell coordinates and a stream segment number (row, column, segment), or (3) by just the model cell coordinates (row, column), or alternatively (4) by the number of a stream segment and the number of a reach, or (5) simply by the reach number, which in any case is uniquely associated with a segment number. Option (3) does not require any data information from the SFR1 package but is only possible if a unique identification of a reach is not necessary. Such a unique identification is important if more than several stream segments pass through one model cell. Farms that are adjacent to a canal and therefore can divert “routed” deliveries from a head-gate cannot receive “semi-routed” deliveries at the same time. If coordinates of a point of diversion mistakenly are entered for a semi-routed delivery, then the program exits and prints an error message that asks the user to set the coordinates for that farm to zero.

'Fully-Routed' Deliveries

Fully-routed deliveries represent surface-water deliveries routed through a conveyance network to a farm. If fully routed streamflow deliveries are user-specified for each stress period, the 'routed-delivery flag,' IRDFL, must be equal to 1. Applying the SFR1 package jointly with the FMP1 facilitates the routing of streamflow by way of a 'river to canal' conveyance network directly to a farm's head gate reach. The data requirements can be obtained below.

Stream-Segment Data

A list that specifies stream segment data is required for each stress period (as defined by the SFR1 package input requirements), if the semi-routed delivery flag ISRDFL = 1 or 2 or if the fully routed delivery flag IRDFL = 1. The user should refer to the input instructions for the SFR1 package (Prudic and others, 2004) if the SFR1 package and the FMP1 are used together. Attributes of stream segments are defined for each stress period. They are described below as input variables of the stream segments list. The parameters attributed to stream segments in the following list are a suggestion as to which parameters are required at minimum if the SFR1 package is used jointly with the FMP1.

- Parameters for the entire segment:
 - *Segment Number (ID)*
 - *ICALC*: option for stream stage calculation (see below)
 - *Downstream tributary segment number*
 - *Upstream segment number* from which diversion occurs (no record if segment is not a diversion segment)
 - *IPRIOR*: type of diversion (see below)
 - *Inflow rate* into segment (for example, first reach of headwaters or diversion segments)
 - *Specified losses and gains* are optional¹⁰: *overland runoff*, *stream evaporation*, *stream precipitation*
 - *Streambed Roughness* (Manning's n; if Manning's formula is chosen as an option for computing stream stage)
- Parameters for the upstream and downstream end of the segment:
 - *Vertical Hydraulic Conductivity* of Streambed
 - *Thickness* of Streambed
 - *Elevation of Top of Streambed*
 - *Stream Width* (if assuming rectangular channel)

The description of input requirements for the SFR1 in conjunction with the FMP1 are limited here to suggestions for the following two: SFR1 options for stream-stage calculation (ICALC) and for diverting water out of a stream for irrigation purposes (IPRIOR). However, the user should be advised that the SFR1 offers numerous other options, which are described in the SFR1 user guide (Prudic and others, 2004).

- Suggested option for stream-stage calculation:
Manning's formula using a rectangular channel (flag in SFR1: ICALC = 1)
- Suggested option for diversions:
Fixed water right type diversion, meaning diversion is reduced to available streamflow, if specified diversion is greater than streamflow (Hanson and others, 2003) (flag in SFR1: IPRIOR = 0).

For most irrigation networks, the upstream and downstream parameters for the vertical hydraulic conductivity and the thickness of the streambed are specified, as well as for the stream width which may be assumed to remain equal or unequal.

The stream-segment parameter, which typically takes different values at the upstream and downstream end of the segment, is the elevation of the top of the streambed. The elevation of the top of the streambed at the upstream and downstream end of a segment is used to calculate the elevation of the midpoint of a stream reach in two different ways, depending on the settings of IRDFLG flag in the SFR1 data input file (Prudic and others, 2004).

¹⁰When using the SFR1 together with the FMP1 for a conjunctive surface-water/ground-water model in (semi-)arid areas, those fluxes typically have a negligible impact on the overall ground-water budget if related to canal segment.

If IRDFLG = 0: The elevation of the top of the streambed of all segments is interpolated between the elevation of the upstream and downstream ends of the segments, as specified in SFR1 input file.
 If IRDFLG = 1: The elevation of the top of the streambed of all segments that are not diversion segments is interpolated between the elevation of the upstream and downstream ends of the segments, as specified in SFR input file.

The elevation of the top of the streambed of diversion segments (canals/laterals) follows the slope of ground surface at a depth defined by the interpolation of:

- (1) the difference between the ground surface elevation and the elevation of the upstream end of a diversion segment, as specified in the SFR input file; and
- (2) the difference between the ground surface elevation and the elevation of the downstream end of a diversion segment, as specified in the SFR input file.

Note limitation: IRDFLG = 1 cannot be chosen if the number of the diversion segment is equal to the total number of segments.

Note that the IRDFLG flag in SFR1 also serves as a print flag, which tells to print input data for a stress period when IRDFLG = 0, and not to print input data for a stress period when IRDFLG > 0 (Prudic and others, 2004).

Water-Rights Data

Surface-water allotments may be introduced into a model as a lumped equal appropriation allotment height for any stress period in units of [L] for an entire irrigation district (IALLOT = 1) or as water rights calls per stress period in units of [L³/T] for a prior appropriation system of ranked individual farms or irrigation regions (IALLOT > 1). The simulation of surface-water deliveries constrained by equal appropriation allotments heights requires the specification of a routing network in the SFR1 input file. However, when simulating surface-water deliveries regulated by a prior appropriation system, then diversions from a river into canals serving the farms will be simulated by the FMP1.

Equal Appropriation

Water rights are set to equal appropriation by specifying IALLOT = 1. The simulation of the actual delivery to the farm in general (eq. 4), and for equal appropriation water rights (eq. 7C) is presented earlier in this report.

The actual delivery to a farm in general (eq. 4) is derived in the ‘Surface-Water Delivery’ section:

$$DEL_{act\ f}^{t,k} = \min(TFDR_f^{t,k} - TNRD_f^{t,k}, DEL_{pot\ f}^{t,k}, Q_{constr\ f}^t)$$

The actual delivery to a farm for equal appropriation water rights (eq. 7C) is derived in the “Water Rights Allocations” section:

$$DEL_{act\ f}^{t,k} = \min(TFDR_f^{t,k} - TNRD_f^{t,k}, Q_{in\ r\ f}^{t,k}, Q_{allot\ f}^t)$$

For equally appropriated farms,

- the potential delivery to a farm’s head gate, $DEL_{pot\ f}^{t,k}$, is equal to the inflow into the head gate reach, $Q_{in\ r\ f}^{t,k}$:
 $DEL_{pot\ f}^{t,k} = Q_{in\ r\ f}^{t,k}$, and
- the water rights system specific delivery constraint, $Q_{constr\ f}^t$, is equal to the a farm allotment rate, $Q_{allot\ f}^t$:
 $Q_{constr\ f}^t = q_{allot}^t \cdot A_f = Q_{allot\ f}^t$.

The farm allotment rate, $Q_{allot\ f}^t$, is the product of an equal appropriation allotment flux, q_{allot}^t [L/T], and the respective farm area, A_f .

- Equal Appropriation Allotment Height [L]

The only input parameter required for equal appropriation is a spatially lumped value of an *allotment height* [L] for the entire domain and for a stress period. The FMP1 converts the allotment height internally into an allotment flux, q_{allot}^t [L/T] by dividing the height by the duration of the respective stress period.

Prior Appropriation

Water rights are set to prior appropriation by specifying IALLOT > 1. The simulation of the actual delivery to the farm in general (eq. 4), and for a prior appropriation water rights system (eq. 8C) is presented earlier in this report:

The actual delivery to a farm in general (eq. 4) is derived in the “Surface-Water Delivery” section:

$$DEL_{act_f}^{t,k} = \min(TFDR_f^{t,k} - TNRD_f^{t,k}, DEL_{pot_f}^{t,k}, Q_{constr_f}^t)$$

The actual delivery to a farm for prior appropriation water rights (eq. 8C) is derived in the “Water-Rights Allotments” section:

$$DEL_{act_f}^{t,k} = \min(TFDR_f^{t,k} - TNRD_f^{t,k}, Q_{in_r,f}^{t,k} - Q_{C-min_r,f}^{t,k}, Q_{call_f}^t)$$

For a prior appropriation water rights system,

- o the potential delivery to a farm’s head gate, $DEL_{pot_f}^{t,k}$, is equal to the inflow into the head gate reach,

$Q_{in_r,f}^{t,k}$ minus a minimum canal streamflow, $Q_{C-min_r,f}^{t,k}$:

$$DEL_{pot_f}^{t,k} = Q_{in_r,f}^{t,k}, \text{ and}$$

- o the water rights system specific delivery constraint, $Q_{constr_f}^t$, is equal to user-specified Water Rights Calls:

$$Q_{constr_f}^t = Q_{call_f}^t.$$

- Prior Appropriation with Water Rights Calls:

If the user specifies IALLOT = 2, then a farm-related list of *Water Rights Calls* [L³/T] is required as data input for each stress period:

Farm ID	Call [L ³ /T] per S-PER
1	
2	
3	

- Prior Appropriation without Water Rights Calls:

If the user specifies IALLOT = 3, then the prior appropriation system is implemented only based on a water rights ranking of all farms represented by the 2D array of farm IDs, where a lower farm ID indicates a higher water rights rank. There is not data input required for this option.

Data Input Instructions

Data input for the FMP1 is read from the file designated as type “FMP” in the name file. The chapter ‘data input instructions’ contains three sections. The first section describes the data input requirements for each input item. An input item can consist of a comment, of flags, or of scalar-, list- or array-variables. Optional variables and optional flags are shown in brackets, [], and curly braces, { }, respectively. Two-dimensional arrays are listed together with their array dimensions (NCOL, NROW). Data lists or arrays, which are read by MF2K or FMP1 utility modules are indicated by “read*” and by a footnote that explains, which utility array readers are used, respectively. The second section explains the input structure of the array and list reading utility modules, and instructs how to apply scale factor multipliers to the variables. The third section provides an explanation of the fields itemized in the input instructions in the first section.

Input Data for the FMP1

Data for each Simulation

Item No.	Input instruction for each item	
0	[#Text] read if '#' is specified (can be repeated multiple times)	
1	[PARAMETER NPFWL MXL] read if word 'PARAMETER' is specified	
2	MXACTW NFARMS NCROPS NSOILS IRTFL ICUFL IPFL IFTEFL IIESWFL IEFFL IEBFL IROTFL IDEFFL {IBEN} {ICOST} ICCFL INRDFL {MXNRDT}, ISRDFL IRDFL IALLOT {PCLOSE} IFWLCB IFNRCB ISDPFL {IOPFL} {IPAPFL} {Option} read	
3	[PARNAM PARTYPARVAL NLST] read if NPFWL > 0	Repeat items 3 + 4 NPIWL times
4	[Layer Row Column Farm-Well-ID Farm-ID QMAXfact] [xyz] read* NLST times with [3] if NPFWL > 0	Repeat items 3 + 4 NPIWL times
5	GSURF(NCOL,NROW) read* with [2]	
6	FID(NCOL,NROW) read* with [1]	
7	[Farm-ID OFE] read* NFARMS times with [5]] if IEFFL = 1	
8	SID(NCOL,NROW) read* with [1]	
9	Soil-ID CapFringe [A-Coeff B-Coeff C-Coeff D-Coeff E-Coeff, or Soil-ID CapFringe [Soil-Type] (parameters in brackets only if ICCFL = 1) read* NSOILS times with [6]	
10	[CID(NCOL,NROW)] read* with [1] if IROTFL >= 0	
11	[Crop-ID ROOT] read* NCROPS times with [4] if IRTFL = 1	
12	[Crop-ID FTR FEP FEI] read* NCROPS times with [5] if IFTEFL = 1	
13	[Crop-ID FIESWP FIESWI] read* NCROPS times with [5] if IIESWFL = 1	
14	[Crop-ID PSI(1) PSI(2) PSI(3) PSI(4)] read* NCROPS times with [5] if ICCFL = 1	
15	[Crop-ID BaseT MinCutT MaxCutT C ₀ C ₁ C ₂ C ₃ BegRootD MaxRootD RootGC] read* NCROPS times with [5] if IRTFL = 3, or ICUFL = 3, or IPFL = 3	
16	[TimeSeriesStep MaxT MinT Precip ETref] read* LENSIM times with [5] if IRTFL = 3, or ICUFL = 3, or IPFL = 3 (LENSIM = length of simulation expressed as total number of time-series steps; length of time-series step defined by ITMUNI in the Discretization File)	
17	[Crop-ID IFALLOW] read* NCROPS times with [7] if IDEFFL = -2	
18	[Crop-ID WPF-Slope WPF-Int Crop-Price] read* NCROPS times with [5] if IDEFFL > 0 and if IBEN = 1	
19	Farm-ID GWcost1 GWcost2 GWcost3 GWcost4 SWcost1 SWcost2 SWcost3 SWcost4] read* NFARMS times with [5] if IDEFFL > 0 and ICOST = 1	
20	[Farm-ID Row Column Segment Reach] read* NFARMS times with [7] if ISRDFL = 1	

Data for each Stress Period

Item No.	Input instruction for each item
21	ITMP NP read
22	[Layer Row Column Farm-Well-ID Farm-ID QMAX] [xyz] read* ITMP times with [3] if ITMP > 0
23	[Pname] read NP times if NP > 0
24	[Farm-ID OFE] if IEFFL = read* NFARMS times with [5] if IEFFL = 2
25	[CID(NCOL,NROW)] read* with [1] if IROTFL = -1
26	[Crop-ID ROOT] read* NCROPS times with [4] if IRTFL = 2
27	[Crop-ID CU] read* NCROPS times with [4] if ICUFL = 2
28	[Crop-ID FTR FEP FEI] read* NCROPS times with [5] if IFTEFL = 2
29	[Crop-ID FIESWP FIESWI] read* NCROPS times with [5] if IIESWFL = 2
30	[PFLX(NROW,NCOL)] read* with [2] if IPFL = 2
31	[Crop-ID WPF-Slope WPF-Int Crop-Price] read* NCROPS times with [5] if IDEFFL > 0 and if IBEN = 2.
32	[Farm-ID GWcost1 GWcost2 GWcost3 GWcost4 SWcost1 SWcost2 SWcost3 SWcost4] read* NFARMS times with [5] if IDEFFL > 0 and ICOST = 2.
33	[Farm-ID (NRDV NRDR NRDU)Type1, ()Type2, ... () TypeMXNRDT] read* NFARMS times with [5] if INRDFL = 1. A maximum number of MXNRDT types of nonrouted deliveries is read for each farm. One set of variables NRDV, NRDR, and NRDU is read for a certain unranked type t_u of a nonrouted delivery by () _{Type t_u} .
34	[Farm-ID Row Column Segment Reach] read* NFARMS times with [7] if ISRDFL = 2
35	[ALLOT] read if IALLOT = 1
36	[Farm-ID CALL] read* NFARMS times with [5] if IALLOT = 2

Explanation of the use of Array-Reading Utility Modules

* In order to keep the structure of the FMP-data-input-file simple, it is recommended to specify for each respective line of the FMP-input-file, from which a utility module reads, one of the following:

- Name of a file or cross-reference to a file, from which the utility module will read the data array or list records (see use of the keywords "OPEN/CLOSE" and "EXTERNAL" below),
- Constant(s), in case 2D-arrays or lists may be lumped together.

	Utility-Module	FREE-FORMAT CONTROL RECORD options			
		CONSTANT	INTERNAL	EXTERNAL	OPEN/CLOSE
[1]	U2DINT	⊗	x	x	⊗
[2]	U2DREL	⊗	x	x	⊗
[3]	FMP1WELRD		x	x	⊗
[4]	FMP1LSTRD	⊗	x	x	⊗
[5]	FMP1DPLSTRD	⊗	x	x	⊗
[6]	FMP1DPWDLSTRD	⊗	x	x	⊗
[7]	FMP1INTLSTRD	⊗	x	x	⊗

⊗ Constants or file-names are recommended in order to maintain a line-by-line FMP1 input file structure for each input item.

x Internal arrays or unit numbers for external files are technically possible, but the user has to define such unit numbers in the Name File. However, if data are desired to be read from the same file for multiple stress periods, then cross-referenced "external" files are of advantage, since they remain open.

Input Structure of Array and List Reading Utility Modules

A control record item “a” is read from the FMP1 input file by all utility modules. A keyword signals whether to use a lumped constant value for 2D-arrays or data lists, or whether to read 2D-data arrays and data lists internally from the FMP1 input file or externally from a data file. For 2D-data arrays read by standard MF2K utility modules, a “Multiplier Constant” can be applied to scale any input data array.

For data lists read by FMP-embedded list reading utility modules, a second control record item “b” is optionally read if the use of scale factor multipliers is desired. If item b is included, the respective line must begin with “SFAC.” For internal data lists, this control record item b is read from the next line of the FMP1 input file. For external lists, item b is read from the first line of the external data file.

Control-Record Item a

Module	Keyword	Constant(s) or cross-reference	Multiplier constant	Read format	Print flag
For the use of Standard MODFLOW 2D-array reading Utility Modules:					
[1]	CONSTANT	Integer Scalar			
	INTERNAL		1*	(FREE)**	-1***
	OPEN/CLOSE	FILENAME	1*	(FREE)**	-1***
	EXTERNAL	Nunit	1*	(FREE)**	-1***
[2]	CONSTANT	Real Scalar			
	INTERNAL		Real Scalar	(FREE)**	-1***
	OPEN/CLOSE	FILENAME	Real Scalar	(FREE)**	-1***
	EXTERNAL	Nunit	Real Scalar	(FREE)**	-1***
For the use of list reading Utility Modules embedded in the FMP1:					
[3],[4],[5],[6], [7]	CONSTANT	Real [3],[4] or Double Precision [5],[6], or Integer [7] Scalar(s)			
	INTERNAL				
	OPEN/CLOSE	FILENAME			
	EXTERNAL	Nunit			

* It is not recommended to “scale” 2D integer arrays of identifiers (such as farm-ID, crop-ID, or soil-ID).

** Since the FMP1 allows the use of free format, the user is advised to read 2D data arrays by the standard MODFLOW utilitymodules as well in free format.

*** It is not recommended to reprint known input data in order to avoid a very large listing file, where results are to be printed.

Keywords:

The keyword “CONSTANT” indicates that the scalar, which follows the keyword, represents a lumped value for 2D-arrays or for data lists with only one attribute. For data lists with multiple attributes, as many constants must be entered after the keyword “CONSTANT,” as fields are attributed to the multi-dimensional variable, while omitting the identifier attribute in the first field. Distributed data may be read as 2D arrays or as data lists either internally in the FMP1 input file, as indicated by the keyword “INTERNAL,” or externally from a file.

External data can be read by using a keyword of “OPEN/CLOSE” and thereafter specifying a filename directly in the FMP1 input file. The obvious advantage of using “OPEN/CLOSE” is that no further referencing of the file name in the Name File is necessary. However, each file will be closed after reading and no further use of that file for future stress periods is possible.

Alternatively, data can be read by using a keyword of “EXTERNAL” and specifying a file unit number, Nunit, in the FMP1 input file that cross-references to a file name contained in the name file and the key term “DATA.” The advantage of using “EXTERNAL” is that the file, from which a respective module reads, will not be closed and data for future stress periods can continuously be read from the same file.

Read Format:

The read format for the Standard MODFLOW 2D-array reading utility modules, [1] and [2], must either be a standard Fortran format that is enclosed in parenthesis, or “(FREE)” which indicates free format, or “(BINARY)” which indicates binary (unformatted) data. A suggested print flag of -1 indicates that an array should not be printed to the listing file after it has been read. For further instructions on use of array readers, print flags and associated codes, refer to Harbaugh and others (2000, p. 86) and Schmid (2004, p. 159).

The read format for the list reading utility modules embedded in the FMP1, [3],[4],[5], [6], and [7] is by standard in free format and therefore not required to be specified. The farm-wells list reading utility module [3] prints the read variables including auxiliary variables to the listing file in integer and scientific notation unless “NOPRINT” is not specified for {option} in item 2. The other, less complex, list reading modules, [4], [5], [6], and [7] do not re-print the read input data to the listing file.

Control-Record Item b

If item “b” is included, it must begin with the keyword “SFAC.” The keyword “SFAC” indicates whether a scale factor is to be multiplied with parameter values of a designated attribute or a range of attributes. Alternatively, a list of scale factors can be read from yet another external data file. If the control-record item “b” is not included, the Scale is 1.0.

Module	Keyword 1	Constant or keyword 2	Cross-reference
For the use of list reading Utility Modules embedded in the FMP1:			
[3],[4],[5],[6]	SFAC	Real ([3],[4]) or Double Precision ([5],[6]) Scalar(s)	
[5]	SFAC	OPEN/CLOSE	FILENAME
	SFAC	EXTERNAL	Nunit

Constant Scale Factor:

A scale factor can be applied to all lists read by the utility modules embedded in the FMP1, [3], [4], [5], and [6]. For each item, a constant real or double precision scalar may be multiplied by the parameter value(s) associated with the following respective attribute or range of attributes:

Item	SFAC applies to parameter(s)	Read by module
4.	QMAXfact	[3]
7.	OFE	[5]
9.	CapFringe	[6]
11.	ROOT	[4]
12.	FTR,FEP,FEI	[5]
13.	FIESWP, FIESWI	[5]
14.	PSI(1), PSI(2), PSI(3), PSI(4)	[5]
19.	GWcost1, GWcost2, GWcost3, GWcost4, SWcost1, SWcost2, SWcost3, SWcost4	[5]
22.	QMAX	[3]
24.	OFE	[5]
26.	ROOT	[4]
27.	CU	[4]
28.	FTR, FEP, FEI	[5]
29.	FIESWP, FIESWI	[5]
32.	GWcost1, GWcost2, GWcost3, GWcost4, SWcost1, SWcost2, SWcost3, SWcost4	[5]
36.	CALL	[5]

For items 4 and 22, the values of the list variables that are automatically printed to the listing file include the effect of the Scale.

List of Scale Factors:

A list of scale factors can be applied to parameters of a data list that requires different multipliers for each parameter. This option is available only for lists read by utility module [5]. As before, item b must begin with the first keyword "SFAC." A second control record keyword indicates whether the file containing the list of scale factors is specified directly by its file name, or by a file unit number, that cross-references to a file name contained in the Name File.

The first column in a list of scale factors contains the attribute or field number of a data list. The second column contains the individual scale factor for each respective attribute. For example, multiple scale factors for the three different attributes (1: WPF-Slope, 2: WPF-Int, 3: Crop-Price) in item 18 could be defined as follows:

Attribute	Scale factor
1	1.0
2	2.0
3	1.0
4	10.0

The first attribute always defines an ID, which is why the scale factor always must be 1.0. Parameters related to any other attribute that is not to be scaled, must also be equipped with a scale factor of one. In the example, the slope of the water-production function was multiplied by 2.0, and the crop market price per unit weight was multiplied by 10.

Explanation of Fields Used in the Input Instructions

Dimensions and Flags (item 2)

Parameter Dimensions (item 2)

NPFWL	Number of farm well parameters (changeable parameter is a multiplier of the maximum capacity)
MXL	Maximum number of parameter farm wells.
MXACTFW	Maximum number of active farm wells including parameter and nonparameter farm wells. Nonparameter farm wells are wells, whose maximum capacity is different for each stress period. In this case, each well-list (layer, location, farm-well farm ID, max. capacity) would have to be read for each stress period. However, since the maximum capacity in most cases is thought to be constant for the entire simulation, usually the maximum number of nonparameter farm-wells will be zero, that is, MXL = MXACTFW.
NFARMS	Number of farms
NCROPS	Number of crop types
NSOILS	Number of soil types

'When-to-Read-Flags' (item 2):

When-to-Read-Flags indicate, when to read or calculate a variable:

1 = specified for the entire simulation

2 = specified for each stress period

3 = calculated as average for each time step from time series

IRTFI Root depth flag (1,2,3 possible)

ICUFL Consumptive use flag (2,3 possible)

IPFL Precipitation flag (2,3 possible)

IFTEFL Fraction-of-transpiration-and-evaporation-of-crop-consumptive-use flag (1,2 possible)

70 User Guide for the Farm Process (FMP1) for the U.S. Geological Survey's MODFLOW-2000

IIESWFL Fraction-of-inefficiency-losses-to-SW-runoff flag (0,1,2 possible)
(0 = The fraction of inefficiency losses to surface-water runoff is proportional to the slope of ground surface. The slope is estimated by the FMP1 by a third order finite difference method using all eight outer points of the 3×3 kernel surrounding the cell. The slope is not calculated at cells directly adjacent to the boundary of the grid domain. Thus, farm boundaries must not reach the model boundary if IIESWFL is zero. There is no data input required for FIESWP and FIESWI if IIESWFL is zero.)

IEFFL Efficiency Flag (1, 2 possible)

Water Policy Flags (item 2):

IEBFL Efficiency Behavior Flag

1 = Conservative Behavior – Constant Efficiency over Time Step

2 = Conservative Behavior – Constant Delivery over Time Step with evaluation of initial total delivery requirement (TDR) per cell at first iteration of first time step of each stress period.

