NETWORK ANALYSIS OF RAW WATER SUPPLIES UNDER COMPLEX WATER RIGHTS AND EXCHANGES:
Documentation for Program MODSIM3

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DOCUMENTATION FOR PROGRAM MODSIM3

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I. INTRODUCTION

The increasing complexity of water supply planning and management for municipalities such as Fort Collins requires use of computer models as an aid for City Staff and Water Board members. A generalized model called MODSIM3 is documented herein which allows a wide variety of water supply configurations and operating criteria to be simulated through appropriate specification of input data. The focus is on water supply evaluations in a complex water rights structure that includes direct flow rights, storage rights, and water exchange possibilities with other users.

Program MODSIM3 is not intended for use in day-to-day decisions in systems operations, but rather as a means of obtaining monthly or possibly weekly management guidelines over the entire water supply system. Daily system management is best left to the river commissioner under the Office of the State Engineer. The model is capable of generating optimal operational plans while satisfying formal water right structures and informal water exchange mechanisms. Allocation of streamflows in strict accordance with water right priorities can result in waste of valuable water supplies. MODSIM3 has been designed to analyze water exchanges based on guidelines input by the user. Water exchanges provide a flexible means of meeting water demands from a variety of water sources while protecting the rights of senior water right holders in the basin.

MODSIM3 includes certain improvements over two earlier versions of MODSIM in being able to include both physical and accounting transfers of water for exchange purposes. More realistic operating rules for reservoirs have been included which encourage "balanced" operations. In addition, water demand priorities can be made dependent on the

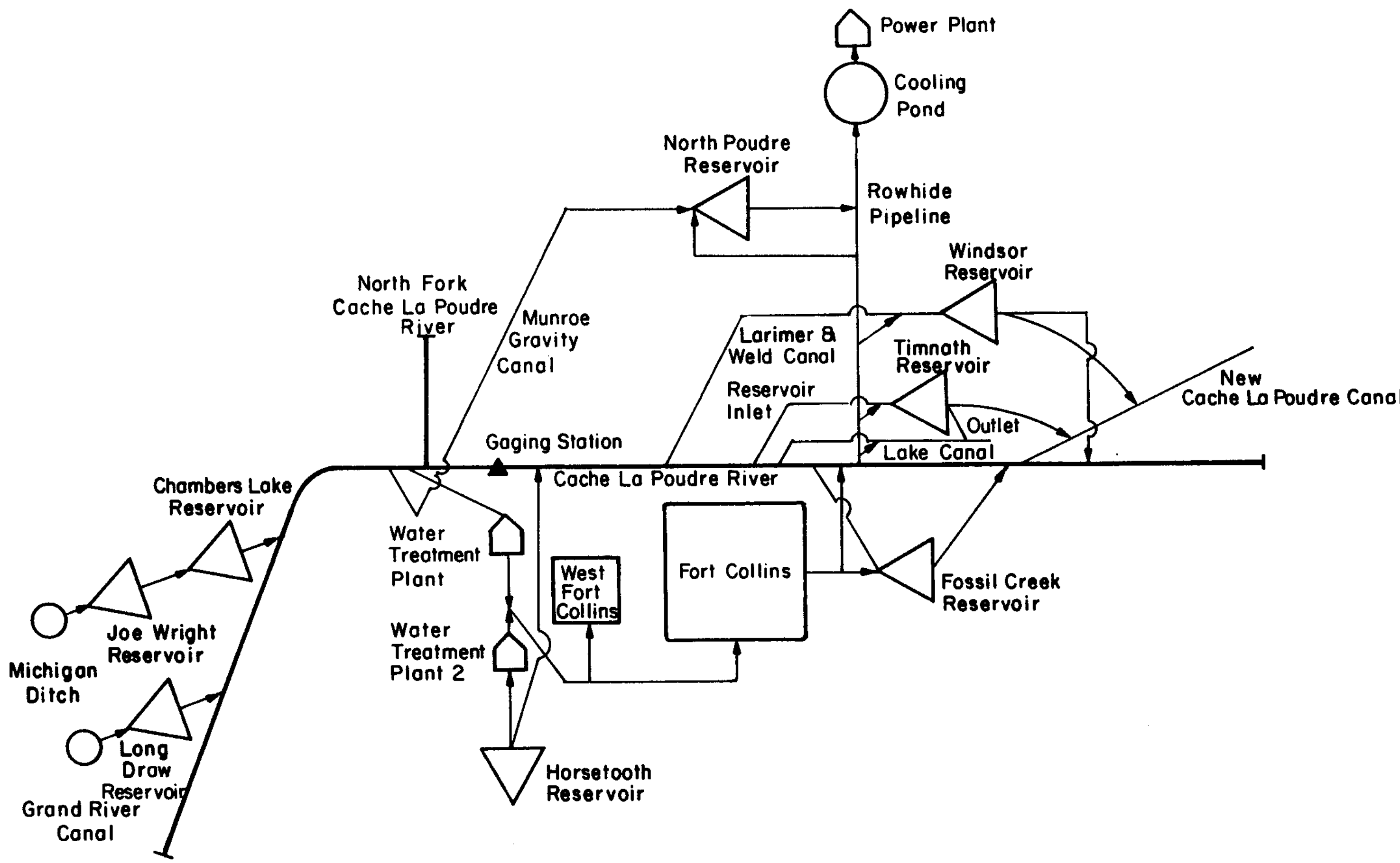

Figure 1. Major components of Poudre River basin for Rawhide Project Study

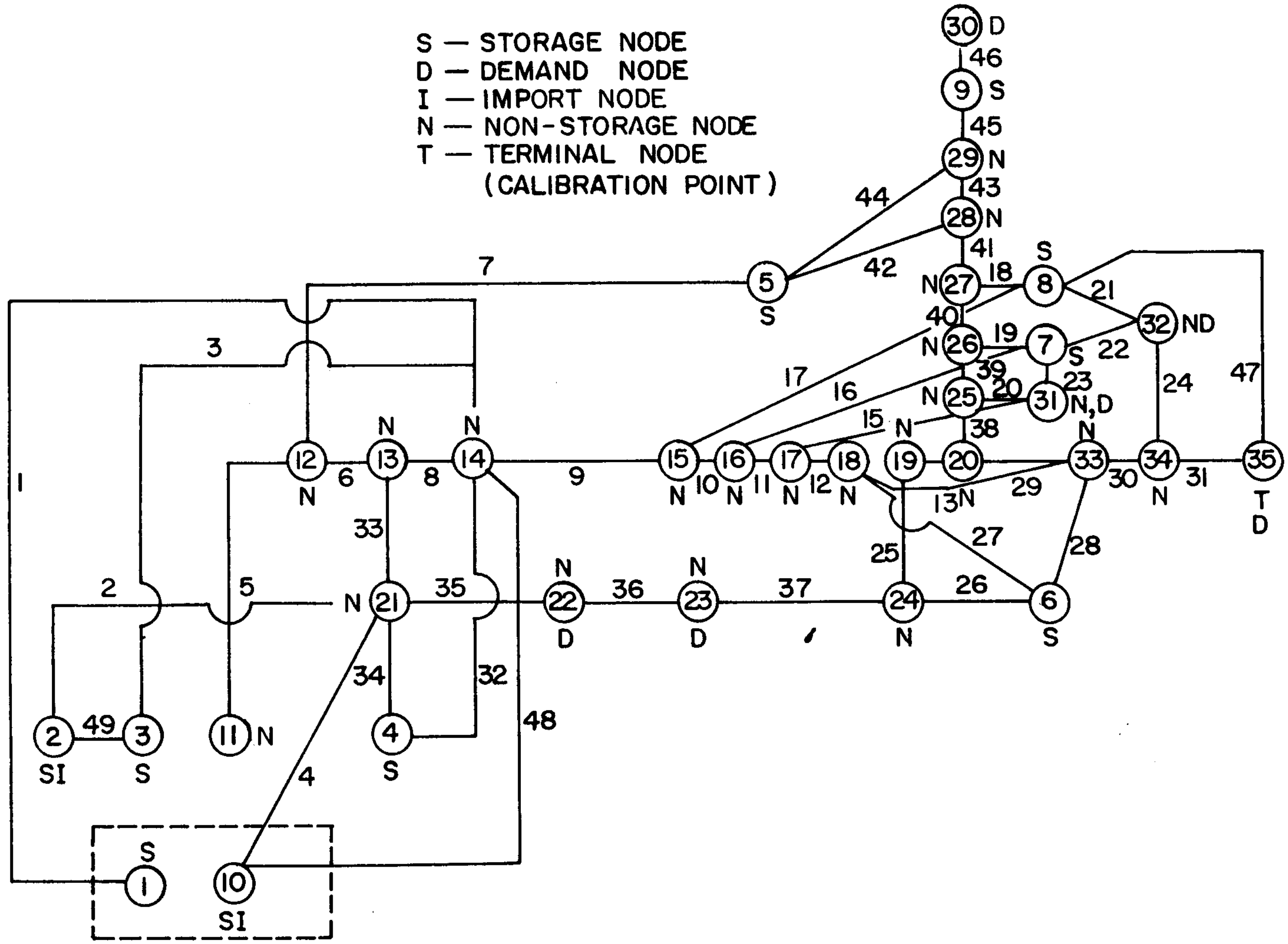

Figure 2. Network configuration for Rawhide Project Study

Table 1. Description of Rawhide Project Network Components (Shafer, 1979).

Node #	Name	Node #	Name
1	Long Draw Reservoir	19	Ft. Collins Return Flow
2	Joe Wright Reservoir	20	Rawhide Pipeline Diversion
3	Chambers Lake Reservoir	21	Ft. Collins Inflow
4	Horsetooth Reservoir	22	West Ft. Collins
5	North Poudre No. 6 Reservoir	23	Consumptive Loss
6	Fossil Creek Reservoir	24	Dummy node
7	Timnath Reservoir	25	Rawhide Pipeline
8	Windsor Reservoir	26	Rawhide Pipeline
9	Rawhide Cooling Pond	27	Rawhide Pipeline
10	Portion of Long Draw Storage Allocated for Transbasin Diversions	28	Rawhide Pipeline
		29	Rawhide Pipeline
		30	Rawhide Power Plant
11	Upper Stem Poudre River	31	Lake Canal
12	Munroe Canal Diversion	32	New Cache la Poudre Canal
13	Ft. Collins Pipeline Diversion	33	Release from Fossil Creek
14	Confluence N. Fork Poudre River	34	New Cache la Poudre Canal Diversion
15	Larimer Weld Canal Diversion		
16	Timnath Reservoir Inlet	35	Terminal node
17	Lake Canal Diversion		
18	Fossil Creek Reservoir Inlet		

are of the simulation type only, such as HEC 5 (Hydrologic Engineering Center, 1979), MITSIM (Lenton and Strzepek, 1977) and CORSIM II (Fleming et al., 1975) which means that operating policies that meet all specified priorities must be found by trial and error procedures. MODSIM3 effectively blends simulation and optimization together in such a way as to accentuate the advantages of each while guaranteeing that operating targets, priorities and constraints are satisfied in a computationally efficient manner rather than by trial and error. MODSIM3 is a modified and updated version of a network model called SIMYLD II, originally developed by the Texas Water Development Board (1972). The two earlier versions of MODSIM were developed by Shafer (1979), Labadie and Shafer (1979), Labadie (1983), and Faux (1983). The first version of MODSIM is essentially a water supply model, with version 3 providing substantial improvements in water right considerations, reservoir operating rules, computer core memory requirements, and model output design. Version 2 is primarily used for hydropower studies in a river basin.