3 = Conservative Behavior – Constant Delivery over Time Step with evaluation of initial total delivery requirement (TDR) per cell at first iteration of each time step.

IROTFL Crop rotation flag:

< 0 Crop Type changes temporally and spatially at every stress period (CID 2D array is read for each stress period)

= 0 No crop rotation (CID 2D array is read for the entire simulation)

> 0 No crop rotation (CID 2D array is read for the entire simulation), and
IROTFL = Stress period that is equal to Non-Irrigation Season

IDEFFL Deficiency Scenario flag:

-2 = Water Stacking

-1 = Deficit Irrigation

0 = "Zero Scenario" where no policy is applied and if demand exceeds supply, it is assumed to be supplied by other imported sources

1 = Acreage-Optimization

2 = Acreage-Optimization with Water Conservation Pool

(only if SFR1 is specified in Name File, if a diversion from a river segment into a canal segment is specified (IALLOT = 1), and if routed or semi-routed deliveries from such a canal into farms occur (IRDFL = 0; ISRDFL = 1).

IBEN Crop-Benefits Flag (only to specify if IDEFFL > 0):

1 = crop benefits list read for the entire simulation

2 = crop benefits list read for each stress period

ICOST Water-Cost Coefficients Flag (only to specify if IDEFFL > 0):

0 = lumped water cost coefficients for the entire simulation

1 = water cost coefficients for each farm for the entire simulation

2 = water cost coefficients for each farm for each stress period

Crop Consumptive-Use Flag (item 2):

ICCFL Concept used for the approximation of ET-fluxes with changing head:

1 – for consumptive use Concept 1 = plant-and soil-specific pseudo steady state transpiration approximated by analytical solution:

A restriction of active root zone corresponding to anoxia- or wilting-related pressure heads is determined by the FMP1 by using analytical solutions of a vertical pseudo steady state pressure head distribution over the depth of the total root zone.

2 – for consumptive use Concept 2 = nonplant- and nonsoil-specific simplification of Concept 1

Surface-Water Flags (item 2):

INRDFL Nonrouted Surface-Water Delivery Flag:

0 = no Nonrouted Surface-Water Delivery exists.

1 = Nonrouted Surface-Water Deliveries exist. A farm related list of Volumes, Ranks, and Use-Flags of Nonrouted Surface-Water Delivery will be read.

MXNRDT Maximum number of nonrouted delivery types (read if INRDFL = 1).

ISRDFL Semi-Routed Surface-Water Delivery Flag:

0 = no Semi-Routed Surface-Water Delivery exists

1 or 2 = Semi-Routed Surface-Water Deliveries exist. (Routing surface-water along a river or major canal, and allocating nonrouted deliveries from a point of diversion). A farm related list of Row- and Column-coordinates for a point of diversion will be read (only if SFR1 is specified in Name File).

1 = List of Row- and Column-coordinates is read for the entire simulation.

2 = List of Row- and Column-coordinates is read for each stress period.

IRDFL Routed Surface-Water Delivery Flag:

0 = no surface-water delivery exists.

1 = routed surface-water delivery using SFR1 exist. Streamflow routed through a conveyance network to a farm (only if SFR1 is specified in Name File).

IRDFLG

A flag of the SFR1, which, if positive, is used to define the method of calculation for the elevation of the midpoint of a diversion segment reach. The choice between IRDFLG = 0 and IRDFLG = 1 is an addendum to the SFR1 code and, therefore, is only described here and not in the SFR1 input instructions (Prudic and others, 2004, p.49). The user is referred to the SFR1 input instructions regarding the location of the IRDFLG flag, which is part of the SFR1 data input block that is read for each stress period.

0 = Elevation of top of streambed of diversion segments (canals/laterals) is interpolated between elevation of upstream and downstream ends of segments, as specified in SFR input file (SFR1 input data for a stress period are printed to the list file).

1 = Streamflow Routed through a Conveyance Network to a Farm (only if SFR is specified in Name File). Elevation of top of streambed of all segments that are not diversion segments is interpolated between the elevation of the upstream and downstream ends of the segments, as specified in SFR input file.

Elevation of top of streambed of diversion segments (canals/laterals) follows the slope of ground surface at a depth defined by the interpolation of:

- (1) the difference between the ground surface elevation and the elevation of the upstream end of a diversion segment, as specified in the SFR input file; and
- (2) the difference between the ground surface elevation and the elevation of the downstream end of a diversion segment, as specified in the SFR input file.

Note limitation: IRDFLG = 1 cannot be chosen if the number of the diversion segment is equal to the total number of segments (SFR1 input data for a stress period are not printed to a list file).

IALLOT

Surface-water allotment flag

0—No surface-water allotment specified,

1—Equally appropriated surface-water allotment height [L] specified per stress period (specification of diversions from a river into canals in SFR1 input file required if ISRDFL = 1 or 2, or IRDFL = 1).

2—Prior appropriation system with Water Rights Calls [L^3/T] (diversion rates from a river into canals are simulated

if ISRDFL = 1 or 2, or IRDFL = 1; specification of a farm-specific water rights calls list required for each stress period).

3—Prior appropriation system without Water Rights Calls [L^3/T] (diversion rates from a river into canals are simulated

if ISRDFL = 1 or 2, or IRDFL = 1).

PCLOSE

User specified closure criterion for simulated canal diversions if prior appropriation is chosen [L^3/T] (only to specify if IALLOT > 1)

Mandatory Print Flags (item 2):

- IFWLCB** Farm well budget print flags
- < 0 A list (farm-well ID, farm ID, layer, row, column, farm-well flow rate) is printed to list file for time steps, for which in Output Control "Save Budget" is specified (using words) or ICBCFL is not zero (using numeric codes)
 - = 0 farm-well flow rates not written
 - = 1 A list (farm-well ID, farm ID, layer, row, column, farm-well flow rate) is saved on ASCII file "FWELLS.OUT" for all time steps
 - > 1 if "Compact Budget" is not specified in Output Control:
 - A cell-by-cell 2D-array of farm-well flow rates will be saved as binary file on a unit number specified in the Name File for time steps, for which in Output Control "Save Budget" is specified (using words) or ICBCFL is not zero (using numeric codes).
 if "Compact Budget" is specified in Output Control:
 - A list (node, farm-well flow rate) will be saved as binary file on a unit number specified in the Name File for time steps, for which in Output Control "Save Budget" is specified (using words) or ICBCFL is not zero (using numeric codes).
- IFNRCH** Farm net recharge budget print flags
- < 0 A cell-by-cell 2D-array of farm net recharge flow rates is printed to list file for time steps, for which in Output Control "Save Budget" is specified (using words) or ICBCFL is not zero (using numeric codes)
 - = 0 farm net recharge flow rates not written
 - = 1 A cell-by-cell 2D-array of farm net recharge flow rates is saved on ASCII file "FNRCH_ARRAY.OUT" for all time steps
 - = 2 A list (stress period, time step, total time, farm ID, cumulative farm net recharge flow rates) will be saved as ASCII file "FNRCH_LIST.OUT"
 - = 3 A list (stress period, time step, total time, farm ID, cumulative farm net recharge flow rates) will be saved as binary file "FNRCH_LIST_BIN.OUT" for all time steps
 - > 3 if "Compact Budget" is not specified in Output Control:
 - A list (farm ID, cumulative farm net recharge flow rates) will be saved as binary file on a unit number specified in the Name File for time steps, for which in Output Control "Save Budget" is specified (using words) or ICBCFL is not zero (using numeric codes).
 if "Compact Budget" is specified in Output Control:
 - if number of model layers = 1:
 - A cell-by-cell 2D-array of farm net recharge flow rates will be saved as binary file on a unit number specified in the Name File for time steps, for which in Output Control "Save Budget" is specified (using words) or ICBCFL is not zero (using numeric codes)
 - if number of model layers > 1:
 - A 2D integer-array of each cells uppermost active layer, and a 2D real-array of each cell's farm net recharge flow rate will be saved as binary file on a unit number specified in the Name File for time steps, for which in Output Control "Save Budget" is specified (using words) or ICBCFL is not zero (using numeric codes)
- ISDPFL** Farm supply and demand print flags
- = -3 A list (A) of current demand and supply flow rates will be printed to the list file at each iteration, and a list (B) of final demand and supply flow rates will be printed to the list file for each time step:
 - List (A): (FID, OFE, TFDR, NR-SWD, R-SWD, QREQ);
 - List (B): (FID, OFE, TFDR, NR-SWD, R-SWD, QREQ, Q, [COMMENTS])
 - = -2 A list of final demand and supply flow rates will be printed to the list file for each time step:
 - List: (FID, OFE, TFDR, NR-SWD, R-SWD, QREQ, Q, [COMMENTS])
 - = -1 A list of final demand and supply flow rates will be printed to the list file for time steps, for which in Output Control "Save Budget" is specified (using words) or ICBCFL is not zero (using numeric codes):
 - List: (FID, OFE, TFDR, NR-SWD, R-SWD, QREQ, Q, [COMMENTS])
 - = 0 farm demand and supply flow rates not written
 - = 1 A list of initial demand and supply flow rates and of final demand & supply flow rates after the application of a deficiency scenario will be saved on ASCII file "FDS.OUT" for all time steps:

List: (PER, TSTP, TIME, FID, OFE, TFDR-INI, NR-SWD-INI, R-SWD-INI, QREQ, TFDR-FIN, NR-SWD-FIN, R-SWD-FIN, QREQ, Q, DEF-FLAG)

- > 1 if "Compact Budget" is not specified in Output Control:
 - A list of initial demand & supply flow rates and of final demand and supply flow rates after the application of a deficiency scenario will be saved as binary file on a unit number specified in the Name File for all time steps
 - List: list attributes are equal to ISDPFL = 1
- if "Compact Budget" is specified in Output Control:
 - A list of initial demand & supply flow rates and of final demand & supply flow rates after the application of a deficiency scenario will be saved as binary file on a unit number specified in the Name File for time steps, for which in Output Control "Save Budget" is specified (using words) or ICBCFL is not zero (using numeric codes)
 - List: list attributes are equal to ISDPFL = 1

Optional Print Flags (item 2):

IOPFL

Optional print settings if Acreage-Optimization is chosen (if IDEFFL > 0)

- = -4 A tableaux matrix will be printed to the list file for iterations, during which optimization occurs.
- = -3 Original and optimized flow rates of resource constraints and a list of fractions of optimized cell areas will be printed to the list file for any farm and iteration that are subject to optimization:

List:	(Row,	Column,	Crop ID,	A-tot-opt/	A-gw-opt/	A-sw-opt/	A-nr-opt/
				A-tot-max,	A-tot-opt,	A-tot-opt,	A-tot-opt)
- = -2 Original and optimized flow rates of resource constraints will be printed to the list file for any farm and iteration that are subject to optimization
- = -1 A cell-by-cell 2D-array of fractions of active cell acreage will be printed to the list file for all time steps.
- = 0 No original & optimized flow rates, and no optimized cell areas are written.
- = 1 A cell-by-cell 2D-array of fractions of active cell acreage is saved on ASCII file "ACR_OPT.OUT" for all time steps.
- = 2 Original and optimized flow rates of resource constraints are saved on ASCII file "ACR_OPT.OUT" for any farm and iteration that are subject to optimization.
- = 3 Original and optimized flow rates of resource constraints and a list of fractions of optimized cell areas is saved on ASCII file "ACR_OPT.OUT" for any farm and iteration that are subject to optimization:

List:	(Row,	Column,	Crop ID,	A-tot-opt/	A-gw-opt/	A-sw-opt/	A-nr-opt/
				A-tot-max,	A-tot-opt,	A-tot-opt,	A-tot-opt)
- = 4 A tableaux matrix is saved on ASCII file "ACR_OPT.OUT" for iterations, during which optimization occurs.

IPAPFL Optional print settings if Prior Appropriation is chosen (if IALLOT >1)

- = -1 A budget at the point of canal-diverions from the river and a budget at the point of a farm-diversion from the canal will be printed to the list file for all iterations.
- = 1 A budget at the point of canal-diverions from the river and a budget at the point of a farm-diversion from the canal will be saved on ASCII file "PRIOR.OUT" for all iterations.

Optional Flags (item 2):

AUX "abc" Defines an auxilliary variable, "abc", which will be read for each farm-well as part of items 4 and 22. Up to five auxilliary attributes "abc" can optionally be specified, each of which must be preceded by "AUX." These values will be read after the QMAXfact or QMAX variable of item 4 or item 22, respectively.

AUX QMAXRESET	The specification of the optional flag "AUX QMAXRESET" for {option} in item 2 will prompt the FMP1 to reset QMAX as simulated by the MNW package to the default QMAX as defined by FMP1 at the beginning of each time step. The optional flag "AUX QMAXRESET" requires FMP1 to read an auxiliary variable in column 7 of the farm wells list in items 4 or 22. If a "1" is read in column 7 of the farm wells list, then the MNW-simulated QMAX is reset to the default QMAX in the first iteration of each time step.
CBC	Indicates that memory should be allocated to store cell-by-cell flow for each well to make these flows available for use in other processes.
NOPRINT	Indicates that a list of specified farm well attributes will not be printed to the list file

Farm-Well Related Variables (items 3, 4, 22, 23)

Farm Well Parameter Definition (item 3):

PARNAM	Parameter name for list of parameter farm-wells (called for each stress period to activate a list of parameter wells). This name can consist of 1 to 10 characters and is not case sensitive.
PARTYP	Parameter type (the only allowed parameter type is QMAX, which defines values of the volumetric maximum well capacity).
PARVAL	Parameter value (multiplier applied to parameter-wells).

Farm-Wells List (items 4, 22):

Layer	Layer number of cell containing the farm-well (for farm-wells linked to multi-layer wells defined in the Multi-Node Well package: Layer No. = 0)
Row	Row number of cell containing the farm well
Column	Column number of cell containing the farm well
Farm-Well-ID	Farm-well identity associated with the farm well (to establish a link of a farm-well to a well defined in the Multi-Node Well package: use "negative" Farm-Well-ID)
Farm-ID	Farm identity to which the farm-well is attributed
QMAXfact	Maximum Well Capacity factor ($QMAXfact \times PARVAL = QMAX$) [L^3/T].
QMAX	Maximum Well Capacity [L^3/T] (positive value = maximum possible discharge rate)
[xyz]	Represents any auxiliary variables for a farm-well that have been defined in item 2. The auxiliary variables must be present in each repetition of items 4 and 22. If the optional flag for {Option} in item 2 is set to "AUX QMAXRESET," then the auxiliary variable for [xyz] in column 7 of the farm wells list is defined to be a binary parameter that tells when to reset the MNW-simulated QMAX rate to the FMP1-defined default QMAX rate. The parameter in column 7 of the well list is ignored, if the option flag "AUX QMAXRESET" is not specified. 0 = The MNW-simulated QMAX is reset at the beginning of each stress period. 1 = The MNW-simulated QMAX is reset at the beginning of each time step.

Farm-Well Flags and Dimensions for each Stress Period (items 4, 22, 23):

NLST	Number of parameter farm-wells included in the parameter-well-list related to one parameter.
ITMP	flag and counter > 0 ITMP = number of nonparameter farm-wells read for the current stress period. = 0 no nonparameter farm-wells are read for the current stress period. < 0 nonparameter farm-well data from the last stress period will be reused.
NP	Number of multiplier parameters in use in the current stress period.
Pname	Name of multiplier parameter that is being used in the current stress period. NP parameter names will be read.

Two-Dimensional Arrays (items 5, 6, 8, 10, 25, 30)

GSURF	Ground-surface elevation
FID	Farm identity
SID	Soil type identity
CID	Crop type identity
PFLX	Precipitation flux (see climate related data) [L/T]

Farm Related Data Lists (items 7, 19, 20, 24, 32, 33, 34, 36)

Farm-ID	Farm identity to which the parameters below are attributed	
OFE	On-farm Efficiency per farm (real number between 0 and 1; $0 < OFE \leq 1$.)	
GWcost1,2,3,4 SWcost1,2,3,4	} definitions see “Water Cost Coefficients” below	
NRDV NRDR NRDU		} definitions see “Nonrouted Surface-Water Deliveries” below
Row Column Segment Reach	} definitions see “Semi-Routed Surface-Water Deliveries” below	
CALL		

Soil Type Related Data List (item 9)

Soil-ID	Soil type identity to which the parameters below are attributed
CapFringe	Capillary Fringe [L]

The following parameters are only needed if ICCFL = 1:

Either:

A-Coeff, B-Coeff, C-Coeff Coefficients a, b, c for function $DRZ = f(T_{c-pot}, TRZ)$

D-Coeff, E-Coeff Coefficients d, e for function $n = f(DRZ)$

Or:

Soil-Type Soil type in words:

3 options are available:

SANDYLOAM, SILT, and SILTYCLAY (not case-sensitive).

(For these three options, the FMP1 code contains intrinsic soil type specific coefficients a,b,c and d,e for the functionalities $DRZ = f(T_{c-pot}, TRZ)$ and $n = f(DRZ)$. If a soil type is entered as a word, then a,b,c,d,e are not read).

The intrinsic coefficients in the program are as follows (Schmid, 2004):

Soil type	a	b	c	d	e
SANDYLOAM	0.201	-0.195	3.083	3.201	-3.903
SILT	0.320	-0.329	2.852	1.303	-2.042
SILTYCLAY	0.348	-0.327	1.731	0.530	-0.377

The parameters DRZ and n allow the fitting of a vertical pseudo steady state pressure head distribution over the total root zone:

- (3) The Depleted Root Zone (DRZ) is a function of the potential Transpiration and the Total Root Zone. It is defined as the lower part of the root zone at which the pressure head increases with depth from the minimum (negative) pressure head (defined as ψ_4 in stress response function, see below) to zero at the bottom of the root zone.

$$DRZ=[exp(a \cdot \ln(TRZ \cdot MLT)+b \cdot \ln(TPOT \cdot MLT)+c)]$$

- (4) The Sinuosity Coefficient (n) expresses the curvature of the vertical pressure head configuration over depth, which increases with increasing DRZ.

$$NEXP=d \cdot \ln(DRZ)+e$$

Although the intrinsic parameters a,b,c,d,e were derived based on CENTIMETER length units, multipliers in the program (MLT) can adjust the equations accordingly to length units of METER or FEET, if so chosen as LENUNI = 2 or = 1 in the Discretization file (Harbaugh and others, 2000).

Crop-Type-Related Data List (Natural Crop Growth Parameters) (items 11–15, 25–29)

Crop-ID	Crop type identity, to which the parameters below are attributed
ROOT	Depth of root zone [L]
CU	Consumptive use flux [L/T]
FTR	Transpiratory fraction of consumptive use ($0 < FTR \leq 1$)
FEP	Evaporative fraction of consumptive use related to precipitation ($0 \leq FEP \leq 1$)
FEI	Evaporative fraction of consumptive use related to irrigation ($0 \leq FEI < 1$)
FIESWP	Fraction of in-efficient losses to surface-water related to precipitation ($0 \leq FIESWP \leq 1$)
FIESWI	Fraction of in-efficient losses to surface-water related to irrigation ($0 \leq FIESWI \leq 1$)
PSI(1)	Absolute value of negative pressure head, at which root uptake becomes zero due to anoxia (absolute value > 0) [L]
PSI(2), PSI(3)	Absolute values of negative pressure heads, between which root uptake is optimal (absolute value > 0) [L]
PSI(4)	Absolute values of negative pressure head, at which root uptake becomes zero due to wilting (absolute value > 0) [L]
BaseT	Base temperature
MinCutT	Minimum cutoff temperature
MaxCutT	Maximum cutoff temperature
C_0, C_1, C_2, C_3	Polynomial coefficients for CGDD – K_c functionality (see Chapter “General Data Requirements”)
BegRootD	Beginning root depth [L]
MaxRootD	Maximum root depth [L]
RootGC	Root growth coefficient

Climate-Related Data (items 16, 30)

Climate Time Series (item 16):

TimeSeriesStep	Time-step in climate time series. The length of a time series time step must consistently be equal to the MODFLOW time unit chosen in the Discretization File (ITMUNI). For ICUFL = 3 or IRTFL = 3, the MODFLOW time unit must be days (ITMUNI = 4). For IPFL = 3 (while ICUFL \neq 3, and IRTFL \neq 3), all MODFLOW time units are possible (seconds, minutes, hours, days, years; ITMUNI = 1, 2, 3, 4, 5). However, ITMUNI = 1 or 2 for units of seconds or minutes should be avoided for very long periods of simulation due to the possibility of insufficient computer memory.
Precip	Precipitation flux [L/T]

MaxT	Maximum temperature
MinT	Minimum temperature
ETref	Reference Evapotranspiration flux [L/T]
LENSIM	Total number of steps in a time series = length of the simulation.

Precipitation Array (item 30):

PFLX	Precipitation Flux Array or Constant [L/T]
------	--

Crop-Type-Related Data Lists (Agro-Economic Parameters) (items 17, 18, 31)

Fallow List (item 17):

Crop-ID	Crop-type identity to which the parameter below is attributed.
IFallow	Fallow-Flag: 1 = Crop type fallowed 0 = Crop type not fallowed (for example, pecan trees)

Crop Benefits List (items 18, 19):

Crop-ID	Crop-type identity to which the parameters below are attributed.
WPF-Slope	Slope of crop-specific water-production function (yield vs. ET_{crop})
WPF-Int	Intercept of crop-specific water-production function (yield vs. ET_{crop}) (can be zero).
Crop-Price	Market-price per crop [value/weight]

Water Cost Coefficients (items 19, 32)

Farm-ID	Farm identity to which the cost coefficients below are attributed.
---------	--

Ground-Water Cost Coefficients:

GWcost1	Ground water Base Maintenance Costs per unit volume [$\$/L^3$]
GWcost2	Ground water Costs for Pumping in Well per unit volume, per unit lift [$\$/L^3 \cdot L$]
GWcost3	Ground water Costs for Vertical Lift from Well to Cell per unit volume, per unit lift [$\$/L^3 \cdot L$]
GWcost4	Ground water Delivery Costs per unit volume, per unit distance [$\$/L^3 \cdot L$]

Surface-Water Cost Coefficients:

SWcost1	Fixed Price of (Semi-) Routed Surface-Water per unit volume [$\$/L^3$]
SWcost2	Costs for Vertical Lift of (Semi-)Routed Surface-Water from Reach to Cell per unit volume, per unit lift [$\$/L^3 \cdot L$]
SWcost3	Delivery Costs of (Semi-)Routed Surface-Water per unit volume, per unit distance [$\$/L^3 \cdot L$]
SWcost4	Fixed Price of Nonrouted Surface-Water per unit volume [$\$/L^3$]

Nonrouted Surface-Water Deliveries—Farm-Related Data List (item 33)

Farm-ID	Farm identity to which the parameter below are attributed
NRDV	Volume of Nonrouted Delivery Type [L^3]
NRDR	Rank of Nonrouted Delivery Type
NRDU	Binary “NRD _{use} -Flag” of Nonrouted Delivery Type: if 0: only the amount sufficient is used to meet the farm’s demand, if 1: the absolute amount available is used; surplus recharged into canal at farm’s head gate. if 2: the absolute amount available is used; surplus injected into farm wells attributed to farm ID.

Semi-Routed Surface-Water Deliveries–Farm-Related Data List (items 20, 34)

Farm-ID Farm identity to which the parameter below are attributed
 Row Row number of point of diversion
 Column Column number of point of diversion
 Segment Number of stream segment in which the diversion reach is located (must be equal to the number of the identical stream reach specified in the SFR1 input file)
 Reach Number of reach from which diversion occurs (must be equal to the number of the identical reach specified in the SFR1 input file)

Five options of data input (marked by x) are available in order to uniquely identify the point of diversion within a cell:

Row	Column	Segment	Reach	Comments	
x	x	x	x	full set of information is available	(maximum information)
x	x	x	0/-	if more than one segment pass through the cell	(user prefers identification of location by coordinates)
x	x	0/-	0/-	if just one segment passes through the cell	
0	0	x	x	if more than one segment pass through the cell	user prefers identification of location by reach number
0	0	0	x	if more than one reach are within one cell	(minimum information)

Surface-Water Allotment (items 35, 36)

Equal Appropriation:

ALLOT Surface-water allotment height [L] for a stress period.

Prior Appropriation:

Farm-ID Farm identity to which the parameter below is attributed
 CALL Water Rights Call attributed to a farm [L³/T]

Output Data for Farm Process

Simulation results from the FMP1 can be reported to five auxiliary data sets in addition to the main MF2K listing and global files. These data sets consist of the following components. Various options to either print these data to the MF2K listing file or to save them to ASCII or binary files are controlled by the associated flags in parenthesis:

- (1) Farm-well budget (IFWLCB);
- (2) Farm net-recharge budget (IFNRCB);
- (3) Farm supply and demand budget (ISDPFL);
- (4) Optimized flow rates and optimized acreage of farms that experience a deficiency (IOPFL); only if acreage-optimization is chosen as a deficiency scenario (IDEFFL > 0);
- (5) Budget at the point of canal-diversions from the river and a budget at the point of a farm-diversion from the canal (IPAPFL); only if prior appropriation is chosen as surface-water rights option (IALLOT > 1).