Another model which is quite similar to MODSIM3 is Program WBSM (for Water Balance Simulation Model) (Bercha, 1981), developed for the Alberta, Canada Environment Department. This model also uses a network approach with OKM and has many of the same features as MODSIM3. Program WBSM allows much more detailed reservoir operating criteria than MODSIM3, but also requires a much larger data base.

3. Network optimization techniques (such as the out-of-kilter algorithm used in MODSIM3) are extremely efficient solution techniques. It should be noted that internally, MODSIM3 calculations mostly involve integer numbers, whereas standard linear programming codes require real number calculations. This greatly facilitates the speed of MODSIM3 and the ability to run it successfully on lower accuracy minicomputers if

desired. Klingman et al. (1981) report that modern, efficient network algorithms are over 100 times faster than state-of-the-art linear programming packages. Recent research has suggested that perhaps primal methods are more efficient, but the OKM is still an attractive approach. It has the particular advantage that it does not require an initial feasible solution, although mass balance must be satisfied throughout the network. This is easily accomplished by simply starting with zero flows in each link in the solution procedure.

The Tennessee Valley Authority (TVA) (Shane and Gilbert, 1982) have developed a weekly scheduling model for their system called HYDROSIM which utilizes linear programming rather than a network algorithm to find optimal strategies that will meet system targets and objectives in their order of priority. With this model, targets and priorities are considered by the sequential addition of lower priority constraints, thereby requiring multiple runs of the model. There are many similarities between HYDROSIM and MODSIM3. The primary difference is that MODSIM3 prioritizes targets by attaching weighting factors to an "objective function" which the model then attempts to optimize, rather than through the addition of constraints. The objective function for MODSIM3 is described subsequently. Also, as mentioned previously, network algorithms are much more efficient than the revised simplex method of linear programming.

4. Network optimization to meet operational goals is actually performed in a sequential fashion, rather than in a fully dynamic sense. Fully dynamic deterministic optimization assumes perfect foreknowledge of future inflows and demands, which is obviously an impossibility in practical management problems. It is possible, however, to indirectly incorporate extended forecasts into real-time operational decisions

through appropriate adjustment of monthly or weekly operational priorities or weighting factors, as described by Shafer (1979).

Several network algorithms have been developed which perform a fully dynamic optimization (e.g., Sigvaldason, 1976), but the computational requirements are much more stringent and a direct function of the number of time periods being considered. Since MODSIM3 performs the optimization sequentially without foresight, the model can be treated as a simulation model whereby hundreds or even thousands of years of historical and synthetic streamflow data could be input into the model. The model output, such as predicted water supply yields and demand shortages, can then be analyzed by various statistical methods. This allows calculation of the probability of failing to achieve certain water supply goals under various development and operational alternatives.

A Kalman filtering streamflow forecasting model has been developed by Lazaro (1981) and Lazaro et al. (1981) and can be attached to MODSIM3 for real-time use of the model. Note that unregulated or virgin streamflows must be supplied to the model since there is no provision for watershed rainfall-runoff relationships. A version of MODSIM called CONSIM (Labadie et al., 1983), which was designed for analysis of conjunctive use of surface and groundwater, does make such provision.

Wunderlich and Giles (1981) have performed an analysis for the Tennessee Valley Authority (TVA) reservoir system which compares shortsighted models that look only one week ahead of time, and farsighted models that try to anticipate several weeks or months ahead of time. The latter tend to be overly risky and the former too conservative. They concluded that a combination of the two is needed to provide balance. Labadie et al. (1981) have performed similar studies for urban drainage studies and have concluded that use of foresight is attractive as long as the potential forecast errors are properly accounted for.

5. As shown by Klingman et al. (1981), network models require considerably less computer core memory than comparable linear programming packages. This means that extremely large-scale networks can be set up. In fact, networks involving several thousand nodes have been successfully solved.

6. Network models with a generalized input structure such as MODSIM3 are particularly valuable when changes need to be made in system structure, operating criteria, and other inputs. This allow interactive use of the model for planning and management purposes.

Though pure network models are clearly advantageous, there are some disadvantages. Pure network models allow only linear costs and two kinds of system constraints:

(a) linear mass balance constraints on each node

(b) known minimum and maximum flow limits or bounds on each link

Consideration of channel losses and reservoir evaporation represent a deviation from these assumptions. Network flow algorithms "with gains" are capable of performing channel loss calculations directly with greater efficiency, but iterative processes are still required for accurate evaporation calculation. Even algorithms "with gains" cannot accurately consider evaporation loss directly. According to the Texas Water Development Board (1975), "gains" algorithms require roughly twice the computer time of standard network algorithms. Since they must still be used within an iterative loop on evaporation calculations, it is deemed here more efficient to use a standard algorithm and adjust evaporation and channel loss together in an iterative process which is described subsequently.

There may be additional constraints called "side constraints" which cannot be accommodated by pure network algorithms, and would therefore require the less efficient linear programing simplex-based methods. However, Klingman et al. (1981) report that new methods of incorporating side constraints into pure network algorithms are being developed and appear to be much faster than the simplex method.

III. PROGRAM METHODOLOGY

A. Basic Assumptions

The underlying principle of the operation of MODSIM3 is that most physical water resource systems can be represented as capacitated flow networks, as illustrated in Figure 2. The term "capacitated" refers to the existence of strict bounds on each link and satisfaction of mass balance at each node. The components of the system are represented in the networks as nodes, both storage (i.e., reservoirs) and non-storage (i.e., river confluences, diversion points, points of inflow, and demand locations) and links or arcs (i.e., canals, pipelines, and natural river reaches). In order to consider demands, inflows, and desired reservoir operating rules, several "artificial" nodes and links must be created in such a way as to insure that mass balance is satisfied throughout the network. These artificial nodes and links are created automatically by MODSIM3, so that the user need only be concerned with the actual system nodes and links. Subsequent sections of this documentation will more clearly explain how artificial nodes and links are defined.

Basic assumptions associated with the core model are listed as follows.

1. All storage nodes and links must be bounded (i.e., minimum and maximum storages and flows must be given). The latter bounds are allowed to vary over time in the model. Losses due to evaporation and seepage are considered iteratively.

2. Each link must be unidirectional with respect to positive flow.

3. All inflows, demands, seepage losses and return flows must accumulate at nodes. Increasing the density of nodes in the network thereby increases simulation accuracy.

Mathematically, the out-of-kilter algorithm solves the following network flow problem iteratively, in a sequential fashion over time. That is, for a given time period (i.e., month or week):

$$\text{minimize} \sum_{i=1}^{N} \sum_{j=1}^{N} c_{ij}(q_{ij}) \cdot q_{ij} \qquad (1)$$

where

q_{ij} = the average, integer-valued flow rate from node i to node j during the current time interval (e.g., acre-feet per month or week, or cfs)

$c_{ij}(q_{ij})$ = the net unit "cost" associated with flow rate q_{ij}, which may not be a real cost but rather a weighting factor representing water rights or operational priorities (a negative cost is treated as a benefit or priority)

subject to:

a) satisfying mass balance at every node j=1,...,N (including all artificial nodes)

$$\sum_{i \varepsilon I_j} q_{ij} - \sum_{k \varepsilon O_j} q_{jk} = 0 \qquad (2)$$

where

I_j = the set of all nodes with links terminating at node j [$i \varepsilon I_j$ means all nodes i which are elements of set I_j]

O_j = the set of all nodes with links originating at node j.

b) minimum flows on every link (i,j)

$$q_{ij} \geq l_{ij}(q_{ij}) \quad \text{for all } i,j = 1,\ldots,N \qquad (3)$$

where

$l_{ij}(q_{ij})$ = the minimum flow on link (i,j), which may be a function of the flow itself

c) maximum flows on every link (i,j)

$$q_{ij} \leq u_{ij}(q_{ij}) \quad \text{for all } i,j = 1,\ldots,N \qquad (4)$$

where

$u_{ij}(q_{ij})$ = the maximum flow on link (i,j), which may be a function of the flow itself.

The nonlinearity of this problem arises from the fact that $c_{ij}(q_{ij})$, $l_{ij}(q_{ij})$ and $u_{ij}(q_{ij})$ can be nonlinear functions of q_{ij} in a general sense. To solve this problem, the model automatically performs the following iterations for the current month or week in the simulation:

1. first guess values of c_{ij}, l_{ij} and u_{ij} and solve the pure network.
2. given flows q_{ij}, update the c_{ij}, l_{ij} and u_{ij} values based on these flows.
3. solve the pure network again with the updated parameters and obtain new flows q_{ij}.
4. repeat this procedure until successive flow estimates converge within some default or user specified error tolerance; then go to the next time period.

In the following sections it is specified how the parameters $c_{ij}(q_{ij})$, $u_{ij}(q_{ij})$ and $l_{ij}(q_{ij})$ are defined for each of the major components of a water supply system. Note that <u>all</u> of these changes, which are described in more detail in the following sections, occur in the same iterative loop.

The system components described in more detail in the following sections include:

1. unregulated inflows
2. reservoirs and evaporation losses
3. demands and water rights
4. conveyances (both natural and manmade) and seepage loss

5. return flows

6. imported water and transbasin diversions

B. Unregulated Inflows

B.1 To Nonstorage Nodes

Unregulated inflows may be based on historical data, future forecasts, drought scenarios, or synthetic generation of streamflows. Any real node in the system can be an inflow node. They are connected by artificial links connecting a single artificial inflow node to each point of inflow. Any node can be designated as an inflow node, including a reservoir. In Figure 3, real nodes 1, 2, 3, and 4 are automatically connected by MODSIM3 to artificial node I, which of course is given a unique integer designation in the model (dashed lines represent artificial nodes or links). The addition of these artificial nodes and links serves to maintain mass balance at each inflow node.

The link "parameters" on the links represent link cost c_{ij}, lower bound l_{ij}, and upper bound u_{ij} or $[l_{ij}, u_{ij}, c_{ij}]$. The I_j are inflows to each node j=1,2 during the current time period (i.e., month or week). The link parameters are automatically defined by MODSIM3, based on inflow data provided by the user. Notice that lower bounds and upper bounds are both set equal to I_j by MODSIM3, thereby guaranteeing that exactly those specified inflows will be input. Notice also that since there are no inflows to node 3 and 4, the links are still defined, but with zero upper and lower bounds.

B.2 To Storage Nodes

Suppose nodes 1 and 2 are actually reservoirs (i.e., storage nodes). Then the link bounds are modified according to Figure 4. Artificial inflow links to storage nodes now include any carryover

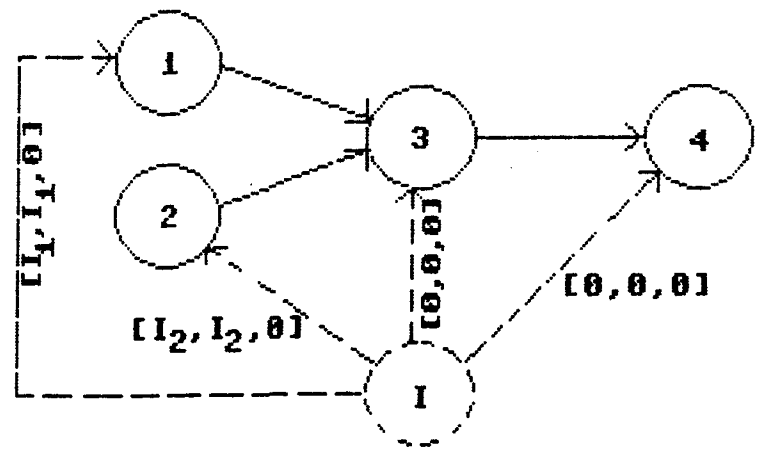

Figure 3. Artificial unregulated inflow links.

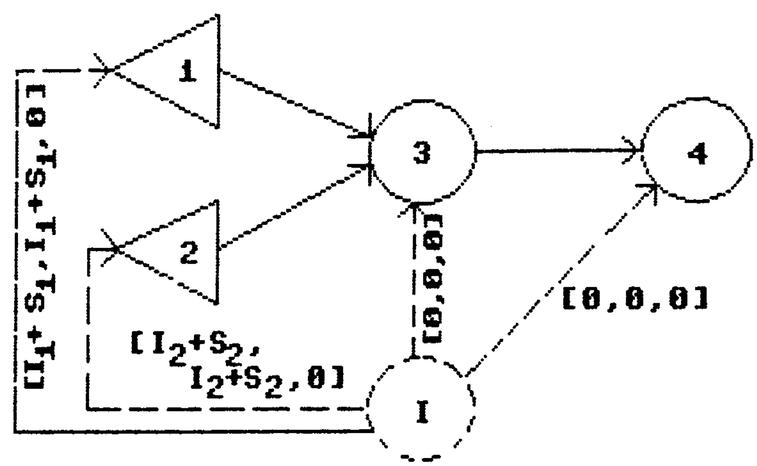

Figure 4. Artificial unregulated inflow links with addition of initial storage.

storage S_j from the previous month or week. That is, the available water for the current period is $I_j + S_j$ for nodes $j=1,2$. It will be shown how mass balance is satisfied at all these nodes as the discussion progresses.

C. Reservoirs and Evaporation Loss

C.1 Link Bounds

In addition to inflow links, the two reservoirs in Figure 4 are connected by two additional artificial links for specifying total carry-over storage to the next time period. These links originate at each reservoir and accumulate at an artificial carryover storage node S, as shown in Figure 5. Link 1 is called the artificial "desired storage link" and link 2 is the artificial "final storage link." The lower bounds on the desired storage links are the minimum reservoir storage or "dead" storage S_{imin} $(i=1,2)$. The upper bounds are user specified <u>end-of-period</u> target storages T_i which represent "ideal" guidecurve levels for the current month or week.

If a large inflow occurs, storage may exceed the "target" level. Any excess flow is carried in link 2. Its lower bound is zero (indicating no excess storage above target level T_i) and its upper limit is $(S_{min}-T_i)$ which represents the maximum excess space above the target level. Note that an infeasibility could occur if the inflow to a reservoir, including carryover storage, is less than the dead storage level S_{imin}. If this happens, MODSIM3 automatically resets S_{imin} for that period to correspond to the actual inflow plus carryover storage. Note that S_{imax} will likely be the top of the conservation pool of the reservoir if there is flood space allocated.

In some cases, it may be desirable to use operating rules which

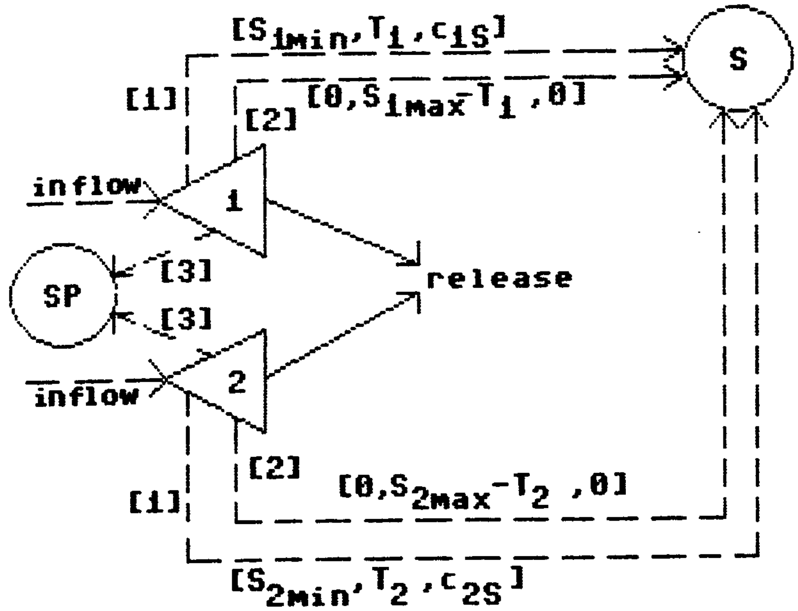

Figure 5. Artificial storage nodes and arcs.

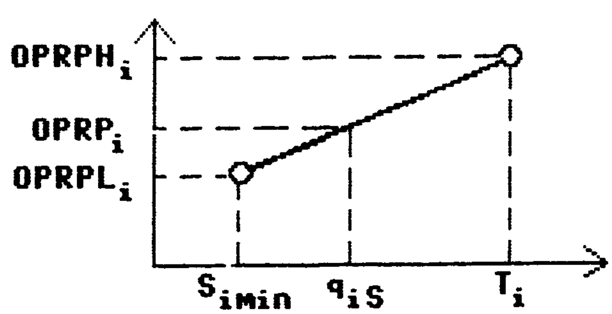

Figure 6. Reservoir operating priorities for 'balanced' operation.

specify release guideline rather than storage guide curves for each time period. This is easily accomplished by specifying an additional "flow-through demand" node downstream of the reservoir with the desired release levels specified as flow-through demands. These releases can be made dependent on storage levels somewhat by using the "hydrologic state" option for the flow-through demands. Flow-through demands are described in more detail in a subsequent section.

C.2 Spillage

If inflow is so large that spillage must occur, the spills are carried in artificial link 3 and collected at artificial spill node SP. Its lower limit is zero and its upper limit is set at total storage capacity in the entire system multiplied by ten. Spills are assumed to be lost from the water supply system. It is generally a good idea to specify all reservoirs as spill nodes, if possible.

C.3 Link "Costs"

The "costs" c_{iS} on the artificial desired storage links are computed as follows to reflect storage right priorities. For reservoir i, the user selects two priorities $OPRPL_i$ and $OPRPH_i$ as integer numbers between 1 and 99. (Note that a lower number represents a higher priority). The parameter $OPRPH_i$ represents the priority number for the reservoir if the initial storage is at the target level, whereas $OPRPL_i$ is the priority number if storage is at the minimum level. In Figure 6, reservoir carryover storage is being given a lower priority number (and hence a higher weighting) as storage level decreases. This means that as storage levels decrease, more weight is attached to maintaining storage to avoid emptying one reservoir while another remains full, if this is desired. Note that the user is allowed to change OPRPH and OPRPL every 12 months or 12 weeks.

MODSIM3 then computes a "cost" c_{iS} as:

$$c_{iS} = -[1000 - (OPRP_i \cdot 10)] \tag{5}$$

Notice that c_{iS} is a negative number, which represents a benefit associated with carryover storage. The cost associated with flow in the final storage link is always set at zero. The costs on the spill links are given the highest positive numbers of any link: 10,000 times the preferential order of spillage.

C.4 Evaporation

Evaporation loss from reservoirs is accounted for as follows:

Compute for each reservoir i:

$$E_{imax} = e_i \; [A_i(S_i) + A_i(S_{imax})]/2 \tag{6}$$

$$E_{imin} = e_i \; [A_i(S_i) + A_i(S_{imin})]/2 \tag{7}$$

$$E_{itarget} = e_i \; [A_i(S_i) + A_i(T_i)]/2 \tag{8}$$

where e_i is evaporation rate for reservoir i (e.g., feet per month) for the current period; A_i is the (interpolated) area-capacity table for reservoir i, S_i is storage at the beginning of the current period, S_{imax} is maximum capacity, S_{imin} is dead storage, and T_i is the user supplied target level.

The storage link parameters are then adjusted as follows:

for desired storage links:

$$[(S_{imin} + E_{imin}),\ (T_i + E_{itarget}), c_{iS}]$$

for final storage links:

$$[0,\ (S_{imax} - T_i) + (E_{imax} - E_{itarget}), 0]$$

This means that the link upper bounds are adjusted to carry enough flow to account for evaporation loss, and the lower bound on the desired storage link is increased so that when evaporation is removed, it will not be violated. After the calculations for the current period are completed, the flows in the carryover storage links (i.e., the total ending storage) are adjusted as follows.

1. An initial guess EVP_i of evaporation loss is first made. The total carryover storage, including evaporation loss is:

$$q_{itotal} = (q_{iS(desired)} + q_{iS(final)})$$

2. The current estimate of actual ending storage is

$$(q_{itotal} - EVP_i)$$

3. Now compute the average surface area $\bar{A}$ over the period:

$$\bar{A}_i = 0.5\ [A_i(S_i) + A_i(q_{itotal} - EVP_i)]$$

and update the evaporation estimate EVP as

$$EVP_i = e_i \cdot \bar{A}_i$$

4. Return to Step 2 and repeat until successive evaporation estimates converge within some predefined error tolerance.

C.5 Hydrologic States

The target storage levels T_i for each reservoir i can either be specified (and allowed to vary) for each period of the simulation, or the target storage can be conditioned on the "hydrologic state." The hydrologic state is defined as

$$R = \sum_{i \varepsilon H} [S_i + I_i] \qquad (9)$$

The set H represents the set of reservoirs for which it is desired to compute a hydrologic state, where S_i is initial storage and I_i is inflow. Since the hydrologic "state" is based on initial storage, then it is fixed at the beginning of the time period and remains at that state throughout that period, even though storage may change dramatically during the period.

The user now defines parameters x_1 and x_2 (it may be necessary to try several values) which are used to define if in the current month or week, the hydrologic "state" is dry, wet, or average. The lower limit on the average state is

$$LB_{ave} = x_1 W \quad (10)$$

$$UB_{ave} = x_2 W \quad (11)$$

where

$$W = \sum_{i \varepsilon H} S_{imax} \quad (12)$$

The hydrologic states are defined as follows:

[D] dry : if $R < LB$

[A] average : if $LB \leq R \leq UB$

[W] wet : if $R > UB$

The user can now define storage targets T_D, T_A and T_W for each reservoir. These targets can change from period to period within a given year, but not from year to year. Likewise, for weekly increments, they can change within a 12 week period only. Note that if the model is being used to simulate operations during a critical low flow period, the user might prefer to represent the states as average, drier, and driest.

With the "hydrologic state" option, only one priority rank is specified per hydrologic state for each reservoir. The designation of two priorities OPRPL and OPRPH for the option of annual or 12 week changes in targets and priorities is a way of allowing priority to change with storage. The concept of hydrologic state also serves this purpose on an aggregate storage level for several reservoirs.