Farm-Well Budget

The simulated farm-well flow rates can either be printed for each well location identified by layer, row, and column to the list file or saved to an ASCII file named “FWELLS.OUT.” In addition, farm-well flow rates can be saved to a binary file for each well location identified by the respective model node, or as a 2D-array for each cell.

Farm Net-Recharge Budget

Simulated farm net recharge flow rates can be printed as a 2D-array for each cell to the list file or to an ASCII file named “FNRCH_ARRAY.OUT.” Alternatively, a list of the cumulative farm net recharge for each farm can be saved to either an ASCII file named “FNRCH_LIST.OUT” or to a binary file named “FNRCH_LIST_BIN.OUT.” In addition, a list of cumulative farm net-recharge flow rates or a 2D-array of cell-by-cell farm net recharge flow rates can optionally be saved to binary files on a unit number specified in the Name File.

Farm Supply and Demand Budget

The simulated components of farm irrigation demand and supply of any current stage of solution during a time step (per iteration) and of the final demand and supply rates at the end of time steps or stress periods may be printed to list file:

Lists of current (iterative) and final farm demand and supply flow rates consist of the following parameters:

- | | |
|-------------|---|
| (1) FID | farm ID |
| (2) OFE | on-farm efficiency |
| (3) TFDR | total farm delivery requirement |
| (4) NR-SWD | non-routed surface-water delivery |
| (5) R-SWD | (semi-)routed surface-water delivery |
| (6) QREQ | ground-water pumping requirement |
| (7) (Q-FIN) | ground-water pumping (only available for list of final rates) |

Notice, that the list of “current” rates is iteratively updated within a present time step and does not yet contain a final supply flow rate from ground-water pumping, Q-FIN, which is available the end of a time step and therefore included into the list of final rates. For cases of irrigation water supply insufficiency, a comment is printed at the end of each record, informing about a possible imbalance of the farm demand and supply budget.

If the final supply exceeds the original or optimized demand by a certain flow rate X, then the following messages will be printed:

For Deficit Irrigation or Zero Scenario (IDEFFL = -1 or 0):

- “QREQ exceeds QMAXF by” X
- For Deficit Irrigation with Water-Stacking (IDEFFL = -2):

- “Original QREQ exceeded QMAXF by” X
- “QREQ of priority crops still exceeds QMAXF by” X

If, for Acreage-Optimization (IDEFFL > 0), the optimized demand is actually less than the original constrained surface-water or ground water resource (by a flow rate of X), then the following messages will be printed:

- “Surface-Water Demand falls behind original Surface-Water Supply by” X
- “Ground Water Demand falls behind original QMAXF by” X

Another, more comprehensive form of saving initial and final farm demand and supply budget is to save the according flow rates to an ASCII file named “FDS.OUT” for all time steps or alternatively to a binary file either for all or for selected time steps. Final rates only differ from initial ones, if either water-stacking or acreage-optimization was applied as deficiency scenario.

A list of initial and final farm demand and supply flow rates for all time steps consists of the following parameters (*table 3*):

Table 3. Summary of Farm Budget Components.

General Information:	
(1) PER:	Stress period
(2) STP:	Time step
(3) TIME [UNIT]:	Elapsed time (in units chosen in discretization file)
(4) FID:	Farm identification
(5) OFE:	Specified or calculated on-farm efficiency
Initial flow rates before invoking a deficiency scenario:	
(1) TFDR-INI:	Initial Total Farm Delivery Requirement
(2) NR-SWD-INI:	Initial Nonrouted Surface-Water Delivery
(3) R-SWD-INI:	Initial (Semi-) Routed Surface-Water Delivery
(4) QREQ-INI:	Initial Pumping Requirement
Final flow rates of a solution found by means a deficiency scenario:	
(1) TFDR-FIN:	Final Total Farm Delivery Requirement
(2) NR-SWD-FIN:	Final Nonrouted Surface-Water Delivery
(3) R-SWD-FIN:	Final (Semi-) Routed Surface-Water Delivery
(4) QREQ-FIN:	Final Pumping Requirement
(5) Q-FIN:	Final Pumping Rate
(6) DEF-FLAG:	Deficiency Scenario Flag

Optimized Flow Rates and Optimized Acreage of Farms

The user has various options of saving different data of interest, if acreage-optimization was chosen as a deficiency scenario (IDEFFL > 0). Fractions of active cell acreage will be printed as a 2D array either to the list file or saved to an ASCII file named "ACR_OPT.OUT" for all time steps. Alternatively, original and optimized flow rates of resource constraints may either be saved for each farm by themselves or in conjunction with a list of fractions of active cell acreage. This option will save the according data either to the list file or to an ASCII file named "ACR_OPT.OUT" for any farm and any iteration that are subject to optimization. For each cell (row, column) within an optimized farm, the list of fractions of cell acreage consists of the following parameters:

- A-tot-opt/A-tot-max fraction of total optimized acreage on total maximum acreage;
- A-gw-opt/A-tot-opt fraction of optimized ground-water irrigated acreage on total optimized acreage;
- A-sw-opt/A-tot-opt fraction of optimized (semi-)routed surface-water irrigated acreage on total optimized acreage;
- A-nr-opt/A-tot-opt fraction of optimized nonrouted surface-water irrigated acreage on total optimized acreage;

Users with specific interest in the definition of the linear optimization tableaux matrix may save this matrix either to the list file or to an ASCII file named "ACR_OPT.OUT." The number of columns in the tableaux matrix equals the number of optimization variables + 1. The number of rows in the matrix equals the number of constraints + 1.

Budgets at Points of Canal Diversion and Farm Diversion

A budget at the point of canal-diversions from the river and a budget at the point of a farm-diversion from the canal are printed to the list file or to an ASCII file named "PRIOR.OUT" if Prior Appropriation is chosen as surface-water allotment option (IALLOT > 1). The "Prior Appropriation Subroutine" in FMP1 solves (1) for the delivery to a farm from a canal and (2) for the diversion into the respective canal from a river. Solutions for (1) and (2) are found iteratively. The budgets for both points of diversion are therefore printed for any farm on an iterative basis. However, after having found solutions for (1) and for (2) for a certain farm, those solutions are not iterated anymore within a current time step. The output budgets for both points of diversion also informs whether a "convergence solution" or "exceedance solution" was found. A "convergence solution" is found if the surface-water delivery to the farm "converges" to the delivery requirement from the farms's head-gate reach. An "exceedance solution" is found if the necessary diversion from the river into the respective canal "exceeds" the river streamflow and consequently the diversion from the canal into a junior water rights farm will be insufficient to satisfy the delivery requirement from that farm's head-gate reach.

The output data set for each farm consists of three blocks of information:

Information about routing system during current iteration:

- Farm-ID;
- Head-gate reach number;
- Canal segment number;
- River segment number.

Budget at Point of Canal-Diversion from River:

- Qstr-in Inflow to point of diversion at the end of current stream segment;
- Qstr-out Outflow from point of diversion past the end of current stream segment;
- Qstr-min Minimum river-streamflow requirement at point of diversion from stream that is not available for diversion to the current farm (necessary to account for the demand and for related conveyance losses to a downstream farm senior farm located at a downstream diverting canal);
- ADIV Actual diversion rate from stream into current canal segment;
- PDIV Potential diversion rate from stream into current canal segment.

Budget at Point of Farm Diversion from Canal:

- RDEL-req Delivery requirement from current head-gate reach;
- Qcn-in Inflow to point of diversion from current canal at beginning of current head-gate reach;
- Qcn-out Outflow from point of diversion from current canal past the beginning of current head-gate reach;
- Qcn-min Minimum canal-streamflow requirement at point of diversion from canal that is not available for farm "f" at its head-gate (necessary to account for senior farm on the same canal);
- DELIVERY surface-water delivery to current farm from current head-gate reach at present iteration.

Comments:

STAGE: A record (in quotes) is printed informing about the current stage of the "prior appropriation" algorithm; three different stages are possible.	RESULT: A record (in quotes) is printed informing about the action taken at a certain stage of the algorithm; three different results are possible at two different stages.
"INITIAL VALUES" (initial values at beginning of algorithm are printed)	
"CUMULATE PDIV" (values are printed after cumulating PDIV by the unsatisfied increment [RDELreq. - Qcn-in])	"Exit and apply new PDIV rates" (exit MF2K and solve with incremented PDIV)
"SOLUTION" (final values are printed once a solution was found)	"Convergence Solution" "Exceedance Solution"

Example Problems

Two hypothetical example problems were simulated with MF2K using the FMP1 jointly with the SFR1 package. The first problem demonstrates the case of equal appropriation of surface water deliveries and the second problem invokes prior appropriation to surface-water deliveries and includes a simple example of a deficiency scenario that used acreage optimization to balance demands with supplies of water. While not all features of the FMP1 are included in these two examples, they illustrate many of the fundamental features needed for many regional hydrologic models that include simulations of supply and demand related to irrigated agriculture.

The two example problems are based on a common hydrologic framework with a single aquifer represented with a single model layer and with areally constant hydraulic properties (*fig. 16, Appendix*). Identical hydraulic properties, no-flow boundaries on the eastern and western boundaries, general-head boundaries on the northern and southern boundaries, and a common streamflow and canal network are used for both problems (*fig. 16*). The model domain consists of an alluvial valley with a slight inclination from west to east, so that the streamflow in canals can follow down the sloped land surface due to gravity (*fig. 16*). A predevelopment steady state simulation with a general-head boundary and a stream-canal-drain network was used to estimate initial heads (*fig. 16*). A development transient-state simulation with the FMP1 then included the farms with crops for the two example problems. The development simulations span a period of 1 year with four 3-month stress periods and weekly time steps. Data sets for the two example problems, including input for all model packages, are given in the *Appendix*.

The examples include four farms (*figs. 17A, B*), with three types of crops (alfalfa, pecans, and onions) with no crop rotation or fallow periods (*fig. 17C*), three soil types (silt, silty clay, and sandy loam) (*fig. 17D*), and a total of ten farm wells (*figs. 17A, B*). Some of the farm wells are coincident with the farms and several are located in areas not coincident with the farms. Note that farm 1 in example problem 1 does not extend to the irrigation canal to facilitate a semi-routed surface-water delivery not adjacent to the diversion canal (*fig. 17A*). In addition, the farms are sequentially numbered in downstream order for example problem 1, but are reordered to reflect surface-water water-rights rankings for example problem 2. Both problems use the consumptive use concept 1 with the three specified soil types that refer to internally stored analytical solutions specific for these soil types and are cross referenced to the soil-ID map (*fig. 17D*). Both problems use fully routed surface-water deliveries with the slopes of the diversion canals interpolated from the endpoints of the canal segments. Both problems have a river/canal system composed of 11 segments that use a constant river streamflow into the problem area of 50,000 m³/d (*fig. 16*). A total number of ten farm wells have different maximum pumping capacities (*figs. 17 A,B*). In example problem 1, the cumulative maximum capacities of all farm wells in a farm are 6,000 m³/d for three farms (farms 1, 2, and 3 in example problem 1; farms 1, 3, 4 in example problem 2) and 8,000 m³/d for one farm (farm 4 in example problem 1; farm 2 in example problem 2). Both problems also simulate four types of nonrouted deliveries with some of these deliveries representing interstate or international water transfers for example problem 2.

In the first example problem with equal surface-water appropriation, many of the crop, climate, and farm attributes are allowed to vary. For example, the root depths, crop consumptive uses, precipitation, fractions of transpiration and evaporation from consumptive use, and farm irrigation efficiency are specified for each stress period. The fractions of losses to inefficient surface-water runoff are chosen to be proportional to the slope of the ground surface, and the farm irrigation efficiency behavior is considered conservative with efficiency being constant over a time step. There are up to four types of nonrouted delivery sources to each farm. In addition to fully routed surface-water deliveries, this problem also has one semi-routed delivery to farm 1 (*fig. 17A*) with diversion model coordinates (row, column) = (3, 5) (surface-water routed along a canal; non-surface-water routed by pipeline). For eight out of ten farm wells, a parameter factor is assigned to the maximum well capacity. Two additional wells (9 and 10 from farms 3 and 4) (*fig. 17B*) have maximum pumping capacities that are held constant.

In the second example problem with prior appropriation of surface-water deliveries and acreage optimization for a deficiency scenario, many of the crop and climate attributes are now allowed to vary from time-series data that result in average values for each time step, as opposed to user specified values for each stress period as was used in problem 1. Thus, the values for root depth, crop consumptive use, and precipitation are now varied for each time step. There are no semi-routed surface-water deliveries and the crop benefit and cost attributes for the acreage optimization are held constant for the entire simulation. For all of the ten farm wells, a parameter-factor is assigned to the maximum well pumping capacity. With additional political boundaries between the four farms in example problem 2 (*fig. 17B*), some of the four types of specified nonrouted deliveries could represent interstate and international water transfers.

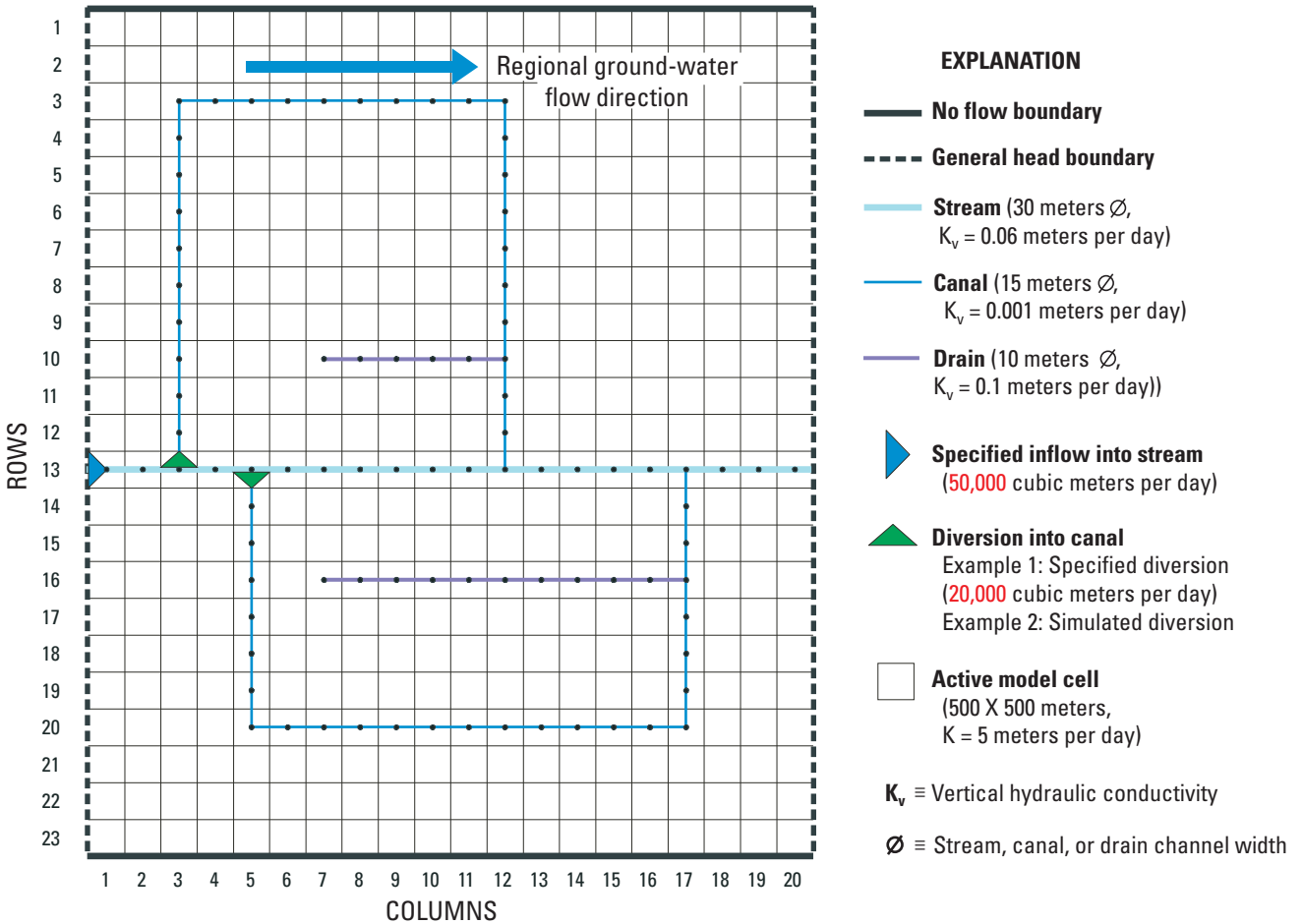
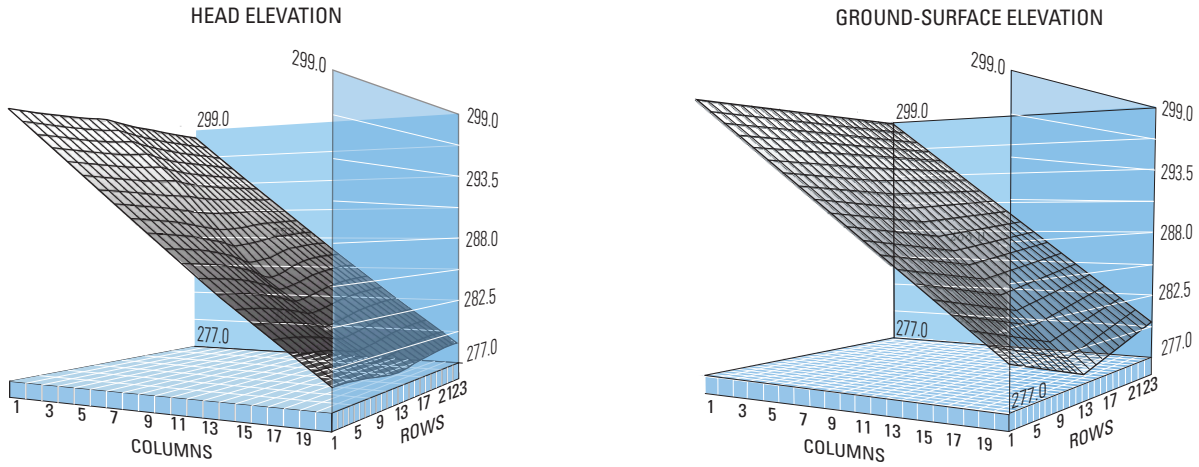
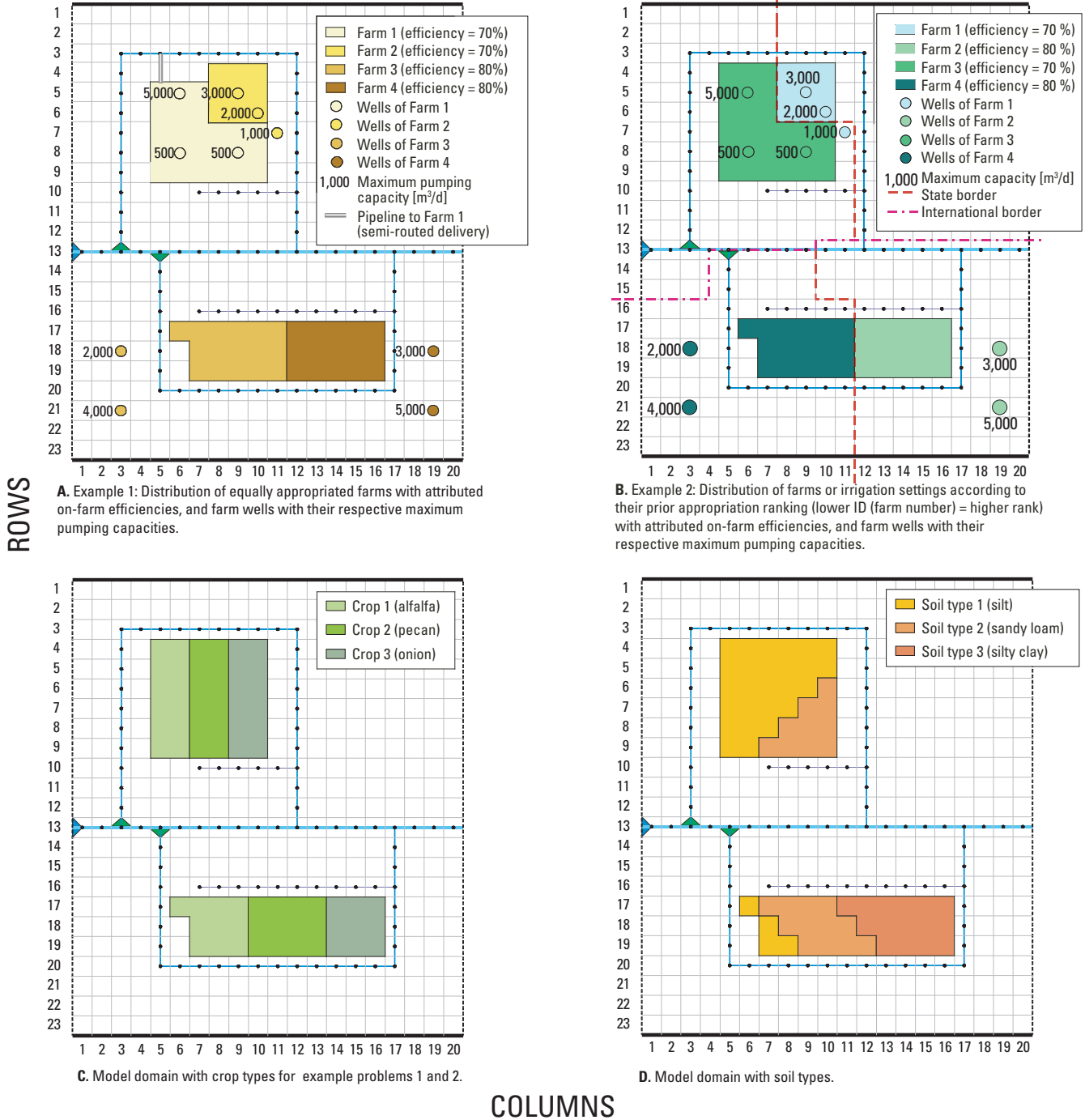


Figure 16. Model domain and boundary conditions and initial heads for the FMP1 example problems.



Model domain of example problems, specified and simulated boundary conditions, hydraulic conductivities (K) of aquifers, conductivities and widths (\emptyset) for beds of stream, canals and drains (see figure 16 for explanation)

Figure 17. Model domain with farms and related wells for example problems 1 and 2 and crops and soils for both problems.

The time series ($\Delta t = 1$ week) of irrigation delivery requirements for each farm and surface-water and ground-water supply were plotted to demonstrate the demand and supply components (figs. 18 and 19) along with the farm demand and supply (FDS) files (tables 4 and 5) for example problems 1 and 2, respectively. For each farm note that the maximum pumping capacity for the sum of all farm wells remains constant for the entire simulation for both example problems.

In example problem 1, the TFDR varies across the four seasonal stress periods for each farm (figs. 18A–D). The TFDR is satisfied for each farm by a combination of surface-water deliveries and ground-water pumpage throughout the entire simulation. For farm 1 (fig. 18A), there is no TFDR for the first stress period (weeks 1–13). The semirouted surface-water delivery [(S)R-SWD-FIN] plus the nonrouted surface-water delivery (NR-SWD-FIN) satisfy the TFDR for the second stress period (weeks 14–26). Additional ground-water pumpage (QREQ-FIN) is needed to supplement the reduced surface-water deliveries in the third stress period (weeks 27–39), when surface-water delivery is constrained by a low allotment, and then the pumpage is not needed for the fourth stress period (weeks 40–52) where the reduced TFDR is again sufficiently satisfied by the semirouted and nonrouted surface-water deliveries. Similarly for farm 2 (fig. 18B), the TFDR is supplied by fully routed surface-water deliveries in the second stress period, requires a small supplement of ground-water pumpage in the third stress period, and the reduced TFDR is only supplied by nonrouted deliveries in the fourth stress period. The demand and supply history for farm 3 (fig. 18C) is similar to farm 1, but shows less ground-water pumpage needed to help satisfy the TFDR in the third stress period because the nonrouted deliveries are larger. In contrast, farm 4 (fig. 18D) is heavily dependent upon supply from ground-water pumpage to satisfy the TFDR demand. The demand and supply history for farm 3 (fig. 18C) is similar to farm 1, but shows less ground-water pumpage needed to help satisfy the TFDR in the third stress period because the nonrouted deliveries are larger. In contrast, farm 4 (fig. 18D) is heavily dependent upon supply from ground-water pumpage to satisfy the TFDR demand. The ground-water pumpage is estimated for the total pumpage for a set of wells associated with each farm (figs. 18 A–D) as well as for each individual farm, as printed into the listing file as follows:

FARM WELLS	PERIOD 3	STEP 13	10 FARMS WELLS	ELAPSED TIME	274.00	DAYS
FARM-WELL ID	FARM ID	LAYER	ROW	COL	RATE	
9	3	1	21	3	-4000.00	
10	4	1	21	19	-5000.00	
1	1	1	5	6	-5000.00	
2	2	1	5	9	-182.339	
3	2	1	6	10	-182.339	
4	2	1	7	11	-182.339	
5	1	1	8	6	-500.00	
6	1	1	8	9	-500.00	
7	3	1	18	3	-2000.00	
8	4	1	18	19	-3000.00	

Note that the wells of farm 2 did not reach their maximum well capacities.