D. Demands and Water Rights

D.1 Terminal Demands

Consider the example network shown in Figure 7. Here, the two demand nodes 3 and 4 are isolated. Though not considered in this exam-

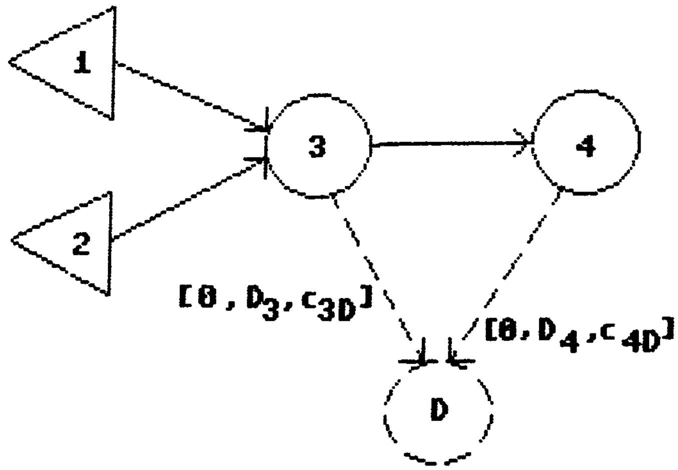

Figure 7. Illustration of terminal demands.

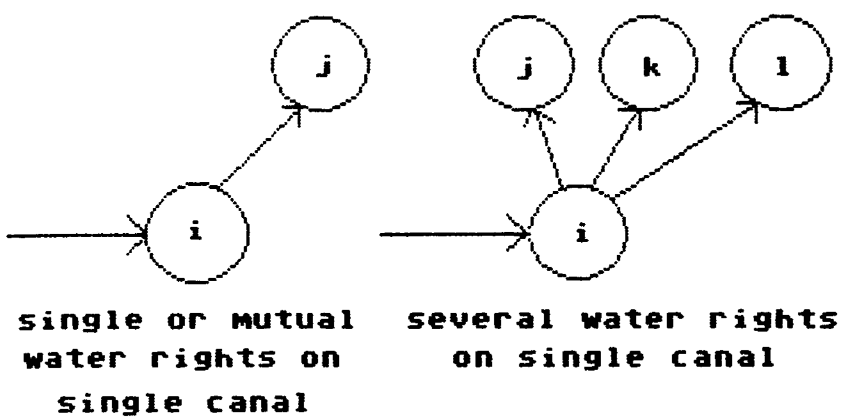

Figure 8. Consideration of multiple water rights on single canal.

ple, nodes 1 and 2 could also be specified as demand nodes, since a storage node can also be a demand node, as well as an inflow node. For example, node 4 might be Fort Collins and node 3 a mutual ditch company (return flows will be covered later). The model automatically sets up artificial links which originate at each demand node and accumulate at a single artificial demand node. The link parameters are shown, with demands D_3 and D_4 specified for each node. These can be:

1. decreed water right amount
2. historical diversions
3. predicted agricultural demands based on evapotranspiration calculations (performed outside the model)
4. projected municipal and industrial demands

The priorities c_{iD} are calculated as follows:

$$c_{iD} = [1000 - (DEMR_i \cdot 10)] \tag{13}$$

for each demand node c_{iD}, where $DEMR_i$ is also a priority number between 1 and 99. Notice that c_{iD} is a negative number like c_{iS}. In fact, the user must select priorities for carryover storage and demands in relation to each other. If shortages must occur, then demands with a lower priority (i.e., a junior water right) are shorted first. This will be illustrated later by a numerical example. As with the storage priorities, the user is permitted to change DEMR every 12 months or weeks. If the hydrologic state option is used, three priorities can be specified for each state which do not change.

Note that in some situations, there are several water rights operating on the same ditch, rather than a mutual aggregation of rights. These rights may differ both in decree amount and priority. In these cases, it is necessary to represent the single ditch by several ditches as shown in Figure 8. It may be convenient to lump together some of the smaller decree amounts if they are of comparable decree date.

D.2 Flow-Through Demand

Instead of a demand accruing at a node, there are some demands which are essentially "link" demands. A good example would be instream flow requirements where there is a certain "demand" established to maintain minimum streamflows for fish and wildlife, water quality control, and recreation. It would be possible to simply establish a lower limit on flows in a particular reach. However, if a particularly low flow sequence were to occur whereby insufficient water was available to meet the minimum requirement, the model would terminate with an error message saying "NO FEASIBLE SOLUTION." Note that the flow-through demand is given a priority just like any other demand.

The flow-through demand works as follows. Isolating nodes 3 and 4 from the previous example, as in Figure 9, assume that a minimum flow of D_3 is desired for reach or link (3,4) and node 4 is a terminal demand as before. Artificial links are again established which originate from nodes 3 and 4 and converge at artificial demand node D. However, the artificial inflow link connecting artificial inflow node I to node 4 is now given the following arc parameters:

$$[D_3,\ D_3,\ 0]$$

If there was an inflow I_4 to node 4, then the parameters would be

$$[I_3+D_3,\ I_3+D_3,\ 0]$$

The flow-through demand is defined at node 3, but it "accrues to" node 4. In essence, to simulate a demand for flow in a link, the flow is removed from the upstream node and put it back into the downstream node.

There are four situations that can occur:

1. Insufficient water is available at node 3 to meet flow-through demand D_3. Therefore a flow $D_3' < D_3$ is actually flowing in artificial

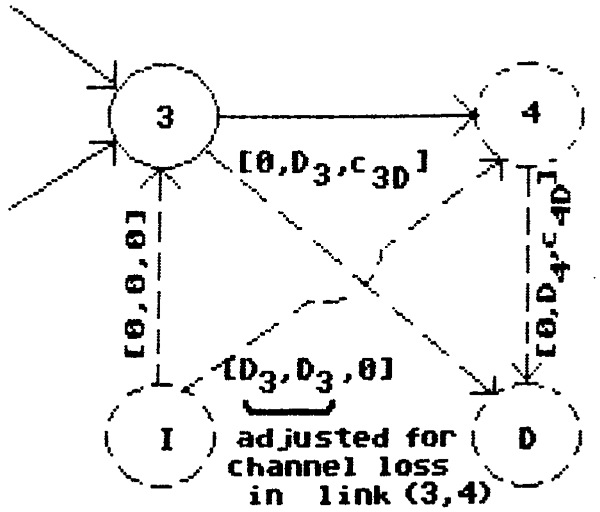

Figure 9. Flow-through demands.

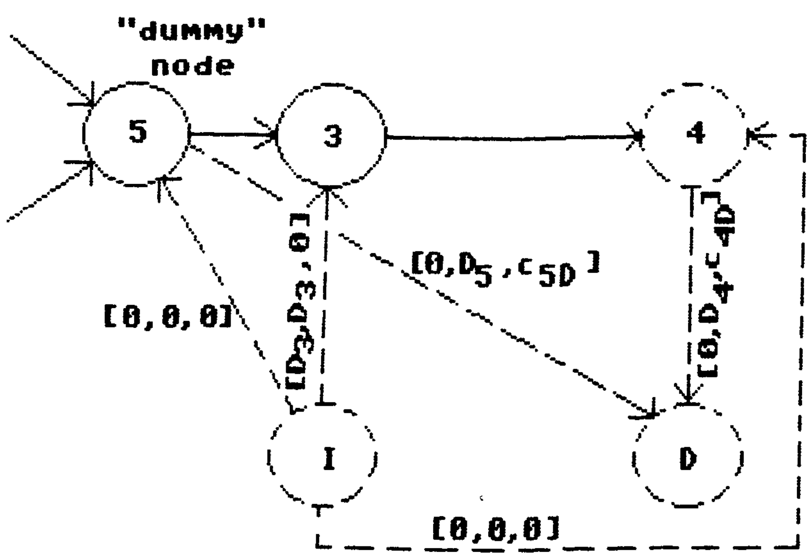

Figure 10. Flow-through demand at 'dummy' node 5 so that link (3,4) carries the entire flow.

link (3,D). Since D_3 is flowing back into node 4, there is an imbalance. This is taken care of by solving the network again, but this time setting the link parameters for artificial link (I,4) to

$$[D_3', D_3', 0]$$

This is repeated until successive values of the flows in links (3,D) and (I,4) agree within some error tolerance, thereby insuring the flows are balanced.

2. Excess water flows into node 3 and demand D_3 has a high priority. In this case, D_3 will be flowing in links (3,D) and (I,4) with the excess flow q_{34}' flowing in real link (3,4). Note, however, that the flow in link (3,4) is actually considered to be:

$$q_{34} = q_{34}' + D_3$$

3. Excess water flows into node 3 and demand D_3 has a low priority. In this interesting situation, there still may be a shortage where the flow in link (3,D) is $D_3' < D_3$. However, since this demand is of low priority, the excess flow q_{34}' passing downstream to the higher priority demand at node 4 may actually be sufficient such that the total actual flow in link (3,4)

$$q_{34}' + D_3' \geq D_3$$

Or, there may still be a shortage.

4. There may be just enough water to exactly meet demand D_3, in which case the "apparent" flow in the real link (3,4) is zero, though the actual flow is D_3. One way to insure that no more than D_3 flows from node 3 to node 4 is to specify a zero upper limit to flows in arc (3,4). Another option would be to <u>not</u> specify any connection between nodes 3 and 4. This is "legal" in MODSIM3.

One difficulty with the situations above is that the flow in link (3,4) as printed out by the computer program may not reflect the actual total flow in that link because of the flow-through demand. Future modification of the program should consider this. In the meantime, the user can add a "dummy" node 5 upstream of node 3 such that link (5,3) is considered to have zero length. Node 5 is now designated as the flow-through demand node, with flow accruing to node 3. In this way, link (3,4) will carry the entire flow (see Figure 10).

D.3 Exchange Nodes

A variation on the concept of a flow-through demand is the "exchange node." Consider the following situations:

1. A junior direct flow water right holder may own storage water, but has no way of directly receiving that water. For example, it may be a terminal reservoir at the end of a ditch. If the user's direct flow rights are inadequate in quantity and/or priority to meet demands, then an exchange with other users is required.

2. A junior water right holder, such as North Poudre Irrigation Company, owns shares in Horsetooth Reservoir but cannot physically receive Horsetooth water because its diverson point is upstream of the Horsetooth discharge point into the Poudre River. An exchange will allow diversion of additional water into Munroe canal for direct application in the North Poudre system.

3. Fort Collins owns shares in various irrigation ditches diverting south of the Poudre River, but has no way of using or storing excess flows available to these ditches if these flows exceed the Fort Collins demand during any period.

These kinds of situations, as well as several others, call for an informal, voluntary exchange of water between users. As a simple illustration, consider two demands at nodes 3 and 4. Node 3 owns water passing into node 2, and node 4 owns water passing into node 1, but does not have direct access to this water (Figure 11). It is not necessary for nodes 3 and 4 to be physically connected in MODSIM3. Since it is not possible to label the same node as both a demand and exchange node, an additional fictitious node 3' must be created (this is not done automatically by the model) as the demand node. The fictitious link (3,3') connecting them should have zero cost and a large enough capacity to meet all demands at node 3. Actually, nodes 3 and 3' are the same node, but must be given a separate designation for the exchange to work. Note also that use of notation 3' is for simplifying the illustration only. The model user would have to give it a unique integer label in relation to all other nodes.