Farm net recharge to and from the ground water system also is estimated on a cell by cell basis, and printed to the listing file. The net recharge represents the difference between outflows as evapotranspiration from ground water and inflows as deep percolation to ground water of water that is in excess of the crop irrigation requirement. Therefore, negative numbers represent a net outflow from the ground-water system and positive numbers represent net inflow to the ground-water system. In example problem 1 for the stress-period 3/time-step 13, net outflow occurred over western parts of farms 1 and 3 and over the northern part of farm 2. Net inflow occurred over the eastern parts of farms 1 and 3, over the southeastern part of farm 2, and over the entire farm 4.

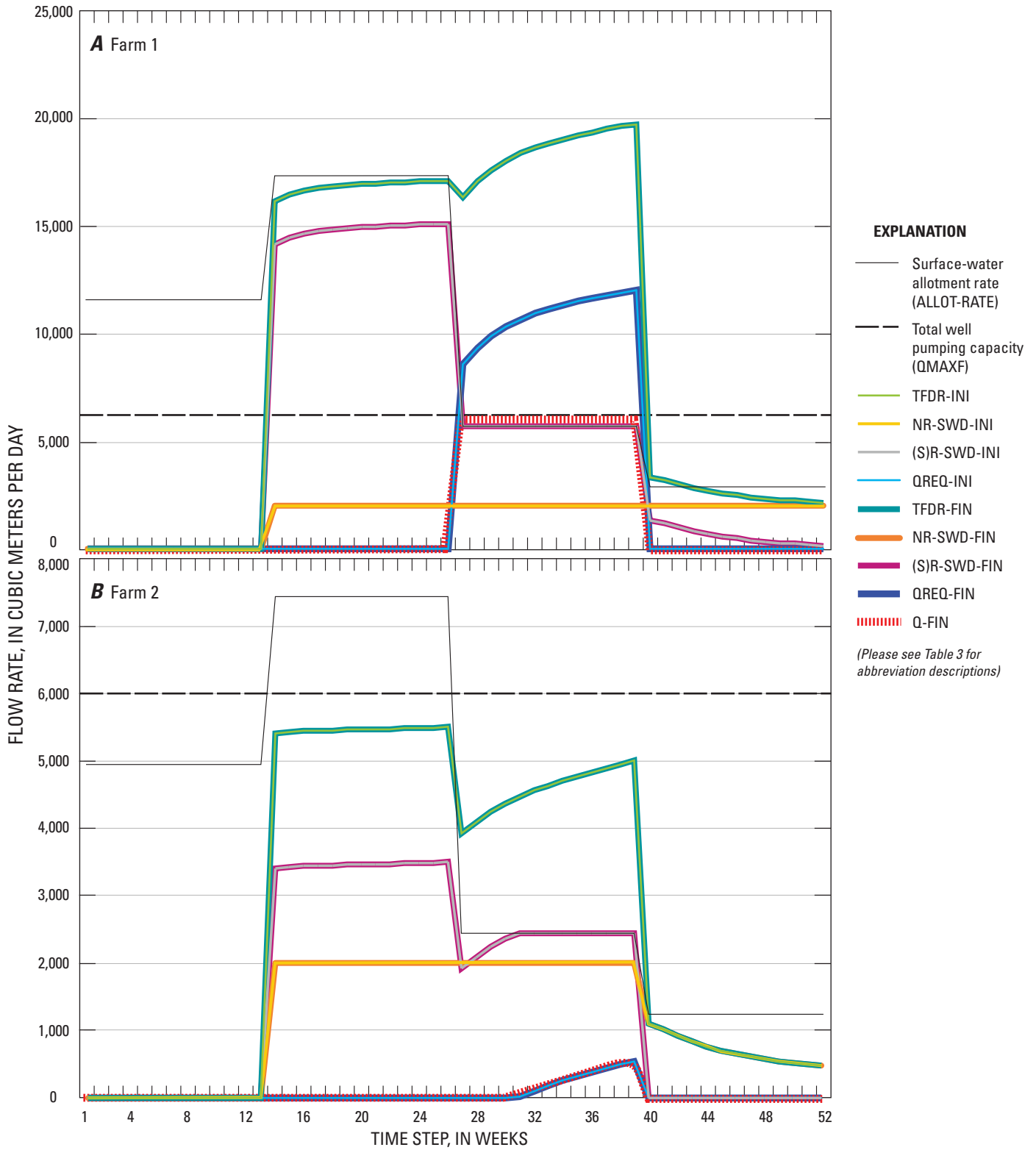


Figure 18. Irrigation Demand and Surface- and Ground-Water Supply for Farms (A) 1, (B) 2, (C) 3, and (D) 4 for Example Problem 1.

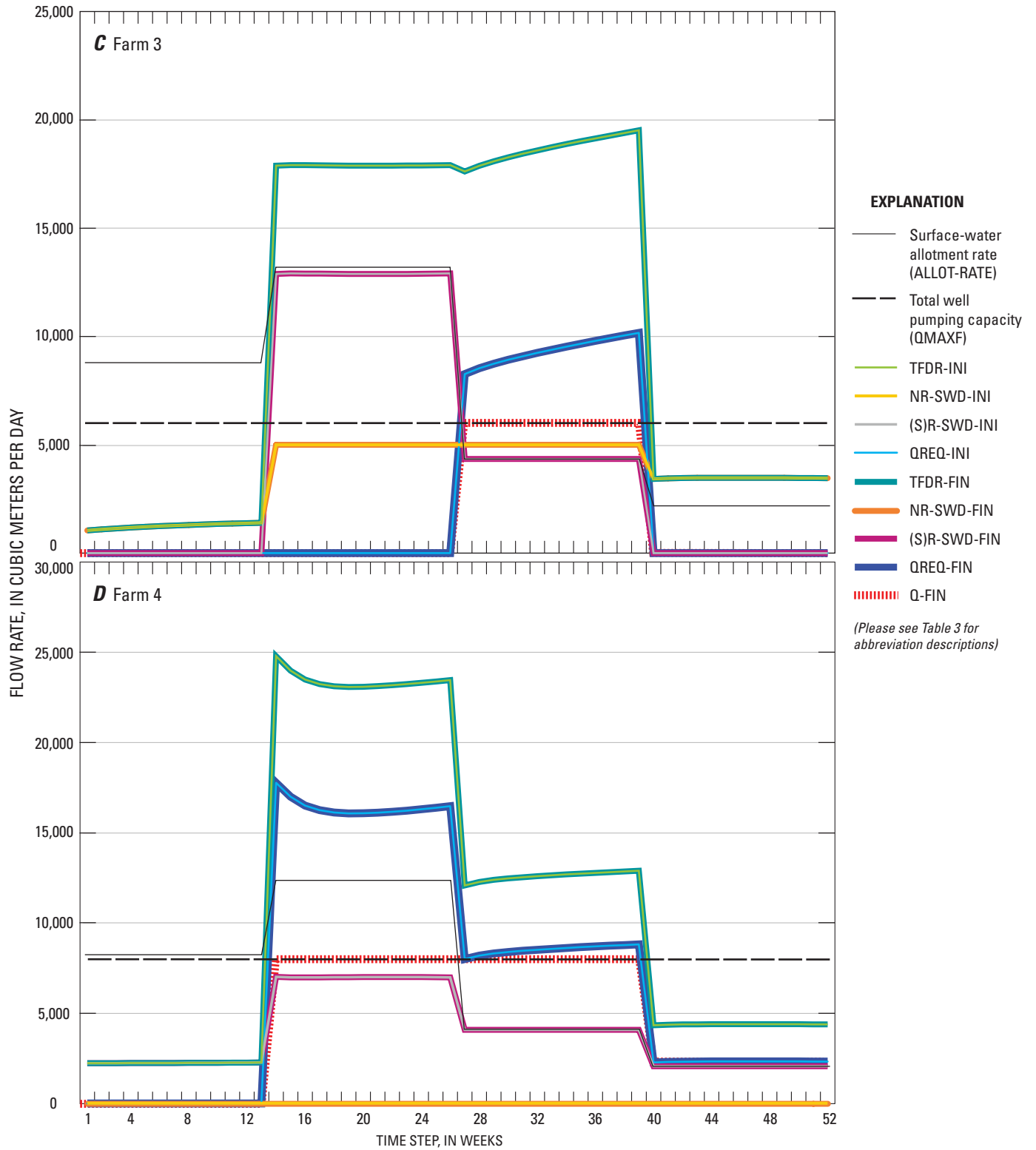


Figure 18.—Continued.

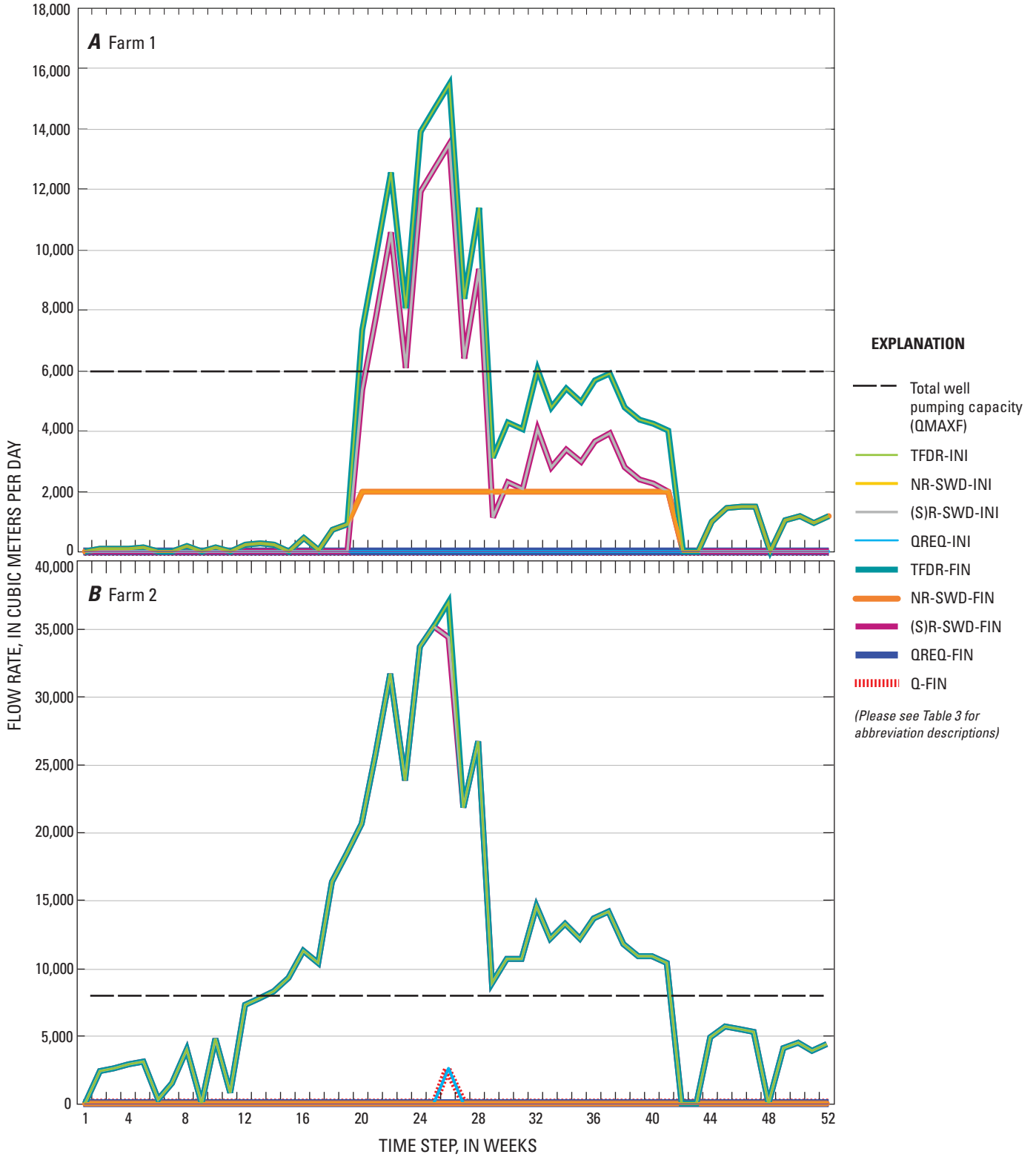


Figure 19. Irrigation demand and surface- and ground-water supply for farms (A) 1, (B) 2, (C) 3, and (D) 4 for example problem 2.

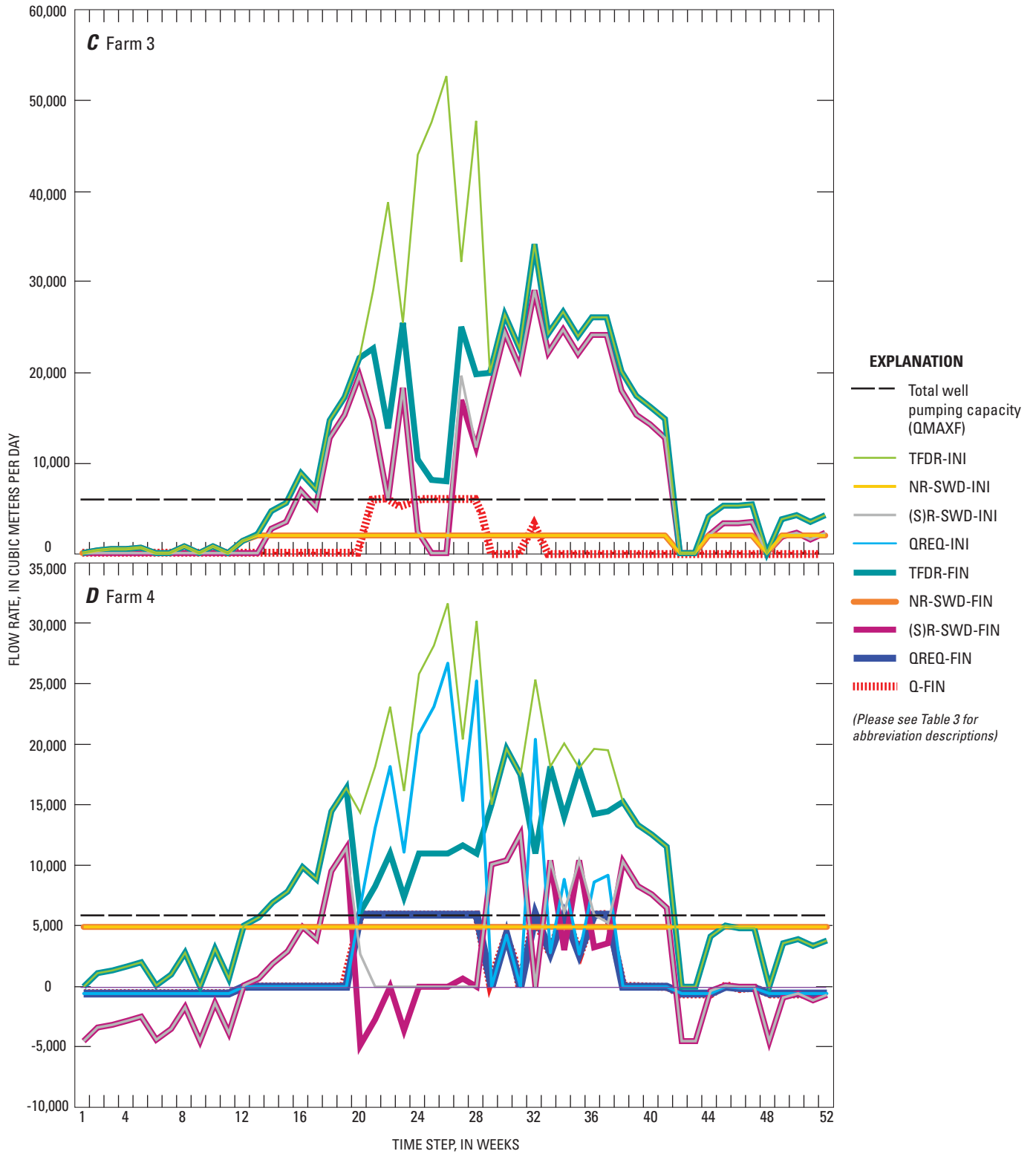


Figure 19.—Continued.

FARM NET RECH. PERIOD 3 STEP 13, 20 COLUMNS, 23 ROWS, 1 LAYERS ELAPSED TIME 274.00 DAYS

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	27.92	-0.5207	-3.304	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	100.5	4.205	-0.3998	0	0	0	0	0	0	0	0	0	0
0	0	0	0	-100.6	62.5	165.5	67.55	3.362	4.409	0	0	0	0	0	0	0	0	0	0
0	0	0	0	-168.8	-86.24	50.64	8.891	4.408	4.408	0	0	0	0	0	0	0	0	0	0
0	0	0	0	-218.6	-124.3	-31.23	383.3	4.408	4.408	0	0	0	0	0	0	0	0	0	0
0	0	0	0	-294.1	-239.3	312.5	336.4	4.408	4.408	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	-384.4	-31.86	-27.35	-24.64	84.93	216.2	224.7	248.6	20.19	20.19	20.19	0	0	0	0
0	0	0	0	0	0	-334.2	-11.16	-22.44	70.83	67.98	215	244.3	20.19	20.19	20.19	0	0	0	0
0	0	0	0	0	0	-323.5	-322	-16.33	82.85	91.56	114.4	268.3	20.19	20.19	20.19	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The total volumetric budget from MF2K demonstrates several features related to the FMP1 for example problem 1. The rate of inflow as ground-water recharge is greater than the outflows related to evapotranspiration from the ground water for this stress period following the excess irrigation from intensive irrigation with surface water and ground water during stress-period 3. However, the cumulative outflow for the first three stress periods is greater than the inflow which is mainly a result of the fact, that, during the first stress period, two out of four farms did not require any irrigation and were entirely supplied by uptake from ground water and precipitation. Other components of the volumetric budget are ground-water pumpage from farm wells, a smaller downward leakage from the stream-canal network to the ground-water system as opposed to a higher upward leakage from the aquifer into the stream network, and inflow from the general-head boundaries. In addition to the farm budget (tables 4 and 5), the ground-water volumetric budget also lists the FMP1 farm wells as "FARM WELLS" and farm net recharge as "FARM NET RECH" in both the inflow and outflow portions of the volumetric summary as follows:

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 13 IN STRESS PERIOD 3					
	CUMULATIVE VOLUMES L**3		RATES FOR THIS TIME STEP		L**3/T
	IN:		IN:		
STORAGE	=	3490324.0000	STORAGE	=	16709.5488
CONSTANT HEAD	=	0.0000	CONSTANT HEAD	=	0.0000
HEAD DEP BOUNDS	=	10468919.0000	HEAD DEP BOUNDS	=	38937.4297
STREAM LEAKAGE	=	614329.1250	STREAM LEAKAGE	=	3415.2991
FARM WELLS	=	0.0000	FARM WELLS	=	0.0000
FARM NET RECH.	=	1150043.3750	FARM NET RECH.	=	3665.5386
TOTAL IN	=	15723615.0000	TOTAL IN	=	62727.8164
	OUT:		OUT:		
STORAGE	=	165089.4219	STORAGE	=	0.0000
CONSTANT HEAD	=	0.0000	CONSTANT HEAD	=	0.0000
HEAD DEP BOUNDS	=	8052081.5000	HEAD DEP BOUNDS	=	28685.1523
STREAM LEAKAGE	=	3629270.0000	STREAM LEAKAGE	=	10739.3281
FARM WELLS	=	2587317.2500	FARM WELLS	=	20547.0156
FARM NET RECH.	=	1291158.6250	FARM NET RECH.	=	2765.2747
TOTAL OUT	=	15724917.0000	TOTAL OUT	=	62736.7695
IN – OUT	=	-1302.0000	IN – OUT	=	-8.9531
PERCENT DISCREPANCY	=	-0.01	PERCENT DISCREPANCY	=	-0.01

In example problem 2, the TFDR varies across the four seasonal stress periods for each farm (figs. 19A–D). The TFDR is reduced through acreage reduction because the various components of supply cannot always satisfy the demand for some of the farms with junior water-rights. This is most pronounced for farms 3 and 4, which have the most junior water rights where ground-water pumpage and reduced TFDR are simulated for these farms. In contrast, farm 4 also may have water available for export in stress periods 1, 2 and 4. For example, farm 4 is simulated to have surface-water return flows in stress-period 2/time-steps 7 and 8 of $-4,841$ and $-2,636$ m³/d, respectively (table 5). These return flows from farm 4 into the adjacent canal are a result of surface-water surplus originating from two reasons. Firstly, nonrouted and routed deliveries were reduced close to zero, because their use was estimated to be unprofitable as a result of the acreage optimization scenario. However, secondly, nonrouted deliveries were specified to be used absolutely in case they are not needed and by majority to be recharged back into the adjacent canal. Because of the water-rights ranking to the surface-water deliveries, the reductions of some farms also may help to increase the potential supply at other farms. For example, in stress-period 3/time-step 1 (table 5) the TFDR for farm 3 is reduced, which makes additional water available for the junior-rights at farm 4 that originally received no routed surface-water. In this case an additional 682 m³/d of surface-water was supplied because of the retirement of 2,728 m³/d from farm 3. Even with additional surface-water supply at farm 4, the supply remains insufficient. Thus, a secondary acreage optimization was carried out, which reduced the additional 2,724 m³/d (2,728 m³/d minus 4 m³/d of conveyance losses) to the profitable amount of about 682 m³/d.

For stress-period 2/time-step 13, the spatial distribution of fractions of active cell acreage is saved as a 2D-array to output file ‘ACR_OPT.OUT’ and illustrated in figure 20. While farm 1 and farm 2 do not show any acreage reduction, the farm land in farm 3 and farm 4 are partially retired. The acreage of cells in green are reduced to zero. One cell experiences a partial reduction to 53 percent of the original cell acreage (row, column = 9,9). Although of lowest surface-water rights rank, farm 4 still can sustain the irrigation of a relatively high consumptive pecan-orchard on the east side of the farm. This is not the case for farm 3 due to a lower total rate of nonrouted deliveries and ground water pumping, as compared to farm 4 (farm 3: 2,000 m³/d in nonrouted deliveries and 6,000 m³/d in ground water pumping; farm 4: 5,000 m³/d in nonrouted deliveries and 6,000 m³/d in ground water pumping).

The penalty of each cell’s acreage reduction depends foremost on the availability of water resources. For a prior appropriation system as in example 2, farm 3 and farm 4 are almost completely retired because of partial or total lack of routed surface water (fig. 20). Another factor that plays an important role is the question “by how much a cell’s acreage is reduced, is the net profit that can be expected from irrigating a cell’s acreage.” This net profit is equal to market dependent benefits of irrigating a certain crop’s acreage minus the costs associated with using certain water types to satisfy the cell’s irrigation.

Table 4. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 1.

[see table 3 for explanation of abbreviations]

Stress Period 1

PER	STP	DAYS	FID	OFE	TFDR-INI	NR-SWD- INI	(S)R-SWD- INI	QREQ-INI	TFDR-FIN	NR-SWD- FIN	(S)R-SWD- FIN	QREQ-FIN	Q-FIN	DEF- FLAG
1	1	7	1	0.49	0	0	0	0	0	0	0	0	0	0
1	1	7	2	0.49	0	0	0	0	0	0	0	0	0	0
1	1	7	3	0.56	1046	1046	0	0	1046	1046	0	0	0	0
1	1	7	4	0.56	2234	0	2234	0	2234	0	2234	0	0	0
1	2	14	1	0.49	0	0	0	0	0	0	0	0	0	0
1	2	14	2	0.49	0	0	0	0	0	0	0	0	0	0
1	2	14	3	0.56	1098	1098	0	0	1098	1098	0	0	0	0
1	2	14	4	0.56	2234	0	2234	0	2234	0	2234	0	0	0
1	3	21	1	0.49	0	0	0	0	0	0	0	0	0	0
1	3	21	2	0.49	0	0	0	0	0	0	0	0	0	0
1	3	21	3	0.56	1142	1142	0	0	1142	1142	0	0	0	0
1	3	21	4	0.56	2235	0	2235	0	2235	0	2235	0	0	0
1	4	28	1	0.49	0	0	0	0	0	0	0	0	0	0
1	4	28	2	0.49	0	0	0	0	0	0	0	0	0	0
1	4	28	3	0.56	1180	1180	0	0	1180	1180	0	0	0	0
1	4	28	4	0.56	2237	0	2237	0	2237	0	2237	0	0	0
1	5	35	1	0.49	0	0	0	0	0	0	0	0	0	0
1	5	35	2	0.49	0	0	0	0	0	0	0	0	0	0
1	5	35	3	0.56	1213	1213	0	0	1213	1213	0	0	0	0
1	5	35	4	0.56	2239	0	2239	0	2239	0	2239	0	0	0
1	6	42	1	0.49	0	0	0	0	0	0	0	0	0	0
1	6	42	2	0.49	0	0	0	0	0	0	0	0	0	0
1	6	42	3	0.56	1243	1243	0	0	1243	1243	0	0	0	0
1	6	42	4	0.56	2241	0	2241	0	2241	0	2241	0	0	0
1	7	49	1	0.49	0	0	0	0	0	0	0	0	0	0
1	7	49	2	0.49	0	0	0	0	0	0	0	0	0	0
1	7	49	3	0.56	1272	1272	0	0	1272	1272	0	0	0	0
1	7	49	4	0.56	2244	0	2244	0	2244	0	2244	0	0	0
1	8	56	1	0.49	0	0	0	0	0	0	0	0	0	0
1	8	56	2	0.49	0	0	0	0	0	0	0	0	0	0
1	8	56	3	0.56	1298	1298	0	0	1298	1298	0	0	0	0
1	8	56	4	0.56	2248	0	2248	0	2248	0	2248	0	0	0
1	9	63	1	0.49	0	0	0	0	0	0	0	0	0	0
1	9	63	2	0.49	0	0	0	0	0	0	0	0	0	0
1	9	63	3	0.56	1323	1323	0	0	1323	1323	0	0	0	0
1	9	63	4	0.56	2251	0	2251	0	2251	0	2251	0	0	0
1	10	70	1	0.49	0	0	0	0	0	0	0	0	0	0
1	10	70	2	0.49	0	0	0	0	0	0	0	0	0	0
1	10	70	3	0.56	1345	1345	0	0	1345	1345	0	0	0	0
1	10	70	4	0.56	2255	0	2255	0	2255	0	2255	0	0	0
1	11	77	1	0.49	0	0	0	0	0	0	0	0	0	0
1	11	77	2	0.49	0	0	0	0	0	0	0	0	0	0
1	11	77	3	0.56	1364	1364	0	0	1364	1364	0	0	0	0
1	11	77	4	0.56	2259	0	2259	0	2259	0	2259	0	0	0
1	12	84	1	0.49	0	0	0	0	0	0	0	0	0	0
1	12	84	2	0.49	0	0	0	0	0	0	0	0	0	0
1	12	84	3	0.56	1382	1382	0	0	1382	1382	0	0	0	0
1	12	84	4	0.56	2263	0	2263	0	2263	0	2263	0	0	0
1	13	91	1	0.49	0	0	0	0	0	0	0	0	0	0
1	13	91	2	0.49	0	0	0	0	0	0	0	0	0	0
1	13	91	3	0.56	1400	1400	0	0	1400	1400	0	0	0	0
1	13	91	4	0.56	2266	0	2266	0	2266	0	2266	0	0	0

Table 4. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 1—Continued.