The model will now add an artificial demand link leading from node 3' to the artificial demand node, as usual. The model also iteratively adds whatever total flow enters node 3, call it ITHRU, as an additional inflow to node 2 as shown in Figure 12. This must be done iteratively because until the model is run at least once, ITHRU is an unknown quantity. Following the first run, ITHRU is set for arc (I,2). However, when the model is run again, ITHRU may change since node 2 has now received an additional source of water (assuming node 4 has other sources of water). The model is then run again with ITHRU adjusted until convergence occurs.

It should be noted that in this current scheme, there is no provision for making sure that there is enough water available from the node 3 sources to meet the ITHRU exchange requirement. In the current version of the model, this must be considered after the model has been run for all time periods. If, for some months or weeks, it appears that there is insufficient water owned by node 3 to meet the ITHRU requirement at node 2, then the capacity of link (1,3) and/or (2,4) for that

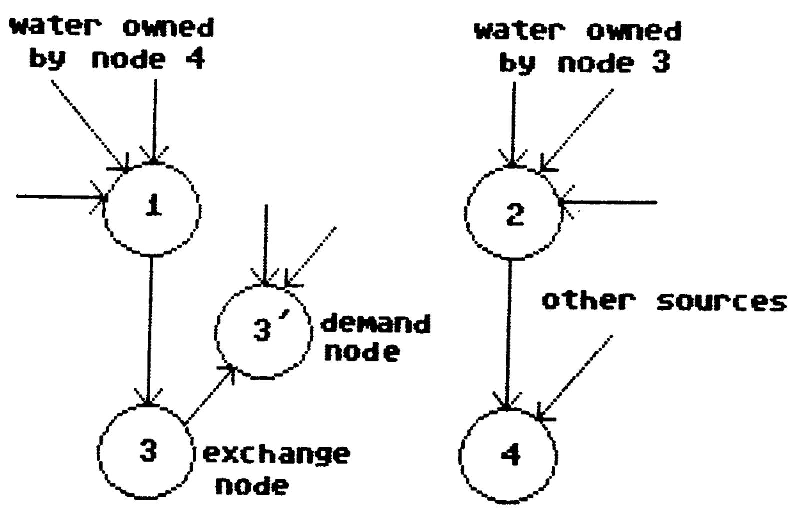

Figure 11. Illustration of exchange nodes.

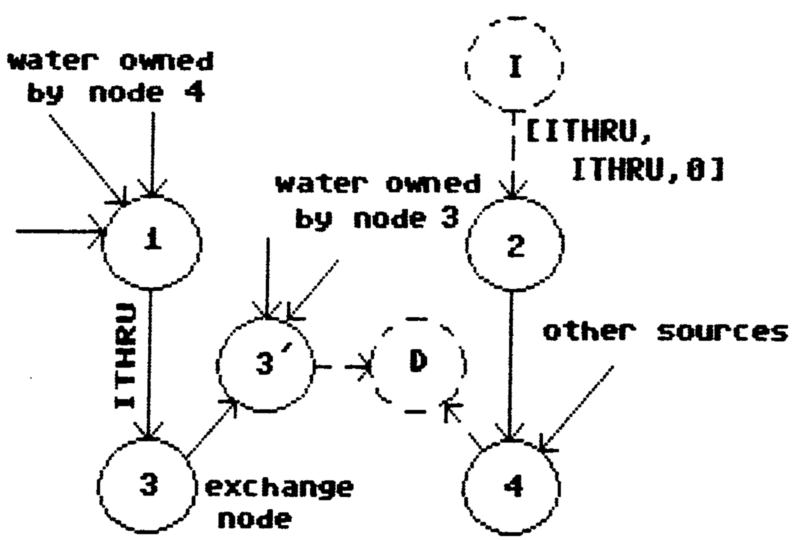

Figure 12. Exchange node illustration showing adjustment of ITHRU.

period should be reduced to that level, and the model run again by the user. This is not done automatically by the model.

Another situation that could arise is when ITHRU exceeds what demand node 4 needs. For those periods where this occurs, the model would have to be run again by the user, with the capacity of link (1,3) adjusted to reflect the actual needs of node 4.

If node 4 has storage available, then there is more flexibility. Node 2 might be a reservoir whereby if ITHRU exceeds the needs of node 4 for a particular period, the excess flow can be "credited" in reservoir 2 for later use by node 4. It is critical, however, that all credits be used by the end of the season. Again, it is still necessary to check if there is sufficient water available from node 3 sources at node 7. If not, the model must be run again by the user with adjustment of capacities of link (1,3) and/or link (2,4). This is one reason why it is a good idea to include links (1,3) and (2,4) in the network, even though it might seem they are not necessary.

There are other complex aspects associated with exchanges which may require some trial and error adjustments. For example, the concept of "hydrologic state" might be useful for a reservoir at node 2 because separate target levels could be used to regulate how much exchange water is used by node 4 in each period. Setting high target storage levels for wet hydrology, such as during the wetter spring and early summer periods would likely control exchange releases since the reservoir would reduce releases in order to reach the target storage level (assuming it starts at zero storage); i.e., no "credits left over from the previous season." As the season progresses into the dry, late summer and early fall period, it would be desirable to be able to go to a reduced target level and/or priority rank associated with dry hydrology in order to encourage releases for exchange purposes.

An important point needs to be mentioned with regard to exchanges. With this simple example, node 4 is exchanging with one owner. Suppose, however, that the waters entering node 1 were owned by more users than just node 3. If exchanges are occurring between nodes 3 and 4 only, then node 3 water must be separated from the other sources. This requires specifying an additional link that just carries node 3 water, even though all water is actually flowing in the same channel (Figure 13). Also, if water is being "credited" to node 4 from several owners exchanging with node 4, then the single reservoir owned by node 4 may have to be represented as more than one reservoir (Figure 14). Note that the total capacities of fictitious reservoirs 2 and 2' must equal the actual capacity of the reservoir. However, to give the model enough flexibility, it is suggested that user run MODSIM3 using arbitrarily large capacities for 2 and 2'. If the total storage turns out to be within the actual capacity of the reservoir, then the model run is acceptable. Otherwise, decisions would have to be made as to which of the exchanges to limit. Or, another alternative would be to mix the waters of various ownership and run the model, and then sort the exchanges out based on the model output. In this approach, total "credits" could likely be forced to zero at the end of the season, but individual credits may not balance. That is, one user may end up giving more water to another user in exchange for less water. However, as long as all demands are met, or at least users that take shortages would have had shortages anyway without the exchanges, then perhaps this is acceptable.

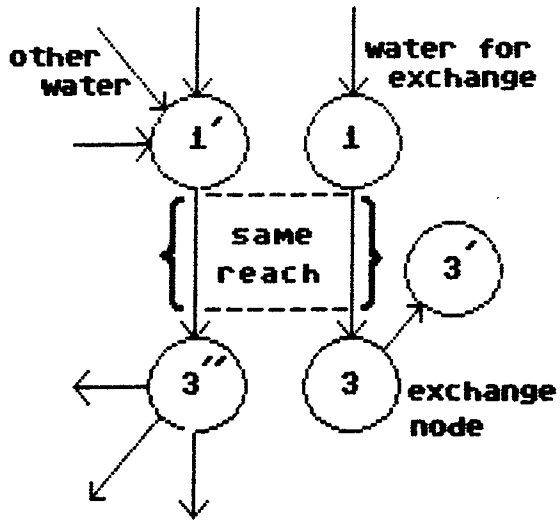

Figure 13. Exchanges under multiple ownership.

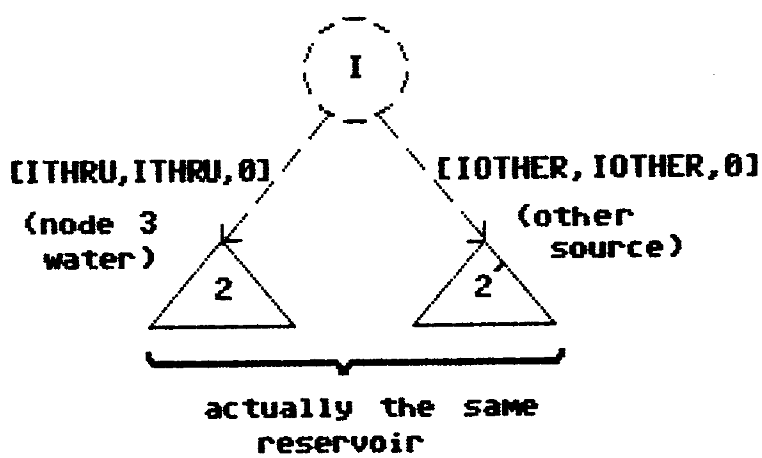

Figure 14. Crediting waters from several owners.

D.4 Storage Rights

If storage rights in a reservoir are senior, then target levels can be specified for the decreed amount and the reservoir allowed to fill to that level. If storage rights are junior, then the user must specify an additional inflow node and a fictitious, zero capacity reservoir. Consider the example in Figure 15. If the storage right is senior to all other downstream rights, then case "a" applies and the analysis is straightforward. If the storage right is junior, then the unregulated inflow into reservoir 1 comes into node 3 rather than node 1. Any senior direct flows that pass through reservoir 1 downstream should be taken out here. If it is assumed that these are known apriori, then node 3 can be designated as both an inflow node and a demand node. Otherwise, the link leaving node 3 would be connected to other portions of the network. The assumption is that there is sufficient capacity downstream of reservoir 1 to carry the senior direct flow requirements plus any additional reservoir releases. Now, the flow carried into node 2 is unregulated inflow, less direct senior requirements.

The flow entering node 2 from node 3 is the "storage right" for reservoir 1. Node 2 is designated both as a reservoir (with no capacity) and a flow-through demand accruing to the "real" reservoir 1. This flow-through demand is set at the same unregulated inflow to node 3. The reason this needs to be done is that there may be opportunities to exchange water with the senior user taking water from node 3. Therefore, a link enters node 2 from other parts of the system representing exchanges with the senior right. The direct flow requirement cannot simply be reduced by this amount since it is being computed by MODSIM3. This means that reservoir 1 can capture some or all of the direct flow right allocation if there is sufficient exchangable water. However,

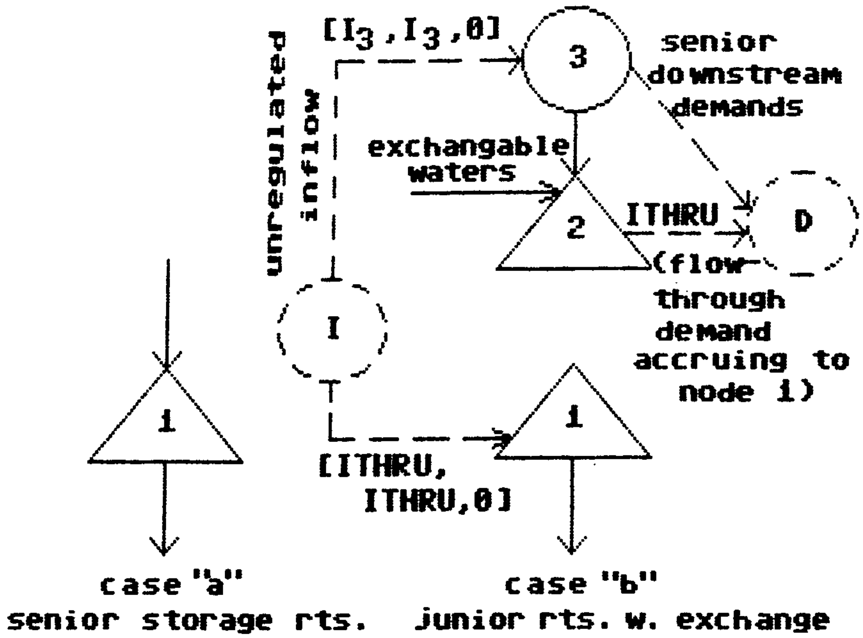

Figure 15. Consideration of storage rights.