[see table 3 for explanation of abbreviations]

Stress Period 2

PER	STP	DAYS	FID	OFE	TFDR-INI	NR-SWD- INI	(S)R-SWD- INI	QREQ-INI	TFDR-FIN	NR-SWD- FIN	(S)R-SWD- FIN	QREQ-FIN	Q-FIN	DEF- FLAG
2	1	98	1	0.63	16118	2000	14118	0	16118	2000	14118	0	0	0
2	1	98	2	0.63	5393	2000	3393	0	5393	2000	3393	0	0	0
2	1	98	3	0.72	17882	5000	12882	0	17882	5000	12882	0	0	0
2	1	98	4	0.72	24773	0	7008	17765	24773	0	7008	17765	8000	0
2	2	105	1	0.63	16451	2000	14451	0	16451	2000	14451	0	0	0
2	2	105	2	0.63	5418	2000	3418	0	5418	2000	3418	0	0	0
2	2	105	3	0.72	17907	5000	12907	0	17907	5000	12907	0	0	0
2	2	105	4	0.72	23976	0	6982	16994	23976	0	6982	16994	8000	0
2	3	112	1	0.63	16632	2000	14632	0	16632	2000	14632	0	0	0
2	3	112	2	0.63	5431	2000	3431	0	5431	2000	3431	0	0	0
2	3	112	3	0.72	17906	5000	12906	0	17906	5000	12906	0	0	0
2	3	112	4	0.72	23484	0	6982	16502	23484	0	6982	16502	8000	0
2	4	119	1	0.63	16743	2000	14743	0	16743	2000	14743	0	0	0
2	4	119	2	0.63	5439	2000	3439	0	5439	2000	3439	0	0	0
2	4	119	3	0.72	17899	5000	12899	0	17899	5000	12899	0	0	0
2	4	119	4	0.72	23225	0	6983	16241	23225	0	6983	16241	8000	0
2	5	126	1	0.63	16817	2000	14817	0	16817	2000	14817	0	0	0
2	5	126	2	0.63	5445	2000	3445	0	5445	2000	3445	0	0	0
2	5	126	3	0.72	17892	5000	12892	0	17892	5000	12892	0	0	0
2	5	126	4	0.72	23103	0	6990	16113	23103	0	6990	16113	8000	0
2	6	133	1	0.63	16872	2000	14872	0	16872	2000	14872	0	0	0
2	6	133	2	0.63	5451	2000	3451	0	5451	2000	3451	0	0	0
2	6	133	3	0.72	17887	5000	12887	0	17887	5000	12887	0	0	0
2	6	133	4	0.72	23065	0	6997	16068	23065	0	6997	16068	8000	0
2	7	140	1	0.63	16915	2000	14915	0	16915	2000	14915	0	0	0
2	7	140	2	0.63	5457	2000	3457	0	5457	2000	3457	0	0	0
2	7	140	3	0.72	17883	5000	12883	0	17883	5000	12883	0	0	0
2	7	140	4	0.72	23078	0	7003	16076	23078	0	7003	16076	8000	0
2	8	147	1	0.63	16952	2000	14952	0	16952	2000	14952	0	0	0
2	8	147	2	0.63	5463	2000	3463	0	5463	2000	3463	0	0	0
2	8	147	3	0.72	17882	5000	12882	0	17882	5000	12882	0	0	0
2	8	147	4	0.72	23116	0	7006	16110	23116	0	7006	16110	8000	0
2	9	154	1	0.63	16984	2000	14984	0	16984	2000	14984	0	0	0
2	9	154	2	0.63	5469	2000	3469	0	5469	2000	3469	0	0	0
2	9	154	3	0.72	17884	5000	12884	0	17884	5000	12884	0	0	0
2	9	154	4	0.72	23163	0	7007	16156	23163	0	7007	16156	8000	0
2	10	161	1	0.63	17013	2000	15013	0	17013	2000	15013	0	0	0
2	10	161	2	0.63	5476	2000	3476	0	5476	2000	3476	0	0	0
2	10	161	3	0.72	17888	5000	12888	0	17888	5000	12888	0	0	0
2	10	161	4	0.72	23224	0	7005	16219	23224	0	7005	16219	8000	0
2	11	168	1	0.63	17040	2000	15040	0	17040	2000	15040	0	0	0
2	11	168	2	0.63	5482	2000	3482	0	5482	2000	3482	0	0	0
2	11	168	3	0.72	17894	5000	12894	0	17894	5000	12894	0	0	0
2	11	168	4	0.72	23295	0	7001	16294	23295	0	7001	16294	8000	0
2	12	175	1	0.63	17065	2000	15065	0	17065	2000	15065	0	0	0
2	12	175	2	0.63	5489	2000	3489	0	5489	2000	3489	0	0	0
2	12	175	3	0.72	17902	5000	12902	0	17902	5000	12902	0	0	0
2	12	175	4	0.72	23371	0	6995	16376	23371	0	6995	16376	8000	0
2	13	182	1	0.63	17089	2000	15089	0	17089	2000	15089	0	0	0
2	13	182	2	0.63	5496	2000	3496	0	5496	2000	3496	0	0	0
2	13	182	3	0.72	17911	5000	12911	0	17911	5000	12911	0	0	0
2	13	182	4	0.72	23451	0	6988	16463	23451	0	6988	16463	8000	0

Table 4. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 1—Continued.

[see table 3 for explanation of abbreviations]

Stress Period 3

PER	STP	DAYS	FID	OFE	TFDR-INI	NR-SWD- INI	(S)R-SWD- INI	QREQ-INI	TFDR-FIN	NR-SWD- FIN	(S)R-SWD- FIN	QREQ-FIN	Q-FIN	DEF- FLAG
3	1	189	1	0.70	16293	2000	5707	8586	16293	2000	5707	8586	6000	0
3	1	189	2	0.70	3913	2000	1913	0	3913	2000	1913	0	0	0
3	1	189	3	0.80	17613	5000	4348	8266	17613	5000	4348	8266	6000	0
3	1	189	4	0.80	12077	0	4076	8000	12077	0	4076	8000	8000	0
3	2	196	1	0.70	17035	2000	5707	9329	17035	2000	5707	9329	6000	0
3	2	196	2	0.70	4089	2000	2089	0	4089	2000	2089	0	0	0
3	2	196	3	0.80	17877	5000	4348	8530	17877	5000	4348	8530	6000	0
3	2	196	4	0.80	12265	0	4076	8189	12265	0	4076	8189	8000	0
3	3	203	1	0.70	17588	2000	5707	9882	17588	2000	5707	9882	6000	0
3	3	203	2	0.70	4239	2000	2239	0	4239	2000	2239	0	0	0
3	3	203	3	0.80	18088	5000	4348	8740	18088	5000	4348	8740	6000	0
3	3	203	4	0.80	12388	0	4076	8311	12388	0	4076	8311	8000	0
3	4	210	1	0.70	18014	2000	5707	10307	18014	2000	5707	10307	6000	0
3	4	210	2	0.70	4364	2000	2364	0	4364	2000	2364	0	0	0
3	4	210	3	0.80	18271	5000	4348	8923	18271	5000	4348	8923	6000	0
3	4	210	4	0.80	12468	0	4076	8392	12468	0	4076	8392	8000	0
3	5	217	1	0.70	18347	2000	5707	10640	18347	2000	5707	10640	6000	0
3	5	217	2	0.70	4467	2000	2446	21	4467	2000	2446	21	21	0
3	5	217	3	0.80	18436	5000	4348	9088	18436	5000	4348	9088	6000	0
3	5	217	4	0.80	12531	0	4076	8455	12531	0	4076	8455	8000	0
3	6	224	1	0.70	18615	2000	5707	10909	18615	2000	5707	10909	6000	0
3	6	224	2	0.70	4553	2000	2446	107	4553	2000	2446	107	107	0
3	6	224	3	0.80	18590	5000	4348	9242	18590	5000	4348	9242	6000	0
3	6	224	4	0.80	12588	0	4076	8512	12588	0	4076	8512	8000	0
3	7	232	1	0.70	18839	2000	5707	11132	18839	2000	5707	11132	6000	0
3	7	232	2	0.70	4629	2000	2446	183	4629	2000	2446	183	183	0
3	7	232	3	0.80	18736	5000	4348	9388	18736	5000	4348	9388	6000	0
3	7	232	4	0.80	12640	0	4076	8564	12640	0	4076	8564	8000	0
3	8	239	1	0.70	19029	2000	5707	11323	19029	2000	5707	11323	6000	0
3	8	239	2	0.70	4696	2000	2446	251	4696	2000	2446	251	251	0
3	8	239	3	0.80	18876	5000	4348	9528	18876	5000	4348	9528	6000	0
3	8	239	4	0.80	12688	0	4076	8612	12688	0	4076	8612	8000	0
3	9	246	1	0.70	19195	2000	5707	11488	19195	2000	5707	11488	6000	0
3	9	246	2	0.70	4762	2000	2446	316	4762	2000	2446	316	316	0
3	9	246	3	0.80	19011	5000	4348	9663	19011	5000	4348	9663	6000	0
3	9	246	4	0.80	12732	0	4076	8656	12732	0	4076	8656	8000	0
3	10	253	1	0.70	19342	2000	5707	11636	19342	2000	5707	11636	6000	0
3	10	253	2	0.70	4822	2000	2446	376	4822	2000	2446	376	376	0
3	10	253	3	0.80	19142	5000	4348	9794	19142	5000	4348	9794	6000	0
3	10	253	4	0.80	12775	0	4076	8698	12775	0	4076	8698	8000	0
3	11	260	1	0.70	19475	2000	5707	11769	19475	2000	5707	11769	6000	0
3	11	260	2	0.70	4881	2000	2446	436	4881	2000	2446	436	436	0
3	11	260	3	0.80	19269	5000	4348	9921	19269	5000	4348	9921	6000	0
3	11	260	4	0.80	12814	0	4076	8738	12814	0	4076	8738	8000	0
3	12	267	1	0.70	19597	2000	5707	11890	19597	2000	5707	11890	6000	0
3	12	267	2	0.70	4938	2000	2446	492	4938	2000	2446	492	492	0
3	12	267	3	0.80	19392	5000	4348	10044	19392	5000	4348	10044	6000	0
3	12	267	4	0.80	12852	0	4076	8776	12852	0	4076	8776	8000	0
3	13	274	1	0.70	19709	2000	5707	12003	19709	2000	5707	12003	6000	0
3	13	274	2	0.70	4993	2000	2446	547	4993	2000	2446	547	547	0
3	13	274	3	0.80	19512	5000	4348	10164	19512	5000	4348	10164	6000	0
3	13	274	4	0.80	12888	0	4076	8812	12888	0	4076	8812	8000	0

Table 4. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 1—Continued.

[see table 3 for explanation of abbreviations]

Stress Period 4

PER	STP	DAYS	FID	OFE	TFDR-INI	NR-SWD- INI	(S)R-SWD- INI	QREQ-INI	TFDR-FIN	NR-SWD- FIN	(S)R-SWD- FIN	QREQ-FIN	Q-FIN	DEF- FLAG
4	1	281	1	0.63	3314	2000	1314	0	3314	2000	1314	0	0	0
4	1	281	2	0.63	1107	1107	0	0	1107	1107	0	0	0	0
4	1	281	3	0.72	3420	3420	0	0	3420	3420	0	0	0	0
4	1	281	4	0.72	4331	0	2060	2271	4331	0	2060	2271	2271	0
4	2	288	1	0.63	3162	2000	1162	0	3162	2000	1162	0	0	0
4	2	288	2	0.63	1019	1019	0	0	1019	1019	0	0	0	0
4	2	288	3	0.72	3448	3448	0	0	3448	3448	0	0	0	0
4	2	288	4	0.72	4360	0	2060	2299	4360	0	2060	2299	2299	0
4	3	295	1	0.63	2990	2000	990	0	2990	2000	990	0	0	0
4	3	295	2	0.63	924	924	0	0	924	924	0	0	0	0
4	3	295	3	0.72	3462	3462	0	0	3462	3462	0	0	0	0
4	3	295	4	0.72	4376	0	2060	2315	4376	0	2060	2315	2315	0
4	4	302	1	0.63	2832	2000	832	0	2832	2000	832	0	0	0
4	4	302	2	0.63	839	839	0	0	839	839	0	0	0	0
4	4	302	3	0.72	3471	3471	0	0	3471	3471	0	0	0	0
4	4	302	4	0.72	4385	0	2060	2325	4385	0	2060	2325	2325	0
4	5	309	1	0.63	2697	2000	697	0	2697	2000	697	0	0	0
4	5	309	2	0.63	767	767	0	0	767	767	0	0	0	0
4	5	309	3	0.72	3476	3476	0	0	3476	3476	0	0	0	0
4	5	309	4	0.72	4391	0	2060	2330	4391	0	2060	2330	2330	0
4	6	316	1	0.63	2582	2000	582	0	2582	2000	582	0	0	0
4	6	316	2	0.63	707	707	0	0	707	707	0	0	0	0
4	6	316	3	0.72	3478	3478	0	0	3478	3478	0	0	0	0
4	6	316	4	0.72	4394	0	2060	2333	4394	0	2060	2333	2333	0
4	7	323	1	0.63	2486	2000	486	0	2486	2000	486	0	0	0
4	7	323	2	0.63	657	657	0	0	657	657	0	0	0	0
4	7	323	3	0.72	3479	3479	0	0	3479	3479	0	0	0	0
4	7	323	4	0.72	4395	0	2060	2335	4395	0	2060	2335	2335	0
4	8	330	1	0.63	2404	2000	404	0	2404	2000	404	0	0	0
4	8	330	2	0.63	614	614	0	0	614	614	0	0	0	0
4	8	330	3	0.72	3478	3478	0	0	3478	3478	0	0	0	0
4	8	330	4	0.72	4395	0	2060	2334	4395	0	2060	2334	2334	0
4	9	337	1	0.63	2334	2000	334	0	2334	2000	334	0	0	0
4	9	337	2	0.63	578	578	0	0	578	578	0	0	0	0
4	9	337	3	0.72	3476	3476	0	0	3476	3476	0	0	0	0
4	9	337	4	0.72	4393	0	2060	2332	4393	0	2060	2332	2332	0
4	10	344	1	0.63	2274	2000	274	0	2274	2000	274	0	0	0
4	10	344	2	0.63	546	546	0	0	546	546	0	0	0	0
4	10	344	3	0.72	3472	3472	0	0	3472	3472	0	0	0	0
4	10	344	4	0.72	4390	0	2060	2330	4390	0	2060	2330	2330	0
4	11	351	1	0.63	2222	2000	222	0	2222	2000	222	0	0	0
4	11	351	2	0.63	519	519	0	0	519	519	0	0	0	0
4	11	351	3	0.72	3468	3468	0	0	3468	3468	0	0	0	0
4	11	351	4	0.72	4386	0	2060	2326	4386	0	2060	2326	2326	0
4	12	358	1	0.63	2176	2000	176	0	2176	2000	176	0	0	0
4	12	358	2	0.63	494	494	0	0	494	494	0	0	0	0
4	12	358	3	0.72	3463	3463	0	0	3463	3463	0	0	0	0
4	12	358	4	0.72	4382	0	2060	2321	4382	0	2060	2321	2321	0
4	13	365	1	0.63	2135	2000	135	0	2135	2000	135	0	0	0
4	13	365	2	0.63	472	472	0	0	472	472	0	0	0	0
4	13	365	3	0.72	3457	3457	0	0	3457	3457	0	0	0	0
4	13	365	4	0.72	4377	0	2060	2316	4377	0	2060	2316	2316	0

Table 5. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 2.

[see table 3 for explanation of abbreviations]

Stress Period 1

PER	STP	DAYS	FID	OFE	TFDR-INI	NR-SWD- INI	(S)R-SWD- INI	QREQ-INI	TFDR-FIN	NR-SWD- FIN	(S)R-SWD- FIN	QREQ-FIN	Q-FIN	DEF- FLAG
1	1	7	1	0.70	0	0	0	0	0	0	0	0	0	1
1	1	7	2	0.80	0	0	0	0	0	0	0	0	0	1
1	1	7	3	0.70	0	0	0	0	0	0	0	0	0	1
1	1	7	4	0.80	0	5000	-4500	-500	0	5000	-4500	-500	-500	1
1	2	14	1	0.70	75	75	0	0	75	75	0	0	0	1
1	2	14	2	0.80	2417	0	2417	0	2417	0	2417	0	0	1
1	2	14	3	0.70	314	314	0	0	314	314	0	0	0	1
1	2	14	4	0.80	1183	5000	-3317	-500	1183	5000	-3317	-500	-500	1
1	3	21	1	0.70	92	92	0	0	92	92	0	0	0	1
1	3	21	2	0.80	2619	0	2619	0	2619	0	2619	0	0	1
1	3	21	3	0.70	382	382	0	0	382	382	0	0	0	1
1	3	21	4	0.80	1413	5000	-3087	-500	1413	5000	-3087	-500	-500	1
1	4	28	1	0.70	110	110	0	0	110	110	0	0	0	1
1	4	28	2	0.80	2883	0	2883	0	2883	0	2883	0	0	1
1	4	28	3	0.70	459	459	0	0	459	459	0	0	0	1
1	4	28	4	0.80	1701	5000	-2799	-500	1701	5000	-2799	-500	-500	1
1	5	35	1	0.70	128	128	0	0	128	128	0	0	0	1
1	5	35	2	0.80	3148	0	3148	0	3148	0	3148	0	0	1
1	5	35	3	0.70	536	536	0	0	536	536	0	0	0	1
1	5	35	4	0.80	1982	5000	-2518	-500	1982	5000	-2518	-500	-500	1
1	6	42	1	0.70	0	0	0	0	0	0	0	0	0	1
1	6	42	2	0.80	266	0	266	0	266	0	266	0	0	1
1	6	42	3	0.70	0	0	0	0	0	0	0	0	0	1
1	6	42	4	0.80	175	5000	-4325	-500	175	5000	-4325	-500	-500	1
1	7	49	1	0.70	0	0	0	0	0	0	0	0	0	1
1	7	49	2	0.80	1524	0	1524	0	1524	0	1524	0	0	1
1	7	49	3	0.70	55	55	0	0	55	55	0	0	0	1
1	7	49	4	0.80	981	5000	-3519	-500	981	5000	-3519	-500	-500	1
1	8	56	1	0.70	174	174	0	0	174	174	0	0	0	1
1	8	56	2	0.80	4045	0	4045	0	4045	0	4045	0	0	1
1	8	56	3	0.70	738	738	0	0	738	738	0	0	0	1
1	8	56	4	0.80	2806	5000	-1694	-500	2806	5000	-1694	-500	-500	1
1	9	63	1	0.70	0	0	0	0	0	0	0	0	0	1
1	9	63	2	0.80	0	0	0	0	0	0	0	0	0	1
1	9	63	3	0.70	0	0	0	0	0	0	0	0	0	1
1	9	63	4	0.80	0	5000	-4500	-500	0	5000	-4500	-500	-500	1
1	10	70	1	0.70	142	142	0	0	142	142	0	0	0	1
1	10	70	2	0.80	4761	0	4761	0	4761	0	4761	0	0	1
1	10	70	3	0.70	699	699	0	0	699	699	0	0	0	1
1	10	70	4	0.80	3188	5000	-1312	-500	3188	5000	-1312	-500	-500	1
1	11	77	1	0.70	0	0	0	0	0	0	0	0	0	1
1	11	77	2	0.80	817	0	817	0	817	0	817	0	0	1
1	11	77	3	0.70	0	0	0	0	0	0	0	0	0	1
1	11	77	4	0.80	636	5000	-3864	-500	636	5000	-3864	-500	-500	1
1	12	84	1	0.70	240	240	0	0	240	240	0	0	0	1
1	12	84	2	0.80	7287	0	7287	0	7287	0	7287	0	0	1
1	12	84	3	0.70	1280	1280	0	0	1280	1280	0	0	0	1
1	12	84	4	0.80	5104	5000	104	0	5104	5000	104	0	0	1
1	13	91	1	0.70	285	285	0	0	285	285	0	0	0	1
1	13	91	2	0.80	7844	0	7844	0	7844	0	7844	0	0	1
1	13	91	3	0.70	2063	2000	63	0	2063	2000	63	0	0	1
1	13	91	4	0.80	5733	5000	733	0	5733	5000	733	0	0	1

Table 5. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 2—Continued.

[see table 3 for explanation of abbreviations]

Stress Period 2

PER	STP	DAYS	FID	OFE	TFDR-INI	NR-SWD- INI	(S)R-SWD- INI	QREQ-INI	TFDR-FIN	NR-SWD- FIN	(S)R-SWD- FIN	QREQ-FIN	Q-FIN	DEF- FLAG
2	1	98	1	0.70	224	224	0	0	224	224	0	0	0	1
2	1	98	2	0.80	8272	0	8272	0	8272	0	8272	0	0	1
2	1	98	3	0.70	4686	2000	2686	0	4686	2000	2686	0	0	1
2	1	98	4	0.80	6964	5000	1964	0	6964	5000	1964	0	0	1
2	2	105	1	0.70	0	0	0	0	0	0	0	0	0	1
2	2	105	2	0.80	9330	0	9330	0	9330	0	9330	0	0	1
2	2	105	3	0.70	5509	2000	3509	0	5509	2000	3509	0	0	1
2	2	105	4	0.80	7924	5000	2924	0	7924	5000	2924	0	0	1
2	3	112	1	0.70	447	447	0	0	447	447	0	0	0	1
2	3	112	2	0.80	11329	0	11329	0	11329	0	11329	0	0	1
2	3	112	3	0.70	8914	2000	6914	0	8914	2000	6914	0	0	1
2	3	112	4	0.80	9966	5000	4966	0	9966	5000	4966	0	0	1
2	4	119	1	0.70	23	23	0	0	23	23	0	0	0	1
2	4	119	2	0.80	10421	0	10421	0	10421	0	10421	0	0	1
2	4	119	3	0.70	7071	2000	5071	0	7071	2000	5071	0	0	1
2	4	119	4	0.80	8920	5000	3920	0	8920	5000	3920	0	0	1
2	5	126	1	0.70	716	716	0	0	716	716	0	0	0	1
2	5	126	2	0.80	16355	0	16355	0	16355	0	16355	0	0	1
2	5	126	3	0.70	14738	2000	12738	0	14738	2000	12738	0	0	1
2	5	126	4	0.80	14542	5000	9542	0	14542	5000	9542	0	0	1
2	6	133	1	0.70	879	879	0	0	879	879	0	0	0	1
2	6	133	2	0.80	18547	0	18547	0	18547	0	18547	0	0	1
2	6	133	3	0.70	17250	2000	15250	0	17250	2000	15250	0	0	1
2	6	133	4	0.80	16464	5000	11464	0	16464	5000	11464	0	0	1
2	7	140	1	0.70	7341	2000	5341	0	7341	2000	5341	0	0	1
2	7	140	2	0.80	20669	0	20669	0	20669	0	20669	0	0	1
2	7	140	3	0.70	21641	2000	19641	0	21641	2000	19641	0	0	1
2	7	140	4	0.80	14358	5000	2711	6648	6159	5000	-4841	6000	6000	1
2	8	147	1	0.70	9791	2000	7791	0	9791	2000	7791	0	0	1
2	8	147	2	0.80	25800	0	25800	0	25800	0	25800	0	0	1
2	8	147	3	0.70	29096	2000	14700	12396	22700	2000	14700	6000	6000	1
2	8	147	4	0.80	18204	5000	0	13204	8364	5000	-2636	6000	6000	1
2	9	154	1	0.70	12553	2000	10553	0	12553	2000	10553	0	0	1
2	9	154	2	0.80	31844	0	31844	0	31844	0	31844	0	0	1
2	9	154	3	0.70	38841	2000	5836	31005	13836	2000	5836	6000	6000	1
2	9	154	4	0.80	23230	5000	0	18230	11000	5000	0	6000	6000	1
2	10	161	1	0.70	8068	2000	6068	0	8068	2000	6068	0	0	1
2	10	161	2	0.80	23859	0	23859	0	23859	0	23859	0	0	1
2	10	161	3	0.70	25497	2000	18256	5241	25497	2000	18256	5241	5241	1
2	10	161	4	0.80	16192	5000	0	11192	7456	5000	-3543	5999	5999	1
2	11	168	1	0.70	13909	2000	11909	0	13909	2000	11909	0	0	1
2	11	168	2	0.80	33838	0	33838	0	33838	0	33838	0	0	1
2	11	168	3	0.70	44145	2000	2369	39776	10369	2000	2369	6000	6000	1
2	11	168	4	0.80	25905	5000	0	20905	11000	5000	0	6000	6000	1
2	12	175	1	0.70	14668	2000	12668	0	14668	2000	12668	0	0	1
2	12	175	2	0.80	35306	0	35306	0	35306	0	35306	0	0	1
2	12	175	3	0.70	47659	2000	74	45585	8074	2000	74	6000	6000	1
2	12	175	4	0.80	28231	5000	0	23231	11000	5000	0	6000	6000	1
2	13	182	1	0.70	15482	2000	13482	0	15482	2000	13482	0	0	1
2	13	182	2	0.80	37122	0	34528	2594	37122	0	34528	2594	2594	1
2	13	182	3	0.70	52770	2000	0	50770	8000	2000	0	6000	6000	1
2	13	182	4	0.80	31747	5000	0	26747	11000	5000	0	6000	6000	1

Table 5. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 2—Continued.