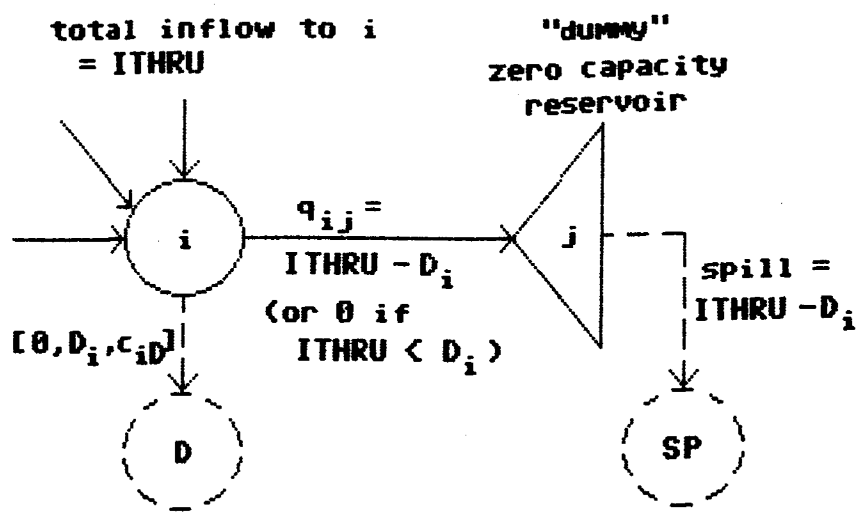

Figure 16. Terminal demands and use of zero capacity reservoirs.

since the total amount captured obviously cannot exceed the actual physical unregulated flow coming into reservoir 1, the flow-through demand must be set at the actual unregulated inflow level.

The reason that reservoir 2 is set at zero capacity is to be able to make sure that any excess flow that cannot be physically captured is spilled at that node. Since spills have the highest cost, the model will attempt to regulate exchange waters in order to avoid this happening. In this way, it is possible to separate exchange or credited water from waters included in the storage right. Notice also that fictitious reservoir 2 and "actual" reservoir 1 are not physically connected in the real system, but are connected by means of artificial nodes and links.

D.5 <u>Terminal Downstream Arcs and Nodes</u>

For certain networks, the structure will be set up where the final downstream arc in the network must carry a certain minimum flow or decreed water rights to users downstream of the study area. In this case, it is best to make the farthest downstream node a zero capacity reservoir, and the immediate upstream node a flow-through demand which accrues at the zero capacity reservoir as seen in Figure 16. The link connecting them should be given sufficient capacity to carry the basin outflows. This method allows for excess flows to be spilled if necessary. Without the zero capacity reservoir, there would be nowhere for the excess flows to go, and MODSIM3 would not be able to find a solution. Artificial arc (j,SP) has sufficient capacity to carry any excess flow (i.e., ten times total storage capacity in the basin). However, since spills have the highest cost of any link cost, MODSIM3 will try, if at all possible, to find exchange and operational solutions that make sure ITHRU = D_i. This will minimize wasted flows from the basin that upstream users are legally entitled to.

On the other hand, if the current period is dry, water will be allocated to the downstream users in accordance with priority c_{iD}, which may result in shortages. If demand D_i represents a senior compact agreement, then c_{iD} should be set to the largest negative value (i.e., DEMR = 1), which will insure that demand D_i is met if water is available.

E. Conveyances and Seepage Loss

The default model option sets pseudo prices c_{ij} for flows in river reaches (i,j) to one unit and pump canals to two units. For certain problems where it would be desirable to include pumping costs, MODSIM3 provides the additional option of user input of a varying cost for each linkage in the network.

MODSIM3 includes the capability of removing seepage losses in channels directly. A loss coefficient for each reach is included in data input. This coefficient represents the fraction of flow at the head of the link that would be lost during transition through the link. Subroutine CHANLS calculates the expected channel losses for each week or month. The procedure used by the model is as follows:

1. For the current time period, the channel loss is zero for the first iteration.
2. The channel loss is next calculated based on the current flow and added as a demand at the next downstream node.
3. An additional iteration is performed with the added channel loss demand. If flows in the link have not changed, then convergence is achieved. Otherwise, iterations are repeated.

This is illustrated in Figure 17, where cl_{ij} is the user-specified channel loss coefficient for reach (i,j). The procedure terminates when

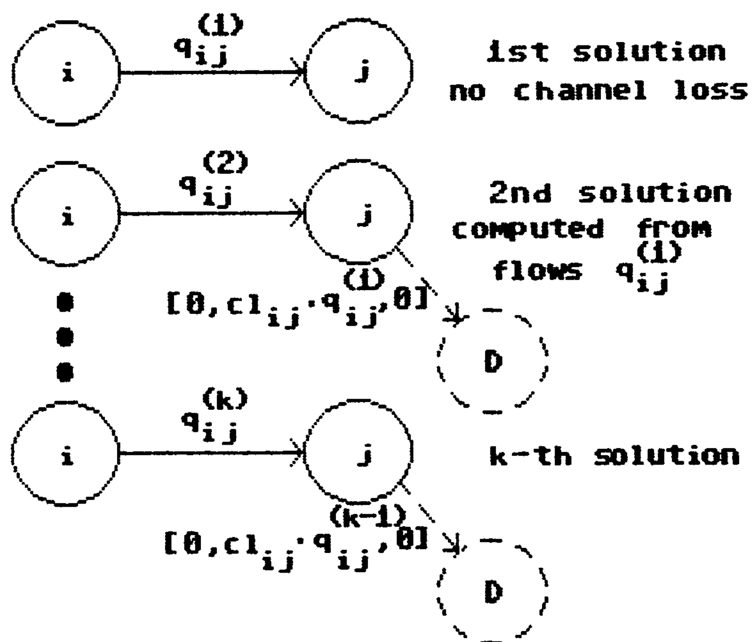

Figure 17. Iterations on channel seepage.

$$q_{ij}^{(k)} = q_{ij}^{(k-1)} \quad \text{for all arcs } (i,j)$$

within some specified error tolerance. As noted earlier, channel losses are also removed from flow-through demands by reducing flows returning back to the downstream node. Again, this means that demands are based on flows at the head of the reach, not the terminus.

If there is no demand at node j, then channel loss is the only "demand" at that node and it is given a high priority which guarantees that channel losses are always removed first since they are demands that must be satisfied. If there already is a demand at node j, then the channel losses are simply added onto those demands. However, this can create problems if that particular demand has a low priority. If there is a shortage of water, an insufficient amount of water may be delivered to node j to at least meet the channel loss requirement, since the channel loss in this case is governed by the same priority as the demand at that node. If this is a problem, it is recommended that a "dummy" node be added upstream of node j which now becomes the terminal node for the upstream links and therefore collects all channel losses in those links. The link connecting the dummy node and node j is assumed to be of zero length so that there are no channel losses added to node j demands.

Note that the bounds on channel capacity can be varied from period to period. This is useful, for example, when icing conditions lower channel capacities during winter months.

Another point to consider is that when dealing with monthly or weekly intervals, daily variations in flow are ignored. For example, average monthly flows may indicate sufficient water to divert to a channel and run at capacity. However, most the flow in that month may have occurred from a flood event such that there was insufficient channel capacity to divert all the flow. This means that, in general, actual diversions may be less than capacity if averaged on a weekly or monthly basis. Model users may desire to perform some daily analyses to determine if channel capacities should be lowered somewhat for use in MODSIM3 in order to remedy this situation.

F. Return Flows

MODSIM3 uses a procedure similar to that of Hodgson (1978) for estimating return flows. This portion of MODSIM3 remains unchanged from the original MODSIM3. A multiple regression approach is used where it is assumed that the return flows at a particular node are correlated with diversions at the next upstream node both for the current and past periods. In addition, the previous return flow estimates are assumed to be correlated. For example, the following regression relation

$$R(t) = a_1+a_2D(t)+a_3D(t-1)+a_4D(t-2)+a_5R(t-1)+a_6R(t-2) \tag{14}$$

specifies that return flow estimates R(t) are correlated to a time lag of two periods with upstream diversions D(t-j) and previous return flow estimates R(t-j).

The user must compute the regression coefficients a_i outside the model. Shafer (1979) summarizes the procedure as follows:

"The number of monthly lags and the components (independent variables) included in the regression equation must be determined off-line. However, once the regression coefficients have been determined, MODSIM3 has the capability of considering up to ten (Note: reduced to five in MODSIM3.) different return flow multiple linear regression equations with up to a maximum six-month lag. The following step-by-step procedure is recommended for use of this option.

1. Determine the number of return flow estimates necessary per month, based on the network design and the nature of the problem.

2. Determine which nodal diversions contribute to each return flow estimate.

3. Determine to which node in the network each monthly return flow estimate will accrue.

4. Using monthly historical data (ditch diversions and return flows), perform statistical correlation studies to determine the appropriate number of monthly lags.

5. Construct a multiple linear regression equation based on the results of the above exercise.

6. Solve for regression coefficients for each return flow equation.

According to user input, MODSIM3 calculates monthly return flows, iterating over demand satisfaction, until acceptable convergence is achieved. Subroutine RTFLOW has been added to MODSIM3 for this purpose."

What this means is that return flows are added to both the upper and lower bounds in flow arcs going to the node that return flows accrue to, much like flow-through demands. The difference is that lagged effects are considered. Adjustments are made in the same iterative loop as channel loss, flow-through demand, exchanges, and evaporation loss.

G. <u>Imported Water</u>

MODSIM3 includes the capability of handling two import nodes representing transbasin diversions. These are treated as unregulated inflows and simply added to the same artificial inflow arc. The difference is that they are computed as fractions of an annual (or 12 week period) total amount in order to break them into monthly or weekly amounts.

H. Summary

In summary, it can be seen from Figure 18 that there are a total of five artificial nodes to accumulate total system reservoir storages (node S), demands (node D), and spills (node SP) and to input total inflows and reservoir storage, at the beginning of the current simulation period (node I). There is also an artificial mass balance node M which guarantees that total inflow equals total outflow plus change in storage. These nodes are connected to each relevant node in the actual network by the artificial arcs, which are shown as dashed lines in Figure 18.

A summary of all link bounds and unit "costs" is shown in Table 2. After all real nodes are numbered, with all reservoirs always numbered first, then the model labels the artificial nodes. If the total number of real nodes is NJ then:

- Node NJ+1 = artificial inflow node I
- Node NJ+2 = artificial storage node S
- Node NJ+3 = artificial demand node D
- Node NJ+4 = artificial spill node SP
- Node NJ+5 = artificial mass balance node

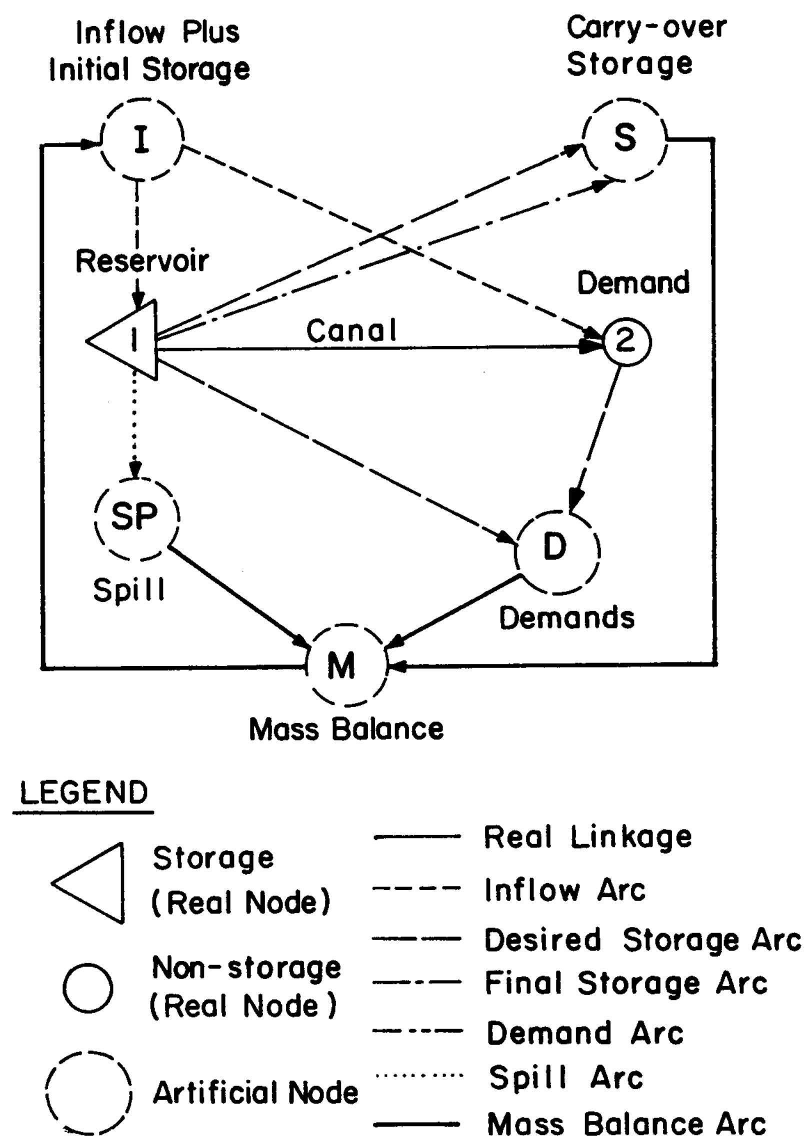

Figure 18. Linkage of all artificial nodes

Table 2. Link types and corresponding lower bounds, upper bounds, and unit costs.

Link type	Lower Bound	Upper Bound	Unit Cost
Physical system links			
river reaches	zero or minimum acceptable flow[1]	river capacity[1]	zero or penalty[1]
canals	zero or minimum requirement[1]	canal capacity[1]	zero or penalty[1]
Artificial links			
initial storage and inflow	previous end-of-period storage plus current period inflow plus current period return flow plus imports plus exchanges plus flow through demands	same as lower bound	zero
desired storage	minimum reservoir storage[1]	target storage[1]	$-(1000-OPRP_i*10)$[2]
excess storage	zero	maximum permitted storage minus target storage[1]	
demand	zero	demand at node plus channel losses in links entering node	$-(1000-DEMR_i*10)$[3]
spill	zero	sum of all reservoir capacities multiplied by ten	spill reservoir priority multiplied by 10,000[1]
Mass balance links			
total initial storage and inflow	sum of lower bounds on initial storage and inflow links	same as lower bound	zero
total final storage	sum of minimum storages	sum of maximum permitted storages	zero
total demand	zero	sum of demands and channel losses	zero
total spill	zero	sum of spill limits	zero

[1] user specified
[2] $OPRP_i$ user specified priorities (between 1 and 99) for storage at node i
[3] $DEMR_i$ user specified priorities (between 1 and 99) for demand at node i

IV. EXAMPLES ILLUSTRATING WATER ALLOCATION ACCORDING TO PRIORITY

We have shown how the link costs c_{ij} are defined, where the user must specify certain costs directly, or input priority factors on reservoir carryover storage OPRP and demand DEMR. The purpose of this section is to illustrate how the model actually allocates flows according to these priorities using some simple examples. This may help the user in properly selecting the priorities.

A. Example 1

Consider the simple network shown in Figure 19 for some given month or week (units are arbitrary for this example). Recall that

$$c_{iD} = -[1000 - DEMR_i \cdot 10]$$

As an example, let $DEMR_1 = 10$ and $DEMR_2 = 20$. So,

$$c_{1D} = -900$$

$$c_{2D} = -800$$

Since node 1 has the higher negative cost (i.e., benefit) it is being given a higher priority than node 2.

Assume that mass balance is satisfied at all the artificial nodes, and write equations (1) to (4) for nodes 1 and 2

$$\text{minimize } -900\ q_{1D} - 800\ q_{2D} \qquad (15)$$

subject to:

$$3000 - q_2 - q_{1D} = 0 \quad : \text{ mass balance at node \#1} \qquad (16)$$

$$q_{12} + 1000 - q_{2D} = 0 \quad : \text{ mass balance at node \#2} \qquad (17)$$

$$0 \leq q_{1D} \leq 2000 \quad : \text{ capacity constraints for link (1,D)} \qquad (18)$$

$$0 \leq q_{2D} \leq 3000 \quad : \text{ capacity constraints for link (2,D)} \qquad (20)$$

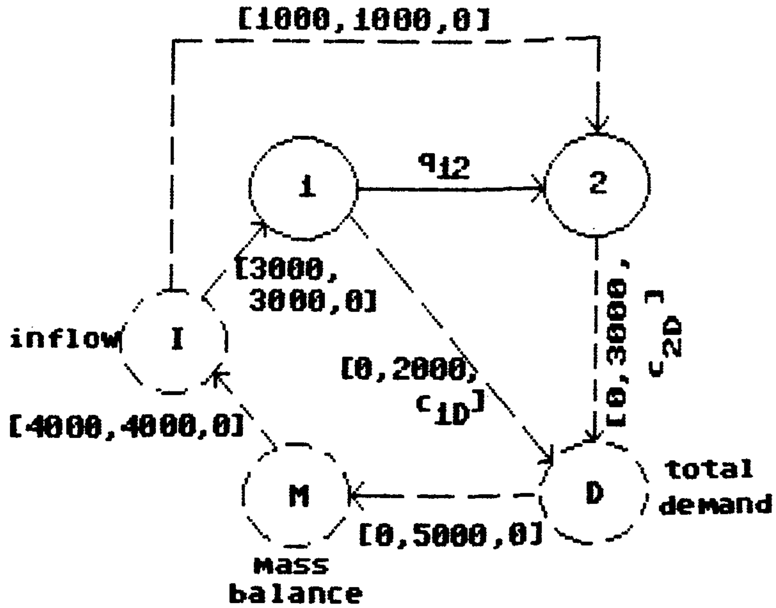

Figure 19. Node diagram for Example #1.

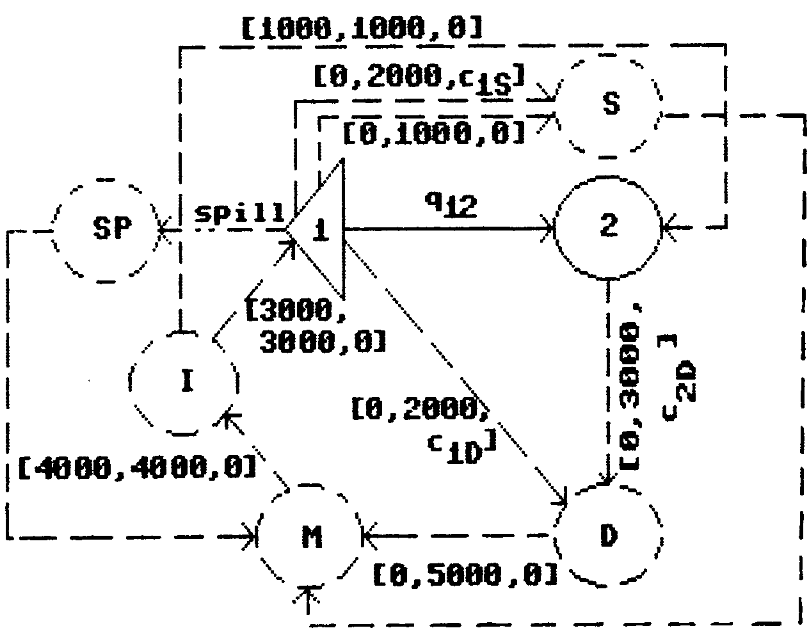

Figure 20. Node diagram for Example #2.

$$0 \leq q_{12} \leq 4000 \quad : \text{ capacity constraints for link (1,2)} \tag{21}$$

MODSIM3 solves this problem by the out-of-kilter method. However, since the method is quite complicated, and yet this problem is a simple one, a simpler procedure can be used which will give the same solution as the OKM would. The reader is referred to the Appendix in Shafer (1979) or Bazaraa and Jarvis (1977) for details on OKM.

Note that:

$$q_{1D} = 3000 - q_{12} \tag{22}$$

$$q_{2D} = 1000 + q_{12} \tag{23}$$

Substituting these into objective function (15) yields:

$$\text{minimize } -900\ (3000-q_{12})-800(1000+q_{12}) \tag{24}$$

or

$$\text{minimize } 900\ q_{12} - 800\ q_{12} = 100\ q_{12} \tag{25}$$

subject to

$$0 \leq (3000 - q_{12}) \leq 2000 \tag{26}$$

$$0 \leq (1000 + q_{12}) \leq 3000 \tag{27}$$

$$0 \leq q_{12} \leq 4000 \tag{28}$$

These can all be combined into one expression:

$$1000 \leq q_{12} \leq 2000 \tag{29}$$

by selecting the most limiting upper and lower bounds from equations (25) to (28).

Since it is desired to minimize $100q_{12}$, the obvious answer is to set

$$q_{12}^{*} = 1000$$

From mass balance, the flows in the other links are:

$q^*_{1D} = 2000$ $\qquad$ $q^*_{DM} = 4000$

$q^*_{2D} = 2000$ $\qquad$ $q^*_{MI} = 4000$

Therefore, node 1 receives its full allocation, while node 2 is shorted by 1000.