[see table 3 for explanation of abbreviations]

Stress Period 3

PER	STP	DAYS	FID	OFE	TFDR-INI	NR-SWD- INI	(S)R-SWD- INI	QREQ-INI	TFDR-FIN	NR-SWD- FIN	(S)R-SWD- FIN	QREQ-FIN	Q-FIN	DEF- FLAG
3	1	189	1	0.70	8387	2000	6387	0	8387	2000	6387	0	0	1
3	1	189	2	0.80	21855	0	21855	0	21855	0	21855	0	0	1
3	1	189	3	0.70	32181	2000	19707	10474	24979	2000	16979	6000	6000	1
3	1	189	4	0.80	20472	5000	0	15472	11682	5000	682	6000	6000	1
3	2	196	1	0.70	11378	2000	9378	0	11378	2000	9378	0	0	1
3	2	196	2	0.80	26764	0	26764	0	26764	0	26764	0	0	1
3	2	196	3	0.70	47812	2000	11757	34055	19757	2000	11757	6000	6000	1
3	2	196	4	0.80	30327	5000	0	25327	11000	5000	0	6000	6000	1
3	3	203	1	0.70	3103	2000	1103	0	3103	2000	1103	0	0	1
3	3	203	2	0.80	8879	0	8879	0	8879	0	8879	0	0	1
3	3	203	3	0.70	19912	2000	17912	0	19912	2000	17912	0	0	1
3	3	203	4	0.80	15109	5000	10109	0	15109	5000	10109	0	0	1
3	4	210	1	0.70	4281	2000	2281	0	4281	2000	2281	0	0	1
3	4	210	2	0.80	10736	0	10736	0	10736	0	10736	0	0	1
3	4	210	3	0.70	26378	2000	24378	0	26378	2000	24378	0	0	1
3	4	210	4	0.80	19735	5000	10439	4296	19735	5000	10439	4296	4296	1
3	5	217	1	0.70	4061	2000	2061	0	4061	2000	2061	0	0	1
3	5	217	2	0.80	10700	0	10700	0	10700	0	10700	0	0	1
3	5	217	3	0.70	22622	2000	20622	0	22622	2000	20622	0	0	1
3	5	217	4	0.80	17582	5000	12582	0	17582	5000	12582	0	0	1
3	6	224	1	0.70	6038	2000	4038	0	6038	2000	4038	0	0	1
3	6	224	2	0.80	14570	0	14570	0	14570	0	14570	0	0	1
3	6	224	3	0.70	34144	2000	29114	3030	34144	2000	29114	3030	3030	1
3	6	224	4	0.80	25470	5000	0	20470	11000	5000	0	6000	6000	1
3	7	232	1	0.70	4783	2000	2783	0	4783	2000	2783	0	0	1
3	7	232	2	0.80	12162	0	12162	0	12162	0	12162	0	0	1
3	7	232	3	0.70	24237	2000	22237	0	24237	2000	22237	0	0	1
3	7	232	4	0.80	18267	5000	10495	2771	18267	5000	10495	2771	2771	1
3	8	239	1	0.70	5380	2000	3380	0	5380	2000	3380	0	0	1
3	8	239	2	0.80	13273	0	13273	0	13273	0	13273	0	0	1
3	8	239	3	0.70	26764	2000	24764	0	26764	2000	24764	0	0	1
3	8	239	4	0.80	20101	5000	6211	8891	14073	5000	3073	6000	6000	1
3	9	246	1	0.70	4948	2000	2948	0	4948	2000	2948	0	0	1
3	9	246	2	0.80	12172	0	12172	0	12172	0	12172	0	0	1
3	9	246	3	0.70	24049	2000	22049	0	24049	2000	22049	0	0	1
3	9	246	4	0.80	18173	5000	10427	2746	18173	5000	10427	2746	2746	1
3	10	253	1	0.70	5661	2000	3661	0	5661	2000	3661	0	0	1
3	10	253	2	0.80	13736	0	13736	0	13736	0	13736	0	0	1
3	10	253	3	0.70	26153	2000	24153	0	26153	2000	24153	0	0	1
3	10	253	4	0.80	19647	5000	5999	8648	14307	5000	3307	6000	6000	1
3	11	260	1	0.70	5901	2000	3901	0	5901	2000	3901	0	0	1
3	11	260	2	0.80	14234	0	14234	0	14234	0	14234	0	0	1
3	11	260	3	0.70	26117	2000	24117	0	26117	2000	24117	0	0	1
3	11	260	4	0.80	19548	5000	5272	9276	14573	5000	3573	6000	6000	1
3	12	267	1	0.70	4791	2000	2791	0	4791	2000	2791	0	0	1
3	12	267	2	0.80	11817	0	11817	0	11817	0	11817	0	0	1
3	12	267	3	0.70	20054	2000	18054	0	20054	2000	18054	0	0	1
3	12	267	4	0.80	15311	5000	10311	0	15311	5000	10311	0	0	1
3	13	274	1	0.70	4385	2000	2385	0	4385	2000	2385	0	0	1
3	13	274	2	0.80	10932	0	10932	0	10932	0	10932	0	0	1
3	13	274	3	0.70	17347	2000	15347	0	17347	2000	15347	0	0	1
3	13	274	4	0.80	13383	5000	8383	0	13383	5000	8383	0	0	1

Table 5. Farm Demand and Supply (FDS.OUT), Farm Budget Output for Example Problem 2—Continued.

[see table 3 for explanation of abbreviations]

Stress Period 4

PER	STP	DAYS	FID	OFE	TFDR-INI	NR-SWD- INI	(S)R-SWD- INI	QREQ-INI	TFDR-FIN	NR-SWD- FIN	(S)R-SWD- FIN	QREQ-FIN	Q-FIN	DEF- FLAG
4	1	281	1	0.70	4250	2000	2250	0	4250	2000	2250	0	0	1
4	1	281	2	0.80	10939	0	10939	0	10939	0	10939	0	0	1
4	1	281	3	0.70	16196	2000	14196	0	16196	2000	14196	0	0	1
4	1	281	4	0.80	12662	5000	7662	0	12662	5000	7662	0	0	1
4	2	288	1	0.70	3990	2000	1990	0	3990	2000	1990	0	0	1
4	2	288	2	0.80	10406	0	10406	0	10406	0	10406	0	0	1
4	2	288	3	0.70	14818	2000	12818	0	14818	2000	12818	0	0	1
4	2	288	4	0.80	11572	5000	6572	0	11572	5000	6572	0	0	1
4	3	295	1	0.70	0	0	0	0	0	0	0	0	0	1
4	3	295	2	0.80	0	0	0	0	0	0	0	0	0	1
4	3	295	3	0.70	0	0	0	0	0	0	0	0	0	1
4	3	295	4	0.80	0	5000	-4500	-500	0	5000	-4500	-500	-500	1
4	4	302	1	0.70	0	0	0	0	0	0	0	0	0	1
4	4	302	2	0.80	0	0	0	0	0	0	0	0	0	1
4	4	302	3	0.70	0	0	0	0	0	0	0	0	0	1
4	4	302	4	0.80	0	5000	-4500	-500	0	5000	-4500	-500	-500	1
4	5	309	1	0.70	1007	1007	0	0	1007	1007	0	0	0	1
4	5	309	2	0.80	4879	0	4879	0	4879	0	4879	0	0	1
4	5	309	3	0.70	4010	2000	2010	0	4010	2000	2010	0	0	1
4	5	309	4	0.80	4135	5000	-365	-500	4135	5000	-365	-500	-500	1
4	6	316	1	0.70	1454	1454	0	0	1454	1454	0	0	0	1
4	6	316	2	0.80	5675	0	5675	0	5675	0	5675	0	0	1
4	6	316	3	0.70	5304	2000	3304	0	5304	2000	3304	0	0	1
4	6	316	4	0.80	5078	5000	78	0	5078	5000	78	0	0	1
4	7	323	1	0.70	1467	1467	0	0	1467	1467	0	0	0	1
4	7	323	2	0.80	5534	0	5534	0	5534	0	5534	0	0	1
4	7	323	3	0.70	5265	2000	3265	0	5265	2000	3265	0	0	1
4	7	323	4	0.80	4879	5000	0	-121	4879	5000	0	-121	-121	1
4	8	330	1	0.70	1478	1478	0	0	1478	1478	0	0	0	1
4	8	330	2	0.80	5349	0	5349	0	5349	0	5349	0	0	1
4	8	330	3	0.70	5394	2000	3394	0	5394	2000	3394	0	0	1
4	8	330	4	0.80	4899	5000	0	-101	4899	5000	0	-101	-101	1
4	9	337	1	0.70	0	0	0	0	0	0	0	0	0	1
4	9	337	2	0.80	0	0	0	0	0	0	0	0	0	1
4	9	337	3	0.70	0	0	0	0	0	0	0	0	0	1
4	9	337	4	0.80	0	5000	-4500	-500	0	5000	-4500	-500	-500	1
4	10	344	1	0.70	1029	1029	0	0	1029	1029	0	0	0	1
4	10	344	2	0.80	4089	0	4089	0	4089	0	4089	0	0	1
4	10	344	3	0.70	3802	2000	1802	0	3802	2000	1802	0	0	1
4	10	344	4	0.80	3634	5000	-866	-500	3634	5000	-866	-500	-500	1
4	11	351	1	0.70	1150	1150	0	0	1150	1150	0	0	0	1
4	11	351	2	0.80	4482	0	4482	0	4482	0	4482	0	0	1
4	11	351	3	0.70	4208	2000	2208	0	4208	2000	2208	0	0	1
4	11	351	4	0.80	3980	5000	-520	-500	3980	5000	-520	-500	-500	1
4	12	358	1	0.70	967	967	0	0	967	967	0	0	0	1
4	12	358	2	0.80	3943	0	3943	0	3943	0	3943	0	0	1
4	12	358	3	0.70	3513	2000	1513	0	3513	2000	1513	0	0	1
4	12	358	4	0.80	3396	5000	-1104	-500	3396	5000	-1104	-500	-500	1
4	13	365	1	0.70	1175	1175	0	0	1175	1175	0	0	0	1
4	13	365	2	0.80	4392	0	4392	0	4392	0	4392	0	0	1
4	13	365	3	0.70	4194	2000	2194	0	4194	2000	2194	0	0	1
4	13	365	4	0.80	3868	5000	-632	-500	3868	5000	-632	-500	-500	1

Benefits not only depend on the market price of the crop but also depend directly on the yield, or in other words on the actual consumptive use. Irrigation costs may be related to both the ground water or surface-water head-lift and to the irrigation needed, which is equal to a “residual consumptive use” that cannot be satisfied by precipitation or uptake from ground water. In turn, the uptake from ground water rests on the soil type, on the depth of the total root zone, on the capillary fringe, and on the depth to the water table.

In summary, all of the factors mentioned (in *italic*) play some role on the question which cell's acreage is reduced and by what percentage. At this point, one could only speculate about the significance of certain factors for this hypothetical example. For instance, ground-water head-lift might be of importance, since the eastern parts of farm 3 and farm 4 are of lower elevation and, hence, are more cost-effective for ground-water pumping. Viewing the situation by crop type, the acreage of onions appears to be left almost within the original extent of crops, while the alfalfa acreage is reduced to zero (*fig. 20*). The reason for this outcome could be that alfalfa got penalized 100 percent during the end of stress period 2, which represents the end of the peak irrigation season. Although onions also experience highest consumption during the peak irrigation season, they might have taken up a considerable portion from a higher ground-water level. That is, the irrigation flux needed for onions might be less and, therefore, the irrigation costs for onions are not as high as for alfalfa. The fact that the pecan orchards of farm 3 are completely reduced while they are not at all retired in farm 4 might have something to do with the fact that onions in farm 3 were economically preferred over pecans, while they do not exist in farm 4.

Overall in example 2, the surface-water water-rights ranking results in farm 1 always receiving its surface-water delivery while the lesser ranked farms do not always receive the full surface-water deliveries (*fig. 19A*). Similarly, farm 2 always meets its TFDR but has to supplement the surface-water deliveries with ground-water pumpage for a couple of weeks in stress period 3 during the peak demand (*fig. 19B*). Overall, the water-rights for surface-water deliveries require additional ground-water pumpage and additional reduction in demand to balance with reduced supplies. For example, in an attempt to supply water to farm 3, ground water was pumped at its maximum capacity and demand was reduced through acreage reduction in stress periods 2 and 3 (*fig. 19C*). In contrast, the most junior farm, farm 4 is simulated with the largest nonrouted deliveries to sustain some farming, which is then supplemented with periodic surface-water deliveries when available and ground-water pumpage (*fig. 19D*).

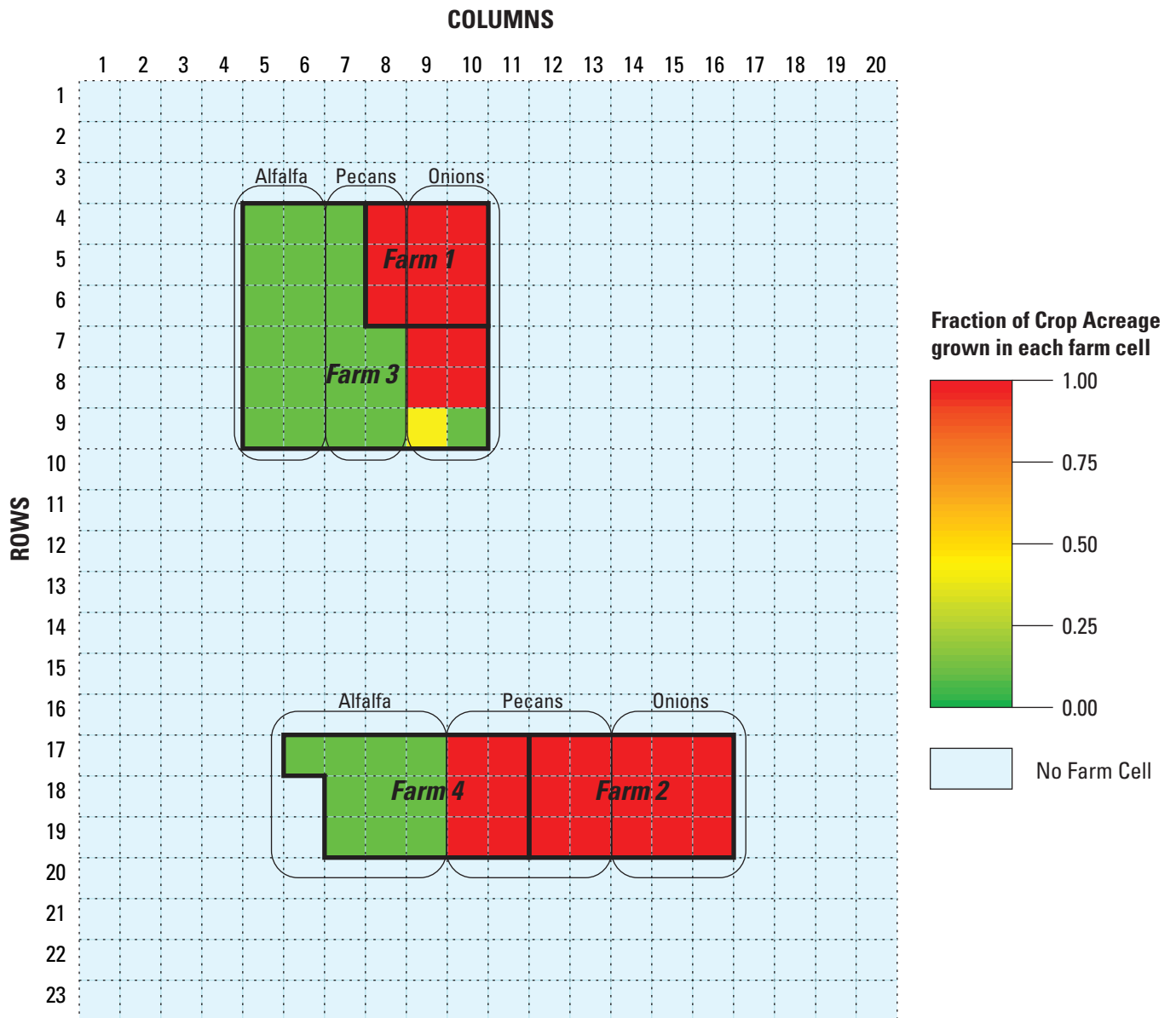


Figure 20. Spatial distribution of fractions of crop acreage for farm cells in example problem 2.

References Cited

- Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., 1998, Crop evapotranspiration - Guidelines for computing crop water requirements: Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper 56, 300 p.
- Arnold, J.G., Williams, J.R., Srinivasan, R., King, K.W., and Griggs, R.H., 1994, SWAT (Soil and Water Assessment Tool) User's Manual. Temple, Texas: USDA, Agricultural Research Service, Grassland, Soil, and Water Research Laboratory, <http://www.brc.tamus.edu/swat/>, accessed December 13, 2005.
- Brooks, R.H. and Corey, A.T., 1964, Hydraulic properties of porous media: Colorado State University, Hydrology paper 3, p. 22–27.
- Brouwer, C., Goffeau, A., and Heibloem, M., 1985, Introduction into irrigation: Food and Agriculture Organization of the United Nations, Land and Water Development Division, Irrigation Water Management: Training manual No. 1, <http://www.fao.org/docrep/R4082E/R4082E00.htm>, accessed September 2005.
- Brouwer, C. and Heibloem, M., 1986, Irrigation water needs: Food and Agriculture Organization of the United Nations, Land and Water Development Division, Irrigation Water Management: Training manual No. 3, <http://www.fao.org/docrep/S2022E/S2022E00.htm>, accessed September 2005.
- California Department of Water Resources, 2005a, Integrated Water Flow Model (IWFM v2.3): Theoretical documentation. Hydrol. Development Unit, Modeling Support Branch, Bay-Delta Office, Sacramento, various pagination, <http://modeling.water.ca.gov/hydro/model/iwfm/documentation.html>, last accessed December 16, 2005.
- California Department of Water Resources, 2005b, Integrated Water Flow Model (IWFM v2.3): User's manual. Hydrol. Development Unit, Modeling Support Branch, Bay-Delta Office, Sacramento, various pagination, <http://modeling.water.ca.gov/hydro/model/iwfm/documentation.html>, last accessed December 16, 2005.
- Colorado's Decision Support Systems, 1995, <http://cdss.state.co.us/develop/taskmemo/1-19/01.14-08.pdf>, accessed September 2005.
- Dastane, N.G., 1978, Effective rainfall in irrigated agriculture: Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper No. 25, 61 p.
- Doorenbos, J. and Kassam, A.H., 1979, Yield response to water: Irrigation and drainage: Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper No. 33, 193 p.
- Doorenbos, J. and Pruitt, W.O., 1977, Guidelines for predicting crop water requirements: Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper No. 24, (revised) 144 p.
- European Environment Agency, 2004, EEA multilingual environmental glossary: http://glossary.eea.eu.int/EEAGlossary/C/consumptive_use_of_water, accessed September 2005.
- Feddes, R.A., Kowalik, P.J., and Zaradny, H., 1978, Field test of a modified numerical model for water uptake by root systems: Water Resources Research, vol. 10, no. 6, p. 1199–1206.
- Gelt, J., Henderson, J., Seesholes, K., Tellman, B., and Woodard, G., 1999, Water in the Tucson Area: Seeking Sustainability —A status report prepared by the Water Resources Research Center: College of Agriculture, The University of Arizona. Issue Paper No. 20, 155 p.
- Halford, K.J. and Hanson, R.T., 2002, User guide for the drawdown-limited, Multi-Node Well (MNW) Package for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, versions MODFLOW-96 and MODFLOW-2000: U.S. Geological Survey Open-File Report 02-293, 33 p. (<http://water.usgs.gov/pubs/of/2002/ofr02293/>)
- Hanson, R.T., Martin, Peter, and Kocot, K.M., 2003, Simulation of ground-water/surface-water flow in the Santa Clara-Calleguas Basin, California: U.S. Geological Survey Water-Resources Investigation Report 02-4136, 214 p. (<http://water.usgs.gov/pubs/wri/wri024136/>)

- Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.
- Hoffman, G.J., Howell, T.A., and Solomon, K.H., eds., 1992, Management of farm irrigation systems: American Society of Agricultural Engineers, Monograph no. 9, 1040 p.
- McCurry, G.N., 2000, Modeling the effects of climate change on the hydrology and water rights of a semi-arid irrigated watershed. Dissertation. University of Colorado at Boulder, 361 p.
- McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water Resources Investigations, Book 6, chap. A1, 586 p.
- Montgomery Watson, 1993, Integrated Groundwater and Surface Water Model Documentation and User Manual, various pagination.
- Mualem, Y., 1976, A new model for predicting the hydraulic conductivity of unsaturated porous media: Water Resources Research, vol. 12, no. 3, p. 513–522.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., and King, K.W., 2002, Soil and Water Assessment Tool, Theoretical Documentation, Version 2000, Grassland, Soil and Water Research Laboratory, USDA-ARS, Temple, Texas. Published by Texas Water Resources Institute, College Station, Texas: TWRI Report TR-191, <http://www.brc.tamus.edu/swat/downloads/doc/swat2000theory.pdf>, accessed December 13, 2005.
- New Mexico State University Climate Center, 1996, <http://weather.nmsu.edu/cropinfo.htm>, accessed September 2005.
- Perkins, S.P., and Sophocleous, M.A., 1999a, Development of a comprehensive watershed model applied to study stream yield under drought conditions: Ground Water, vol. 37, no. 3, p. 418-426.
- Perkins, S.P., and Sophocleous, M.A., 1999b, Documentation of a combined watershed and stream-aquifer modeling program based on SWAT and MODFLOW. vol. 1. User's manual: Kansas Geological Survey, Open-File Report 99-24, 120 p.
- Prudic, D.E., Konikow, L.F., and Banta, E.A., 2004, A new Streamflow-Routing (SFR1) Package to simulate stream-aquifer interaction with MODFLOW-2000: U.S. Geological Survey Open-File Report 04-1042, 95 p.
- Ravi, V. and Williams, J.R., 1998, Estimation of infiltration rate in the vadose zone (vol. 1): Compilation of simple mathematical models: U.S. Environmental Protection Agency, Subsurface Protection and Remediation Division, National Risk Management Research Laboratory, Ada, Oklahoma, 74820 (EPA/600/R-97/128a), 26 pages of paginated text, 50 pages unpaginated appendices .
- Robinson, T.W., 1958, Phreatophytes: U.S. Geological Survey Water-Supply Paper 1423, 84 p.
- Sammis T.W., Mapel, C.L., Lugg, D.G., Lansford, R.R., and McGuckin, J.T., 1985, Evapotranspiration Crop Coefficients Predicted Using Growing Degree Days: ASAE, vol. 28, no. 3, p.773–780.
- Schmid, W., 2004, A Farm Package for MODFLOW-2000: Simulation of Irrigation Demand and Conjunctively Managed Surface-Water and Ground-Water Supply; PhD Dissertation: Department of Hydrology and Water Resources, The University of Arizona, 278 p.
- Simunek, J., Sejna, M., and van Genuchten, M.Th., 1999, HYDRUS-2D/MESHGEN-2D. Simulating water flow and solute transport in two-dimensional variably saturated media.- Handbook, International Groundwater Modeling Center – TPS 53C, Version 2.0, Colorado School of Mines, 227 p.
- Sophocleous, M.A., Koelliker, J.K., Govindaraju, R.S., Birdie, T., Ramireddygar, S.R., Perkins, S.P., 1999, Integrated Numerical Modeling for Basin-wide Water Management—The Case of the Rattlesnake Creek Basin in South-central Kansas: Journal of Hydrology, vol. 214, no. 1–4, p. 179–196.
- Sophocleous, M.A., and Perkins, S.P., 2000, Methodology and application of combined watershed and ground-water models in Kansas: Journal of Hydrology, vol. 236, no. 3–4, p. 185–201.

U.S. Department of Agriculture Natural Resources Conservation Service, 2005a, State Soil Geographic (STATSGO) Database: USDA Natural Resources Conservation Service, accessed September 12, 2005, at <http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/>

U.S. Department of Agriculture Natural Resources Conservation Service, 2005b, Soil Survey Geographic (SSURGO) Database: USDA Natural Resources Conservation Service, accessed September 12, 2005, at <http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/>

van Genuchten, M.Th., 1980, A closed-form equation for predicting the hydraulic conductivity of unsaturated soils: Soil Science Society of America Journal, vol. 44, p. 892–898.

van Genuchten, M.T., Leij, F.J., and Yates, S.R., 1991, The RETC code for quantifying the hydraulic functions of unsaturated soils: U.S. Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory, EPA/600/S2-9/065.

Williamson, A. K., Prudic, D. P., Swain, L.W., 1989, Ground-water Flow in the Central Valley, California: U.S. Geological Survey Professional Paper 1401-D, 127 p.

Appendix

Appendix: Input Data for Example Problems

The test problem illustrates basic features of the Farm Process (FMP1). Details of the test problem and results are discussed in the section titled “Example Problem 1” and “Example Problem 2.” If data sets only are used for a particular example problem, they are noted as such.

Name File Input Data Sets

Example Problem 1:

list	6	ex1.lst
bcf6	9	ex1tr.bc6
bas6	10	ex1tr.ba6
dis	11	ex1tr.dis
fmp	12	example1.fmp
sfr	14	ex1tr-reuse.sfr
ghb	16	ex1tr.ghb
pcg	18	ex1.pcg
oc	19	ex1tr.oc
data	22	ex1.hed
data	20	OFE.in
data	30	ROOT.IN
data	40	CU.in
data	50	FTE.in
data	60	NRDV.in

Example Problem 2:

list	6	ex2.lst
bcf6	9	ex2tr.bc6
bas6	10	ex2tr.ba6
dis	11	ex2tr.dis
fmp	12	example2.fmp
sfr	14	ex2tr-reuse.sfr
ghb	16	ex2tr.ghb
pcg	18	ex2.pcg
oc	19	ex2tr.oc
data	22	ex2.hed
data	50	FTE.in
data	60	NRDV.in

Basic (BAS) Package Input Data Set

Example models 1 and 2

free

constant 1

-.999

internal 1. (free) -1

297.99 296.88 295.76 294.64 293.52 292.40 291.27 290.16 289.04 287.94 286.84 285.76 284.69 283.64 282.60 281.57 280.56 279.57 278.58 277.61
 297.99 296.88 295.76 294.64 293.52 292.39 291.27 290.14 289.03 287.92 286.83 285.74 284.67 283.62 282.58 281.56 280.55 279.55 278.57 277.60
 297.99 296.88 295.77 294.64 293.51 292.38 291.25 290.12 289.00 287.89 286.79 285.71 284.63 283.58 282.54 281.52 280.51 279.52 278.54 277.57
 298.00 296.88 295.76 294.63 293.50 292.36 291.22 290.09 288.96 287.84 286.74 285.65 284.58 283.52 282.49 281.47 280.46 279.47 278.49 277.52
 298.00 296.89 295.77 294.63 293.49 292.34 291.19 290.04 288.90 287.77 286.66 285.57 284.49 283.44 282.41 281.39 280.40 279.41 278.43 277.47
 298.01 296.90 295.77 294.63 293.47 292.31 291.14 289.98 288.82 287.68 286.55 285.46 284.38 283.34 282.31 281.30 280.31 279.33 278.36 277.40
 298.03 296.91 295.78 294.63 293.46 292.28 291.10 289.91 288.72 287.56 286.42 285.31 284.24 283.21 282.19 281.19 280.21 279.24 278.28 277.32
 298.05 296.94 295.80 294.64 293.46 292.26 291.05 289.82 288.60 287.40 286.24 285.13 284.07 283.05 282.05 281.07 280.10 279.13 278.18 277.23
 298.09 296.97 295.83 294.66 293.47 292.25 291.00 289.73 288.46 287.21 286.01 284.88 283.86 282.87 281.89 280.92 279.97 279.02 278.07 277.13
 298.14 297.03 295.89 294.71 293.50 292.26 290.97 289.64 288.30 286.97 285.69 284.52 283.60 282.66 281.72 280.77 279.83 278.89 277.96 277.03
 298.21 297.10 295.96 294.79 293.57 292.30 290.98 289.63 288.26 286.90 285.57 284.25 283.38 282.46 281.54 280.61 279.68 278.76 277.85 276.93
 298.29 297.19 296.07 294.90 293.69 292.39 291.03 289.63 288.21 286.81 285.43 284.05 283.19 282.28 281.36 280.44 279.52 278.63 277.73 276.83
 298.38 297.30 296.20 295.07 293.87 292.54 291.11 289.64 288.15 286.68 285.27 284.04 283.04 282.10 281.17 280.26 279.35 278.49 277.63 276.75
 298.30 297.20 296.07 294.92 293.71 292.42 291.07 289.70 288.31 286.95 285.65 284.44 283.36 282.33 281.34 280.35 279.33 278.53 277.67 276.78
 298.22 297.11 295.98 294.81 293.61 292.36 291.06 289.75 288.45 287.16 285.91 284.73 283.61 282.53 281.50 280.48 279.46 278.62 277.75 276.84
 298.15 297.04 295.90 294.74 293.55 292.32 291.06 289.80 288.55 287.32 286.11 284.94 283.80 282.70 281.63 280.59 279.63 278.75 277.84 276.93
 298.10 296.99 295.85 294.70 293.52 292.32 291.10 289.87 288.66 287.46 286.27 285.12 283.99 282.90 281.84 280.81 279.83 278.89 277.95 277.02
 298.06 296.95 295.82 294.67 293.51 292.32 291.13 289.93 288.74 287.57 286.40 285.26 284.15 283.06 282.00 280.98 279.98 279.01 278.06 277.12
 298.04 296.92 295.79 294.65 293.50 292.33 291.16 289.98 288.81 287.65 286.51 285.38 284.28 283.19 282.14 281.11 280.10 279.12 278.15 277.20
 298.02 296.90 295.78 294.64 293.50 292.34 291.18 290.02 288.87 287.72 286.59 285.47 284.37 283.29 282.24 281.21 280.20 279.20 278.23 277.27
 298.00 296.89 295.77 294.63 293.49 292.35 291.20 290.05 288.91 287.77 286.64 285.53 284.44 283.36 282.31 281.28 280.26 279.27 278.29 277.32
 298.00 296.88 295.76 294.63 293.49 292.35 291.21 290.07 288.93 287.80 286.68 285.57 284.48 283.41 282.35 281.32 280.30 279.31 278.33 277.36
 297.99 296.88 295.76 294.63 293.49 292.36 291.22 290.08 288.94 287.81 286.70 285.59 284.50 283.43 282.38 281.34 280.33 279.33 278.34 277.38

Discretization File (DIS) Input Data Set

Example Problem 1 transient discretization file

1 23 20 4 4 2

0

constant 500

constant 500

OPEN/CLOSE GSE.IN 1.0 (FREE) -1

constant 0

91 13 1 TR

91 13 1 TR

92 13 1 TR

91 13 1 TR

Block-Centered Flow (BCF) Package Input Data Set

-1 2222 0 0 0 0 0

1 0 UNCONFINED

constant 1.0 TRPY

constant 0.05 SF1 SPECIFIC YIELD IF TRANSIENT/UNCONFINED

constant 5. HY OF LAYER 1

PCG2 Package Input Data Set

1000 10 1 NPCOND 1 - mod. incomplete, 2 - polynomial

0.008 10 1. 2 1 1 0 HCLOSE(head),RCLOSE(FLOWRATE: should be relatively higher for m³/day)

Output Control (OC) Package Input Data Set

head print format -3
head save format (20F8.2) label
head save unit 22
period 1 step 13
print head
print budget
save head
save budget
period 2 step 13
print head
print budget
save head
save budget
period 3 step 13
print head
print budget
save head
save budget
period 4 step 13
print head
print budget
save head
save budget

Streamflow Routing (SFR1) Package Input Data Set

Farm Process Example 1 -- SFR1 (acronyms used in explanations: GSE = Ground-surface elevation, ss = Steady-State)
88 11 0 0 86400 0.0001 -1 0 NSTRM NSS NSTRPAR NPARSEG CONST DLEAK ISTCB1 ISTCB2
1 13 11 1 500 KRCH IRCH JRCH ISTRM4 ISTRM5 RCHLEN
1 13 21 2 500
1 13 31 3 500
1 12 32 1 500
1 11 32 2 500
1 10 32 3 500
1 9 32 4 500
1 8 32 5 500
1 7 32 6 500
1 6 32 7 500
1 5 32 8 500
1 4 32 9 500

1 3 3 2 10 500
1 3 4 2 11 500
1 3 5 2 12 500
1 3 6 2 13 500
1 3 7 2 14 500
1 3 8 2 15 500
1 3 9 2 16 500
1 3 10 2 17 500
1 3 11 2 18 500
1 3 12 2 19 500
1 4 12 2 20 500
1 5 12 2 21 500
1 6 12 2 22 500
1 7 12 2 23 500
1 8 12 2 24 500
1 9 12 2 25 500
1 10 7 3 1 500
1 10 8 3 2 500
1 10 9 3 3 500
1 10 10 3 4 500
1 10 11 3 5 500
1 10 12 4 1 500
1 11 12 4 2 500
1 12 12 4 3 500
1 13 4 5 1 500
1 13 5 5 2 500
1 14 5 6 1 500
1 15 5 6 2 500
1 16 5 6 3 500
1 17 5 6 4 500
1 18 5 6 5 500
1 19 5 6 6 500
1 20 5 6 7 500
1 20 6 6 8 500
1 20 7 6 9 500
1 20 8 6 10 500

```

1 20 9 6 11 500
1 20 10 6 12 500
1 20 11 6 13 500
1 20 12 6 14 500
1 20 13 6 15 500
1 20 14 6 16 500
1 20 15 6 17 500
1 20 16 6 18 500
1 20 17 6 19 500
1 19 17 6 20 500
1 18 17 6 21 500
1 17 17 6 22 500
1 16 7 7 1 500
1 16 8 7 2 500
1 16 9 7 3 500
1 16 10 7 4 500
1 16 11 7 5 500
1 16 12 7 6 500
1 16 13 7 7 500
1 16 14 7 8 500
1 16 15 7 9 500
1 16 16 7 10 500
1 16 17 8 1 500
1 15 17 8 2 500
1 14 17 8 3 500
1 13 6 9 1 500
1 13 7 9 2 500
1 13 8 9 3 500
1 13 9 9 4 500
1 13 10 9 5 500
1 13 11 9 6 500
1 13 12 10 1 500
1 13 13 10 2 500
1 13 14 10 3 500
1 13 15 10 4 500
1 13 16 10 5 500
1 13 17 11 1 500
1 13 18 11 2 500
1 13 19 11 3 500
1 13 20 11 4 500
1 1 1 0 ITMP IRDFLG IPTFLG
1 1 5 0 50000. 0. 0. 0. 0.03 NSEG ICALC OUTSEG IUPSEG FLOW RUNOFF ETSW PPTSW
0.06 1. 298.5 30. HCOND1 THICKM1 ELEVUP WIDTH1 (DEPTH1)
0.06 1. 295.5 30. HCOND2 THICKM2 ELEVDN WIDTH2 (DEPTH2)
2 1 4 1 0 20000. 0. 0. 0. 0.03 fifth place: IPRIOR
0.001 1. 296.55 15. GSE = 296.55
0.001 1. 286.98 15. GSE = 286.98; ss head = 286.65
3 1 4 0 0. 0. 0. 0. 0.03
0.1 1. 291.70 10. GSE = 292.40; ss head = 291.30
0.1 1. 284.00 10. ss head = 287.65
4 1 10 0 0. 0. 0. 0. 0.03
0.1 1. 284.00 15.
0.1 1. 282.3 15.
5 1 9 0 0. 0. 0. 0. 0.03
0.06 1. 295.5 30.
0.06 1. 293.5 30.

```

```

6 1 8 5 0 20000. 0. 0. 0. 0.03
0.001 1. 294.61 15.      GSE = 294.61
0.001 1. 281.67 15.      GSE = 281.67; ss head = 280.25
7 1 8 0 0. 0. 0. 0. 0.03
0.1 1. 291.50 10.      GSE = 292.42; ss head = 291.26
0.1 1. 279.50 10.      ss head = 281.10
8 1 11 0 0. 0. 0. 0. 0.03
0.1 1. 279.50 15.
0.1 1. 278.30 15.
9 1 10 0 0. 0. 0. 0. 0.03
0.06 1. 293.5 30.
0.06 1. 282.7 30.
10 1 11 0 0. 0. 0. 0. 0.03
0.06 1. 282.7 30.
0.06 1. 278.7 30.
11 1 0 0 0. 0. 0. 0. 0.03
0.06 1. 278.7 30.
0.06 1. 275.5 30.
-1 0 0
-1 0 0
-1 0 0
    
```

General-Head Boundary (GHB) Package Input Data Set

```

46 -1
46
1      1      1      320.1469851      74.4975
1      2      1      320.1469851      74.4975
1      3      1      320.146314      74.4975
1      4      1      320.1532886      74.5
1      5      1      320.1475168      74.5
1      6      1      320.1440223      74.5025
1      7      1      320.1491155      74.5075
1      8      1      320.1389113      74.5125
1      9      1      320.1368986      74.5225
1      10     1      320.1289985      74.535
1      11     1      320.1309282      74.5525
1      12     1      320.1237859      74.5725
1      13     1      320.1149688      74.595
1      14     1      320.1280925      74.575
1      15     1      320.1309382      74.555
1      16     1      320.1354436      74.5375
1      17     1      320.1313989      74.525
1      18     1      320.132737      74.515
1      19     1      320.1430734      74.51
1      20     1      320.1481793      74.505
1      21     1      320.1416107      74.5
1      22     1      320.1548993      74.5
1      23     1      320.1417501      74.4975
1      1      20     258.4039195      69.4025
1      2      20     258.4110951      69.4
1      3      20     258.4051047      69.3925
1      4      20     258.3953243      69.38
1      5      20     258.3931989      69.3675
1      6      20     258.3959625      69.35
1      7      20     258.3836088      69.33
1      8      20     258.3836991      69.3075
    
```


1	9	20	258.3736041	69.2825
1	10	20	258.3689164	69.2575
1	11	20	258.3723862	69.2325
1	12	20	258.3626374	69.2075
1	13	20	258.3615628	69.1875
1	14	20	258.3555474	69.195
1	15	20	258.3556769	69.21
1	16	20	258.3696418	69.2325
1	17	20	258.3712382	69.255
1	18	20	258.375918	69.28
1	19	20	258.3809524	69.3
1	20	20	258.3838601	69.3175
1	21	20	258.3864936	69.33
1	22	20	258.3917277	69.34
1	23	20	258.3893013	69.345
-1	0			
-1	0			
-1	0			

Farm Process (FMP1) Input Data Sets

Example Problem 1:

Farm Process: example 1 -- ZERO SCENARIO / EQUAL APPROPRIATION

PARAMETER 1 10

10 4 3 3 2 2 2 2 0 2 1 0 0 1 1 4 1 1 1 -1 -1 1

WELLS1 QMAX 1.0 8

OPEN/CLOSE WELLS.IN FREE -1

OPEN/CLOSE GSE.IN 1.0 (FREE) -1

OPEN/CLOSE FID.IN 1 (FREE) -1

OPEN/CLOSE SID.IN 1 (FREE) -1

OPEN/CLOSE SOILLIST.IN

OPEN/CLOSE CID.IN 1 (FREE) -1

OPEN/CLOSE PSI.IN

OPEN/CLOSE SRD.IN

2 1

OPEN/CLOSE WELLSNON.IN

WELLS1

EXTERNAL 20 OFE.IN

EXTERNAL 30 ROOT.IN

EXTERNAL 40 CU.IN

EXTERNAL 50 FTE.IN

CONSTANT 0.000519

EXTERNAL 60 NRDV.IN

0.2

2 1

OPEN/CLOSE WELLSNON.IN

WELLS1

EXTERNAL 20 OFE.IN

EXTERNAL 30 ROOT.IN

EXTERNAL 40 CU.IN

EXTERNAL 50 FTE.IN

CONSTANT 0.000179

EXTERNAL 60 NRDV.IN

0.3

2 1

OPEN/CLOSE WELLSNON.IN

WELLS1

EXTERNAL 20 OFE.IN
 EXTERNAL 30 ROOT.IN
 EXTERNAL 40 CU.IN
 EXTERNAL 50 FTE.IN
 CONSTANT 0.000482
 EXTERNAL 60 NRDV.IN
 0.1
 2 1
 OPEN/CLOSE WELLSNON.IN
 WELLS1
 EXTERNAL 20 OFE.IN
 EXTERNAL 30 ROOT.IN
 EXTERNAL 40 CU.IN
 EXTERNAL 50 FTE.IN
 CONSTANT 0.001107
 EXTERNAL 60 NRDV.IN
 0.05

Example Problem 2:

Farm Process: example problem 2 -- ACREAGE-OPTIMIZATION / PRIOR APPROPRIATION

PARAMETER 1 10
 10 4 3 3 3 3 2 1 1 1 0 1 1 1 1 1 4 0 1 3 1e-2 -1 -1 1 1 1
 WELLS1 QMAX 1.0 10
 OPEN/CLOSE WELLS.IN
 OPEN/CLOSE GSE.IN 1.0 (FREE) -1
 OPEN/CLOSE FID.IN 1 (FREE) -1
 OPEN/CLOSE OFE.IN
 OPEN/CLOSE SID.IN 1 (FREE) -1
 OPEN/CLOSE SOILLIST.IN
 OPEN/CLOSE CID.IN 1 (FREE) -1
 OPEN/CLOSE INEFFSW.IN
 OPEN/CLOSE PSI.IN
 OPEN/CLOSE CROPLIST.IN
 OPEN/CLOSE CLIMATE.IN
 OPEN/CLOSE CROPBEN.IN
 CONSTANT 0.1 0.04 0.08 0. 0.28 0. 0. 0.28
 0 1
 WELLS1
 EXTERNAL 50 FTE.IN
 EXTERNAL 60 NRDV.IN
 0 1
 WELLS1
 EXTERNAL 50 FTE.IN
 EXTERNAL 60 NRDV.IN
 0 1
 WELLS1
 EXTERNAL 50 FTE.IN
 EXTERNAL 60 NRDV.IN
 0 1
 WELLS1
 EXTERNAL 50 FTE.IN
 EXTERNAL 60 NRDV.IN

Farm Process (FMP1) Ancillary Input Data Sets

Example Problems 1 and 2:

Farm Wells – WELLS.IN (parameter wells for problem 1 only)

114 User Guide for the Farm Process (FMP1) for the U.S. Geological Survey's MODFLOW-2000

1 5 6 1 1 5000
 1 5 9 2 2 3000
 1 6 10 3 2 2000
 1 7 11 4 2 1000
 1 8 6 5 1 500
 1 8 9 6 1 500
 1 18 3 7 3 2000
 1 18 19 8 4 3000

Farm Wells – WELLSNON.IN (non parameter wells for problem 1 only)

1 21 3 9 3 4000
 1 21 19 10 4 5000

Farm Wells – WELLS.IN (parameter wells for problem 2 only)

1 5 6 1 3 5000
 1 5 9 2 1 3000
 1 6 10 3 1 2000
 1 7 11 4 1 1000
 1 8 6 5 3 500
 1 8 9 6 3 500
 1 18 3 7 4 2000
 1 18 19 8 2 3000
 1 21 3 9 4 4000
 1 21 19 10 2 5000

Ground-Surface Elevation – GSE.IN

298.50	297.53	296.55	295.58	294.61	293.63	292.66	291.68	290.71	289.74	288.76	287.79	286.82	285.84	284.87	283.89	282.92	281.95	280.97	280.00
298.50	297.53	296.55	295.58	294.61	293.62	292.63	291.64	290.65	289.66	288.68	287.69	286.70	285.71	284.72	283.74	282.75	281.76	280.77	279.78
298.50	297.53	296.55	295.58	294.61	293.60	292.60	291.60	290.59	289.59	288.59	287.59	286.58	285.58	284.58	283.58	282.57	281.57	280.57	279.57
298.50	297.53	296.55	295.58	294.61	293.59	292.57	291.55	290.54	289.52	288.50	287.49	286.47	285.45	284.44	283.42	282.40	281.38	280.37	279.35
298.50	297.53	296.55	295.58	294.61	293.57	292.54	291.51	290.48	289.45	288.42	287.39	286.35	285.32	284.29	283.26	282.23	281.20	280.16	279.13
298.50	297.53	296.55	295.58	294.61	293.56	292.51	291.47	290.42	289.38	288.33	287.28	286.24	285.19	284.15	283.10	282.05	281.01	279.96	278.92
298.50	297.53	296.55	295.58	294.61	293.54	292.48	291.42	290.36	289.30	288.24	287.18	286.12	285.06	284.00	282.94	281.88	280.82	279.76	278.70
298.50	297.53	296.55	295.58	294.61	293.53	292.46	291.38	290.31	289.23	288.16	287.08	286.01	284.93	283.86	282.78	281.71	280.63	279.56	278.48
298.50	297.53	296.55	295.58	294.61	293.52	292.43	291.34	290.25	289.16	288.07	286.98	285.89	284.80	283.71	282.62	281.53	280.45	279.36	278.27
298.50	297.53	296.55	295.58	294.61	293.50	292.40	291.29	290.19	289.09	287.98	286.88	285.78	284.67	283.57	282.46	281.36	280.26	279.15	278.05
298.50	297.53	296.55	295.58	294.61	293.49	292.37	291.25	290.13	289.01	287.90	286.78	285.66	284.54	283.42	282.31	281.19	280.07	278.95	277.83
298.50	297.53	296.55	295.58	294.61	293.47	292.34	291.21	290.07	288.94	287.81	286.68	285.54	284.41	283.28	282.15	281.01	279.88	278.75	277.62
298.50	297.53	296.55	295.58	294.61	293.46	292.31	291.16	290.02	288.87	287.72	286.58	285.43	284.28	283.14	281.99	280.84	279.69	278.55	277.4
298.50	297.53	296.55	295.58	294.61	293.48	292.35	291.22	290.09	288.96	287.83	286.70	285.57	284.44	283.31	282.18	281.05	279.92	278.79	277.66
298.50	297.53	296.55	295.58	294.61	293.49	292.38	291.27	290.16	289.04	287.93	286.82	285.71	284.59	283.48	282.37	281.26	280.14	279.03	277.92
298.50	297.53	296.55	295.58	294.61	293.51	292.42	291.32	290.23	289.13	288.04	286.94	285.85	284.75	283.66	282.56	281.47	280.37	279.28	278.18
298.50	297.53	296.55	295.58	294.61	293.53	292.45	291.37	290.29	289.22	288.14	287.06	285.98	284.91	283.83	282.75	281.67	280.60	279.52	278.44
298.50	297.53	296.55	295.58	294.61	293.54	292.48	291.42	290.36	289.30	288.24	287.18	286.12	285.06	284.00	282.94	281.88	280.82	279.76	278.70
298.50	297.53	296.55	295.58	294.61	293.56	292.52	291.48	290.43	289.39	288.35	287.30	286.26	285.22	284.18	283.13	282.09	281.05	280.00	278.96
298.50	297.53	296.55	295.58	294.61	293.58	292.55	291.53	290.50	289.48	288.45	287.43	286.40	285.37	284.35	283.32	282.30	281.27	280.25	279.22
298.50	297.53	296.55	295.58	294.61	293.60	292.59	291.58	290.57	289.56	288.56	287.55	286.54	285.53	284.52	283.51	282.51	281.50	280.49	279.48
298.50	297.53	296.55	295.58	294.61	293.61	292.62	291.63	290.64	289.65	288.66	287.67	286.68	285.69	284.70	283.70	282.71	281.72	280.73	279.74
298.50	297.53	296.55	295.58	294.61	293.63	292.66	291.68	290.71	289.74	288.76	287.79	286.82	285.84	284.87	283.89	282.92	281.95	280.97	280.00

Soil-IDs – SID.IN

```

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 1 1 1 2 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 1 1 2 2 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 1 2 2 2 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 2 2 2 2 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 1 2 2 2 2 3 3 3 3 3 3 0 0 0 0
0 0 0 0 0 0 1 2 2 2 2 3 3 3 3 3 3 0 0 0 0
0 0 0 0 0 0 1 1 2 2 2 2 3 3 3 3 3 3 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

```

Soil-Type List – SOILLIST.IN (problem 1 only)

```

1 1.8 SILT
2 1.3 SANDYLOAM
3 1.5 SILTYCLAY

```

Soil-Type List – SOILLIST.IN (problem 2 only)

```

SFAC 0.5
1 3.6 SILT
2 2.6 SANDYLOAM
3 3.0 SILTYCLAY

```

Crop-IDs – CID.IN

```

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 2 2 3 3 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 2 2 3 3 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 2 2 3 3 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 2 2 3 3 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 2 2 3 3 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 1 2 2 3 3 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

```

```

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 1 1 1 1 2 2 2 2 3 3 3 0 0 0 0 0
0 0 0 0 0 0 1 1 1 2 2 2 2 3 3 3 0 0 0 0 0
0 0 0 0 0 0 1 1 1 2 2 2 2 3 3 3 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

```

Unsaturated-Zone Pressure Heads – PSI.IN

```

1 0.15 0.3 15. 80.
2 0.15 0.3 5.5 80.
3 0.15 0.3 5. 80.

```

Semi-Routed Deliveries – SRD.IN (problem 1 only)

```

1 3 5
2 0 0
3 0 0
4 0 0

```

Farm Irrigation Efficiency – OFE.IN (problem 1 only)

```

SFAC 0.7
1 0.7
2 0.7
3 0.8
4 0.8
SFAC 0.9
1 0.7
2 0.7
3 0.8
4 0.8
SFAC 1.0
1 0.7
2 0.7
3 0.8
4 0.8
SFAC 0.9
1 0.7
2 0.7
3 0.8
4 0.8

```

Farm Irrigation Efficiency – OFE.IN (problem 2 only)

1 0.7
2 0.8
3 0.7
4 0.8

Root-Zone Depths – ROOT.IN

1 1.524
2 1.219
3 0.1016
1 1.524
2 1.219
3 0.2892
1 1.524
2 1.219
3 0.4572
1 1.524
2 1.219
3 0.4572

Crop Consumptive Uses – CU.IN (problem 1 only)

SFAC 0.3048
1 0.00787
2 0.00308
3 0.00692
SFAC 0.3048
1 0.02904
2 0.01329
3 0.02533
SFAC 0.3048
1 0.02103
2 0.02966
3 0.00338
SFAC 0.3048
1 0.00220
2 0.01407
3 0.00000

Fractions of Crop Consumptive Uses as Transpiration and Evaporation – FTE.IN

1 0.4 0.6 0.5
 2 0.7 0.3 0.2
 3 0.5 0.5 0.5
 1 0.6 0.4 0.3
 2 0.8 0.2 0.1
 3 0.5 0.5 0.5
 1 0.8 0.2 0.1
 2 0.9 0.1 0.0
 3 0.5 0.5 0.5
 1 0.4 0.6 0.5
 2 0.7 0.3 0.2
 3 0.5 0.5 0.5

Nonrouted Surface-water Deliveries – NRDV.IN (problem 1 only)

1 45500 1 0 45500 2 0 45500 3 0 45500 4 0
 2 45500 4 0 45500 1 0 45500 3 0 45500 2 0
 3 318500 1 0 45500 2 0 45500 3 0 45500 4 0
 4 0 1 0 0 2 0 0 3 0 0 4 0
 1 45500 1 0 45500 2 0 45500 3 0 45500 4 0
 2 45500 4 0 45500 1 0 45500 3 0 45500 2 0
 3 318500 1 0 45500 2 0 45500 3 0 45500 4 0
 4 0 1 0 0 2 0 0 3 0 0 4 0

SFAC OPEN/CLOSE NRDFAC.IN

1 45500 1 0 45500 2 0 45500 3 0 45500 4 0
 2 45500 4 0 45500 1 0 45500 3 0 45500 2 0
 3 318500 1 0 45500 2 0 45500 3 0 45500 4 0
 4 0 1 0 0 2 0 0 3 0 0 4 0
 1 45500 1 0 45500 2 0 45500 3 0 45500 4 0
 2 45500 4 0 45500 1 0 45500 3 0 45500 2 0
 3 318500 1 0 45500 2 0 45500 3 0 45500 4 0
 4 0 1 0 0 2 0 0 3 0 0 4 0

Nonrouted Surface-water Deliveries – NRDV.IN (problem 2 only)

1 45500 4 0 45500 1 0 45500 3 0 45500 2 0
 2 0 1 0 0 2 0 0 3 0 0 4 0
 3 45500 1 0 45500 2 0 45500 3 0 45500 4 0
 4 318500 1 1 45500 2 1 45500 3 1 45500 4 2
 1 45500 4 0 45500 1 0 45500 3 0 45500 2 0
 2 0 1 0 0 2 0 0 3 0 0 4 0
 3 45500 1 0 45500 2 0 45500 3 0 45500 4 0
 4 318500 1 1 45500 2 1 45500 3 1 45500 4 2

SFAC OPEN/CLOSE NRDFAC.IN

1 45500 4 0 45500 1 0 45500 3 0 45500 2 0
 2 0 1 0 0 2 0 0 3 0 0 4 0
 3 45500 1 0 45500 2 0 45500 3 0 45500 4 0
 4 318500 1 1 45500 2 1 45500 3 1 45500 4 2
 1 45500 4 0 45500 1 0 45500 3 0 45500 2 0
 2 0 1 0 0 2 0 0 3 0 0 4 0
 3 45500 1 0 45500 2 0 45500 3 0 45500 4 0
 4 318500 1 1 45500 2 1 45500 3 1 45500 4 2

Scaling for Nonrouted Surface-water Deliveries for stress period 3–NRDFAC.IN

1 1.
 2 1.010989011
 3 1.
 4 1.
 5 1.010989011
 6 1.
 7 1.
 8 1.010989011
 9 1.
 10 1.
 11 1.010989011
 12 1.
 13 1.

Additional Data Sets for Example Problem 2:

Fraction of Losses to Inefficient Surface-water Runoff–INEFFSW.IN

1 0.6 0.4
 2 0.5 0.5
 3 0.4 0.6

Crop List – CROPLIST.IN

1	5	-999	999	0.405	0.0011088	-4.2444E-07	3.55752E-11	1.524	0.001166707	1.524
2	15.55555556	-999	999	0.229	0.0015516	-2.41056E-07	-2.01787E-10	1.2192	0.000460947	1.2192
3	4.444444444	4.444444444	21.11111111	0.522353	-0.000648	1.9764E-06	-8.748E-10	0.4572	0.000460947	0.1016

Climate Time-series Data – CLIMATE.IN

1	16.11111111	-1.666666667	0	0.002286
2	17.77777778	-2.222222222	0	0.00254
3	18.33333333	1.666666667	0	0.00254
4	14.44444444	2.222222222	0.00508	0.001016

5	12.77777778	1.11111111	0	0.001778
6	10	-2.22222222	0	0.002794
7	11.11111111	-1.66666667	0	0.00254
8	12.77777778	-3.88888889	0	0.002794
9	15.55555556	-3.88888889	0	0.003048
10	16.11111111	0.55555556	0	0.003048
11	15	3.33333333	0	0.003048
12	17.22222222	-2.77777778	0	0.003048
13	15.55555556	-0.55555556	0	0.00254
14	13.88888889	-1.11111111	0	0.003048
15	14.44444444	-3.88888889	0	0.003048
16	18.88888889	0.55555556	0	0.003302
17	20.55555556	-0.55555556	0	0.003556
18	20	0	0	0.003048
19	21.66666667	-0.55555556	0	0.003556
20	16.66666667	3.33333333	0	0.003302
21	15	3.33333333	0	0.00254
22	14.44444444	-0.55555556	0	0.002794
23	16.66666667	-2.77777778	0	0.003048
24	17.22222222	-1.66666667	0	0.003048
25	18.33333333	1.66666667	0	0.004064
26	18.33333333	0.55555556	0	0.00381
27	19.44444444	-2.77777778	0	0.003302
28	21.11111111	-1.66666667	0	0.004318
29	19.44444444	-1.66666667	0	0.003302
30	17.77777778	-1.11111111	0	0.004064
31	16.11111111	-1.11111111	0	0.003302
32	16.66666667	0	0	0.003556
33	18.88888889	-3.33333333	0	0.003556
34	20.55555556	0.55555556	0	0.00508
35	13.88888889	3.88888889	0	0.003302
36	13.33333333	1.66666667	0	0.003556
37	16.66666667	-3.33333333	0	0.003302
38	17.22222222	0.55555556	0	0.004064
39	18.88888889	3.88888889	0	0.004318
40	12.77777778	4.44444444	0.004318	0.002032
41	14.44444444	-0.55555556	0	0.003302
42	14.44444444	0	0	0.003556
43	13.88888889	2.22222222	0	0.004064
44	15.55555556	-2.22222222	0	0.003048
45	16.66666667	5	0	0.00254
46	10.55555556	3.88888889	0.000762	0.00127
47	10.55555556	0.55555556	0	0.004318
48	13.33333333	-1.66666667	0.000762	0.003302
49	11.66666667	2.22222222	0	0.003048
50	13.88888889	-2.22222222	0	0.003556
51	15	1.11111111	0	0.002794
52	15.55555556	3.33333333	0	0.00381
53	17.77777778	3.88888889	0	0.00508
54	21.11111111	2.77777778	0	0.004826
55	24.44444444	2.22222222	0	0.00635
56	12.22222222	2.77777778	0	0.004318

57	12.22222222	1.11111111	0.004318	0.004572
58	11.66666667	0	0	0.004064
59	11.66666667	-2.77777778	0	0.004572
60	13.88888889	-3.88888889	0	0.004572
61	16.66666667	-1.11111111	0	0.004572
62	22.22222222	-0.55555556	0	0.005334
63	22.22222222	1.66666667	0.025146	0.005842
64	21.11111111	2.77777778	0	0.00508
65	20	8.33333333	0	0.00381
66	11.66666667	1.66666667	0	0.004572
67	13.88888889	-2.77777778	0	0.004064
68	17.22222222	-2.22222222	0	0.004826
69	17.77777778	0	0	0.00508
70	18.88888889	0.55555556	0	0.006096
71	17.22222222	0.55555556	0	0.004826
72	22.22222222	2.22222222	0	0.004826
73	23.33333333	7.22222222	0	0.004826
74	15.55555556	5.55555556	0.006604	0.004064
75	17.77777778	2.77777778	0	0.004318
76	17.77777778	7.77777778	0	0.004826
77	19.44444444	4.72222222	0.000254	0.004318
78	17.77777778	1.66666667	0	0.005334
79	21.11111111	2.22222222	0	0.005334
80	22.77777778	6.66666667	0	0.005588
81	27.22222222	5.55555556	0	0.006604
82	27.77777778	6.66666667	0	0.006096
83	28.88888889	6.66666667	0	0.007112
84	28.33333333	7.22222222	0	0.006858
85	23.33333333	7.22222222	0	0.006096
86	17.22222222	5.55555556	0	0.005842
87	25	3.33333333	0	0.007112
88	20	7.22222222	0	0.006604
89	10	3.33333333	0	0.004826
90	17.22222222	1.11111111	0	0.005842
91	22.22222222	\0	0	0.006604
92	14.44444444	3.33333333	0.000762	0.00635
93	21.11111111	0.55555556	0	0.006096
94	25.55555556	2.77777778	0	0.007112
95	23.88888889	5.55555556	0	0.006604
96	17.77777778	7.22222222	0	0.005842
97	17.22222222	2.77777778	0	0.00635
98	19.44444444	2.22222222	0	0.00635
99	23.33333333	1.66666667	0	0.00635
100	26.66666667	4.44444444	0	0.007112
101	29.44444444	7.22222222	0	0.00889
102	23.33333333	10	0	0.008636
103	23.88888889	5.55555556	0	0.007366
104	25	5	0.003556	0.008128
105	18.88888889	3.88888889	0	0.006858
106	16.11111111	6.11111111	0	0.006604
107	17.77777778	2.22222222	0	0.00635
108	21.66666667	2.77777778	0	0.006096
109	23.88888889	5	0	0.006858
110	26.66666667	6.66666667	0	0.008128
111	23.88888889	8.33333333	0	0.007366
112	27.22222222	8.33333333	0	0.007874

113	31.11111111	10.55555556	0	0.00762
114	29.44444444	13.33333333	0	0.009398
115	27.77777778	12.22222222	0	0.008382
116	20	7.77777778	0	0.00635
117	20	5	0	0.005334
118	23.33333333	5.55555556	0.00381	0.007112
119	23.88888889	10	0	0.006604
120	27.22222222	8.33333333	0	0.007112
121	29.44444444	9.44444444	0	0.008128
122	30.55555556	9.44444444	0	0.007874
123	30.55555556	8.88888889	0	0.008636
124	30.55555556	11.11111111	0	0.00889
125	29.44444444	10	0	0.008636
126	27.77777778	10	0	0.008382
127	28.88888889	8.88888889	0	0.008128
128	23.88888889	10.55555556	0	0.008382
129	27.77777778	7.22222222	0	0.007874
130	31.11111111	8.88888889	0	0.00889
131	28.88888889	10.55555556	0	0.00889
132	29.44444444	10	0	0.008636
133	30	10	0	0.00889
134	26.11111111	12.22222222	0	0.00635
135	26.66666667	7.22222222	0	0.007874
136	33.33333333	8.33333333	0	0.008636
137	33.33333333	17.22222222	0	0.00635
138	35	15	0	0.00762
139	33.88888889	16.11111111	0	0.006604
140	34.44444444	13.33333333	0	0.00635
141	31.66666667	18.33333333	0	0.005334
142	30	15	0	0.007366
143	31.11111111	13.33333333	0	0.00889
144	31.66666667	12.22222222	0	0.008636
145	31.66666667	16.11111111	0	0.008382
146	32.22222222	11.66666667	0	0.008636
147	33.33333333	12.77777778	0	0.00889
148	35	12.77777778	0	0.008636
149	35	12.22222222	0	0.009144
150	34.44444444	13.33333333	0	0.008636
151	35	13.88888889	0	0.00889
152	37.77777778	13.88888889	0	0.009652
153	38.33333333	15.55555556	0	0.009652
154	36.11111111	17.22222222	0	0.01016
155	29.44444444	16.66666667	0	0.009906
156	31.11111111	11.66666667	0	0.009144
157	31.11111111	10.55555556	0	0.009144
158	33.88888889	20.55555556	0	0.01016
159	31.11111111	13.33333333	0	0.009144
160	30.55555556	13.88888889	0	0.006604
161	23.88888889	12.77777778	0.007366	0.002032
162	27.77777778	10	0	0.006858
163	32.77777778	13.88888889	0	0.00762
164	34.44444444	19.44444444	0	0.009906
165	32.22222222	14.44444444	0	0.010414
166	33.88888889	14.44444444	0	0.009144
167	35	15.55555556	0	0.009906
168	33.88888889	16.66666667	0	0.010668

169	35.55555556	13.88888889	0	0.009398
170	38.33333333	14.44444444	0	0.009906
171	37.77777778	15	0	0.009652
172	37.22222222	16.66666667	0	0.009906
173	37.22222222	15.55555556	0	0.009652
174	37.77777778	16.66666667	0	0.009398
175	39.44444444	16.66666667	0	0.00889
176	39.44444444	7.77777778	0	0.009398
177	39.44444444	18.88888889	0	0.010414
178	40.55555556	16.11111111	0	0.009906
179	41.11111111	17.22222222	0	0.010414
180	41.11111111	20	0	0.009906
181	40.55555556	22.22222222	0.000508	0.010922
182	40	22.77777778	0.000254	0.011176
183	41.11111111	19.44444444	0.000254	0.00635
184	34.44444444	20.55555556	0	0.007874
185	35.55555556	22.22222222	0.000254	0.006858
186	34.44444444	20.55555556	0	0.007874
187	33.88888889	21.11111111	0	0.00762
188	33.33333333	19.44444444	0	0.00635
189	35	18.88888889	0.003048	0.007112
190	33.33333333	19.44444444	0	0.006604
191	37.22222222	21.11111111	0	0.008382
192	39.44444444	23.88888889	0	0.00889
193	41.66666667	24.44444444	0	0.009398
194	40.55555556	23.88888889	0	0.010414
195	41.11111111	22.77777778	0	0.009906
196	38.33333333	21.11111111	0	0.009144
197	33.88888889	22.77777778	0	0.007874
198	34.44444444	20	0	0.004572
199	35.55555556	20	0	0.007366
200	36.66666667	21.11111111	0	0.00889
201	36.11111111	21.11111111	0.01524	0.008382
202	33.88888889	18.33333333	0	0.008128
203	33.33333333	21.11111111	0.000508	0.00762
204	30.55555556	20.55555556	0.002032	0.004572
205	31.11111111	20	0	0.005842
206	32.22222222	18.88888889	0	0.007366
207	33.88888889	20.55555556	0.00127	0.007112
208	32.22222222	21.66666667	0	0.004318
209	35.55555556	22.77777778	0	0.008636
210	36.66666667	20.55555556	0	0.007874
211	35	21.66666667	0.00254	0.007112
212	33.33333333	20.55555556	0	0.006858
213	32.22222222	20.55555556	0	0.007366
214	33.33333333	21.66666667	0	0.005588
215	35.55555556	21.11111111	0.001524	0.00762
216	33.88888889	18.33333333	0.005334	0.00762
217	30	15.55555556	0	0.006858
218	31.11111111	17.77777778	0	0.007112
219	33.88888889	17.77777778	0	0.007874
220	36.11111111	18.33333333	0	0.008128
221	35	19.44444444	0	0.006604
222	36.11111111	19.44444444	0	0.00762
223	36.66666667	19.44444444	0	0.008636
224	35	20	0.000762	0.007874

225	30.55555556	18.33333333	0.008382	0.006096
226	33.33333333	18.88888889	0	0.006858
227	33.88888889	17.77777778	0	0.007366
228	34.44444444	18.88888889	0	0.007874
229	35	18.88888889	0	0.007874
230	33.33333333	20.55555556	0	0.006858
231	35.55555556	20.55555556	0	0.007366
232	31.66666667	21.11111111	0	0.006604
233	32.22222222	20.55555556	0	0.007366
234	33.33333333	19.44444444	0	0.006858
235	33.88888889	20	0	0.007112
236	36.11111111	20	0	0.00762
237	36.66666667	20	0.002794	0.00762
238	35	20.55555556	0	0.006604
239	34.44444444	21.66666667	0.000508	0.00635
240	33.33333333	22.22222222	0	0.004826
241	32.77777778	20.55555556	0	0.006096
242	32.77777778	17.77777778	0	0.007366
243	33.33333333	16.66666667	0	0.007112
244	33.33333333	18.33333333	0	0.007366
245	32.77777778	20	0	0.007366
246	28.33333333	20	0	0.002794
247	30	20	0.000254	0.003302
248	33.88888889	20	0	0.007112
249	33.88888889	17.77777778	0	0.007874
250	33.88888889	17.77777778	0	0.007874
251	33.88888889	16.66666667	0	0.007366
252	33.33333333	18.33333333	0	0.007874
253	32.77777778	19.44444444	0	0.007112
254	33.33333333	20	0	0.007366
255	32.22222222	16.66666667	0	0.006604
256	36.11111111	16.11111111	0	0.006604
257	37.77777778	21.66666667	0	0.00889
258	34.44444444	21.66666667	0	0.008128
259	31.11111111	20	0	0.006604
260	31.66666667	18.88888889	0	0.00635
26	33.33333333	17.22222222	0	0.00635
262	35	16.66666667	0	0.00635
263	32.22222222	18.33333333	0	0.00508
264	33.33333333	17.77777778	0	0.005588
265	33.33333333	15	0	0.00635
266	33.88888889	22.77777778	0	0.007112
267	35	17.77777778	0	0.00635
268	33.88888889	20	0.000254	0.00635
269	33.33333333	15.55555556	0	0.00635
270	34.44444444	12.77777778	0	0.00635
271	35	16.66666667	0	0.006858
272	34.44444444	20.55555556	0	0.005842
273	32.77777778	18.33333333	0	0.005334
274	30	16.66666667	0	0.004318
275	29.44444444	12.22222222	0	0.006604
276	30	10.55555556	0	0.00635
277	29.44444444	19.44444444	0	0.00635
278	22.77777778	10	0	0.00635
279	23.88888889	4.44444444	0	0.005588
280	26.11111111	6.66666667	0	0.005842

281	28.33333333	7.77777778	0	0.005588
282	31.11111111	9.44444444	0	0.005842
283	31.11111111	10.55555556	0	0.005842
284	31.66666667	10	0	0.006096
285	32.22222222	12.22222222	0	0.00635
286	31.11111111	13.33333333	0	0.005588
287	31.66666667	12.22222222	0	0.005588
288	30	12.77777778	0	0.006096
289	26.66666667	10	0	0.005842
290	21.66666667	7.77777778	0	0.005842
291	24.44444444	7.22222222	0.000254	0.006096
292	23.33333333	15	0.007112	0.003556
293	16.66666667	10.55555556	0.02286	0.000508
294	15	10.55555556	0.003556	0.001016
295	14.44444444	11.11111111	0.000508	0.000508
296	17.22222222	11.11111111	0	0.001524
297	21.66666667	13.33333333	0	0.002032
298	27.22222222	11.66666667	0	0.004318
299	27.22222222	16.11111111	0.000508	0.004064
300	17.77777778	10	0.042164	0.00127
301	22.22222222	6.11111111	0.000254	0.003302
302	3.33333333	6.66666667	0	0.003556
303	25.55555556	9.44444444	0.000508	0.003302
304	18.88888889	8.33333333	0.001778	0.003302
305	20	5	0	0.003302
306	21.11111111	5.55555556	0	0.00381
307	21.66666667	3.88888889	0	0.00381
308	19.44444444	3.88888889	0	0.003302
309	17.77777778	5	0	0.003302
310	20.55555556	5	0	0.00381
311	20	7.22222222	0	0.004064
312	22.22222222	3.33333333	0	0.003556
313	20	7.77777778	0	0.004572
314	14.44444444	1.66666667	0	0.003556
315	19.44444444	0	0	0.003302
316	20.55555556	7.22222222	0.000762	0.002794
317	19.44444444	6.11111111	0.000762	0.003048
318	22.77777778	4.44444444	0	0.00381
319	22.77777778	3.88888889	0	0.003556
320	24.44444444	2.77777778	0	0.003556
321	23.88888889	2.77777778	0	0.003556
322	23.88888889	5.55555556	0	0.00381
323	22.22222222	4.44444444	0	0.003556
324	14.44444444	4.44444444	0	0.001778
325	18.88888889	2.22222222	0	0.003556
326	21.66666667	-1.11111111	0	0.003302
327	23.88888889	1.11111111	0	0.003556
328	23.33333333	3.88888889	0	0.003556
329	23.61111111	3.61111111	0	0.003683
330	23.88888889	3.33333333	0	0.00381
331	23.88888889	3.33333333	0	0.003302
332	18.88888889	4.44444444	0.004953	0.002921
333	13.88888889	5.55555556	0.009906	0.00254
334	17.22222222	1.66666667	0	0.002794
335	18.88888889	2.77777778	0	0.00254
336	13.88888889	7.22222222	0.00381	0.000508

337	15	3.888888889	0	0.002286
338	18.88888889	3.333333333	0	0.00254
339	19.44444444	2.222222222	0	0.003556
340	10	1.666666667	0	0.002794
341	8.333333333	-1.666666667	0	0.00254
342	9.444444444	-3.333333333	0	0.00254
343	13.33333333	-4.444444444	0	0.002794
344	8.333333333	1.111111111	0	0.00127
345	10.55555556	-2.777777778	0	0.002286
346	12.22222222	-5	0	0.002286
347	15.55555556	-3.888888889	0	0.00254
348	15.55555556	-2.777777778	0	0.00254
349	18.33333333	1.111111111	0	0.003556
350	19.44444444	2.777777778	0	0.003302
351	17.77777778	1.666666667	0	0.003048
352	16.66666667	6.111111111	0.001016	0.002794
353	15	2.222222222	0	0.002032
354	20.55555556	1.111111111	0	0.00381
355	17.22222222	1.666666667	0	0.003556
356	7.222222222	-2.222222222	0	0.002286
357	11.11111111	-4.444444444	0	0.001778
358	11.11111111	-1.666666667	0	0.002032
359	14.44444444	-3.333333333	0	0.002794
360	15.55555556	-3.333333333	0	0.002794
361	19.44444444	-1.111111111	0	0.003048
362	20	-1.666666667	0	0.003048
363	21.11111111	2.222222222	0	0.003302
364	17.77777778	2.222222222	0	0.002032
365	17.77777778	2.222222222	0	0.002032

Crop Benefit List – CROPBEN.IN

- 1 1.2000 0 0.1
- 2 0.2230 0 2.5
- 3 5.0000 0 0.5