Now suppose that the priorities were reversed. That is:

$DEMR_1 = 20$

$DEMR = 10$

Following the same procedure, the objective is to

$$\text{minimize } -100\ q_{12}$$

subject to the same constraint (28). The answer is obviously:

$$q^*_{12} = 2000$$

with

$q^*_{1D} = 1000$ $\qquad$ $q^*_{DM} = 4000$

$q^*_{2D} = 3000$ $\qquad$ $q^*_{MI} = 4000$

B. <u>Example 2</u>

A more complicated example will now be considered: Here, node 1 is now a storage node. There is also a direct demand from node 1. (Recall that a storage node can also be a demand node.) In this example, channel loss and evaporation are neglected. Notice that the target storage for reservoir 1 is 2000, but total capacity is 3000. The inflow link to reservoir 1 is set at [3000,3000,0]. This might represent an inflow of 1000 and a carryover storage from the previous period of 2000, for example.

Now, assume

$DEMR_1 = 10$

$OPRP_1 = 20$

$DEMR_2 = 30$

Notice that demand node 1 is given the highest priority, followed by the reservoir, and lastly by demand node 2. Assume that there is zero flow in the artificial spill link and the final storage link. Again assuming mass balance is satisfied in all the artificial nodes, the problem is:

$$\text{minimize } -900q_{1D} - 800q_{1S} - 700q_{2D}$$

subject to:

$$3000 - q_{12} - q_{1S} - q_{1D} = 0$$

$$q_{12} + 1000 - q_{2D} = 0$$

$$0 \leq q_{1D} \leq 2000$$

$$0 \leq q_{2D} \leq 3000$$

$$0 \leq q_{1S} \leq 2000$$

$$0 \leq q_{12} \leq 4000$$

Solving for q_{1D} and q_{2D}:

$$q_{1D} = 3000 - q_{12} - q_{1S}$$

$$q_{2D} = 1000 + q_{12}$$

Substituting these into the objective function:

$$\text{min } -900(3000-q_{12}-q_{1S})$$

$$-800q_{1S}$$

$$-700(1000+q_{12})$$

or

$$\text{minimize } 200q_{12} + 100q_{1S}$$

subject to:

$$0 \leq (3000-q_{12}-q_{1S}) \leq 2000$$

$$0 \leq (1000+q_{12}) \leq 3000$$

$$0 \leq q_{1S} \leq 2000$$

$$0 \leq q_{12} \leq 4000$$

The only variables remaining are q_{12} and q_{1S}. These constraints can be rewritten as:

$$q_{12} + q_{1S} \leq 3000$$

$$q_{12} + q_{1S} \geq 1000$$

$$q_{12} \leq 2000$$

$$q_{1S} \leq 2000$$

$$q_{12}, q_{1S} \geq 0$$

The feasible region defining the ranges of q_{12} and q_{1S} that satisfy <u>all</u> the above constraints is shown graphically in Figure 21.

The objective is now:

$$\text{minimize } z = 200\, q_{12} + 100\, q_{1S}$$

or

$$q_{1S} = -\frac{200}{100} q_{12} + \frac{z}{100}$$

For any value of z, the slope of the objective function is −2 on this graph. Optimizing z means translating a line of slope −2 to the left as far as possible, while still having at least one feasible point along the line. This point must be optimal, and is clearly:

$$q_{12}^{*} = 0 \qquad q_{1S}^{*} = 1000$$

for this example.

From mass balance, this means that

$$q_{1D}^{*} = 2000 \qquad q_{2D}^{*} = 1000$$

Therefore, demand node 1 receives its full allocation, end of period storage in reservoir 1 is short of the target by 1000, and demand node 2 receives nothing. The final storage of 1000 is then added to inflows for the next period and the next period simulation proceeds. Shifting these priorities would of course change the entire allocation.

C. <u>Extensions</u>

Channel losses and evaporation were neglected in this example. Their inclusion would mean that bounds would be adjusted, which means that the lines in Figure 21 would be shifted in some way, thereby possibly altering the solution (although not in this particular example).

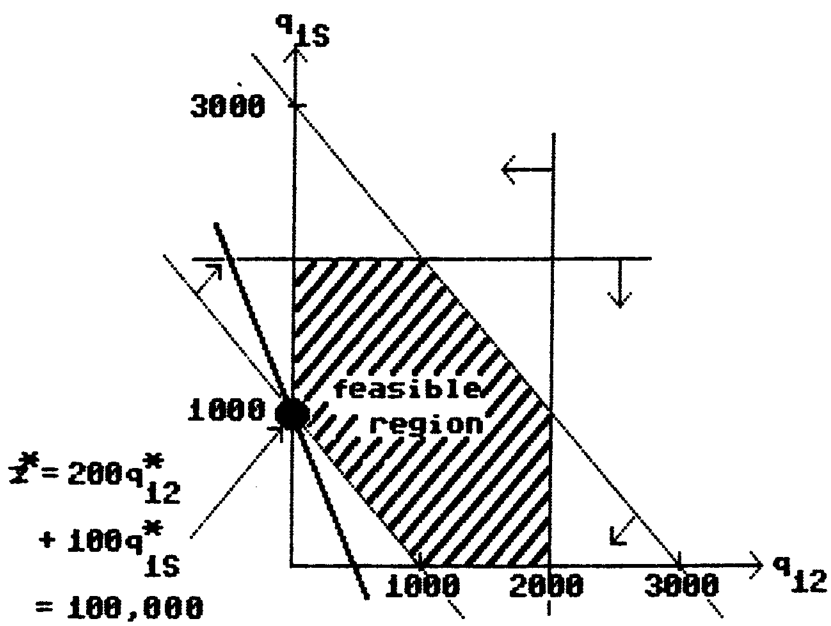

Figure 21. Region of feasible flows for Example #2.

Some variations will now be considered. Suppose $OPRP_1 = 30$ instead of 20. Then

$$z = 200\ q_{12} + 200\ q_{1S}$$

or the slope of the objective function on the above graph is −1. This means that either

$$q^*_{12} = 0 \qquad q^*_{1S} = 1000$$

or

$$q^*_{12} = 1000 \qquad q^*_{1S} = 0$$

are optimal. MODSIM3 will pick one of them arbitrarily. These kinds of ties are rare for complex problems, but it does illustrae that it is better to assign distinct priorities if possible, and preferably not too close together.

V. INPUT DATA PREPARATION

Program MODSIM3 is coded in FORTRAN IV, and all data must currently be input by cards for use on the Fort Collins UNIVAC computer. Future work will likely focus on updating the code to FORTRAN 77 and modifying the interactive conversational data input capabilities developed by Shafer (1979) and Labadie (1982) for use with MODSIM3. Flow charts, FORTRAN variable definitions, and COMMON block definitions are all given in the Appendix.

A. Data Requirements

Two subroutines are used for reading data: Subroutine CARDS (or WSD914) and Subroutine DATA1 (or WSD915). The latter creates a file of unregulated inflows, demands, and evaporation rates, whereas the former contains all network morphology, operational criteria, system capacities, and model control parameters. Inflows can also be read into CARDS at the user's option. However, inflows are defined as imported water here, whose monthly distributions are fixed, even though annual quantities can change. Also, at most two imported water nodes can be designated.

The demand priorities are read into CARDS rather than DATA1. Priorities can be defined for each hydrologic state, if that option is selected, but the demands themselves do not change for each hydrologic state. For reservoir operations, however, it is possible to change the target end-of-period storages with the hydrologic state, which is also done in CARDS.

In the following, each record represents one card and each numbered item is one field within that record:

RECORD #1: Control Options [Format (15X,6I5,F10.2)]

1. LOPT [if = 1, channel loss considered; 0 otherwise]
2. IOTT [if = 1, echo print of input data; 0 otherwise]

3. ISUM [if = 1, additional summary output; 0 otherwise]

4. IALLY [if = 1, user will input priorities for each year; if 0, hydrologic states defined]

5. IRTN [if = 1, return flows calculated; 0 otherwise]

6. ITERIX [maximum number of iterations allowed for flow-through demand or exchange flow convergence]

7. TOL [user specified error tolerance for convergence of total channel loss in the system]

RECORD #2: Title for Current Simulation [Format (20A4)]

RECORD #3: Network Parameters [Format (12I5)]

1. NJ [total number of real nodes $\leq$ 45]

2. NRES [total number of reservoirs $\leq$ 15]

3. NL [total number of real links $\leq$ 70]

4. NR [number of natural river reaches $\leq$ NL]

5. NYEAR [number of years or 12 week seasonal periods to be continuously simulated]

6. ND [number of demand nodes $\leq$ 45]

7. NS [number of reservoirs where spills can occur $\leq$ 15]

8. IYEAR [calender year or season that simulation starts]

9. IMN [number of import nodes $\leq$ 2]

10. IPRNT [if = 1, total link printout option; 0 otherwise]

11. IFROM [number of starting year or season for which detailed output desired]

12. ITOY [number of ending year for detailed output $\geq$ IFROM]

RECORD #4: Input-Output Control Parameters [Format (10X,7I5)]

1. KAPE4 [if = 1, user later reads in both OPRPL and OPRPH for each reservoir; if 0 then OPRPL = OPRP]

2. KAPE1 [record number for start of information on data input disk file 52]

3. JFL [record number for start of information on model output disk file 51]

4. IOUT30 [if = 1, annual (or 12 week seasonal) node data written to file 51 for output summaries; 0 otherwise]

5. IOUT31 [if = 1, output summary for each year (or 12 week seasonal) obtained; 0 otherwise]

6. IOUT32 [if = 1, output summary for each node obtained; 0 otherwise]

7. IOUT33 [if = 1, annual (or 12 week seasonal) total system output summary obtained; 0 otherwise]

<u>RECORD #5</u>: Reservoir Names and Capacities [Format (T11,I5,T1,2A4,T16,4I10)]

1. J [node number for reservoir]

2. RNAME [reservoir name]

3. RCAP [maximum capacity; (volume units)]

4. RMIN [minimum capacity; (volume units)]

5. STEND [initial storage at beginning of simulation; (volume units)]

6. SP [order of spill; integer between 1 and NRES; smallest number associated with reservoir that shoul spill first if spills are necessary]

{repeat this record for each reservoir J=1,...,NRES (all integer, except for character data RNAME}

<u>RECORD #6</u>: Names of all other Nonstorage Nodes [Format (T11,I5,T1,2A4)]

1. J [node number for nonstorage node]

2. RNAME [nonstorage node name (characters)]

{repeat this card for each nonstorage node J= NRES+1,...,NJ}

RECORD #7: Area-Capacity Tables for each Reservoir

Record #7A: [Format (10X,I5)]

1. NPAIRS [number of area-capacity points assumed to be the same for each reservoir]

Record #7B: [Format (10X,I5,6I10)]

1. J [reservoir node number]
2. ACTAB(J,1,1) [reservoir J surface area at first or lowest point]
3. ACTAB(J,1,2) [reservoir J volume at first or lowest point]

[Note: units should be based on volume units, i.e., AREA units = VOLUME units/evaporation rate units.]

Record #7C: [Format (I5X,6I10)]

1. ACTAB(J,K,1) [next reservoir surface area point]
2. ACTAB(J,K,2) [associated volume point]

{repeat Record #7C for remaining points at increasing elevation K = 2,...,NPAIRS}

* {repeat Records #7B and #7C for each reservoir J=1,...,NRES}

RECORD #8: Demand Priorities

Record #8A: [Format (7X,5I3)]

1. J [demand node number]
2. IDSTRM(J) [if a flow-through demand, the node to which flow accrues; if node J is an exchange node, then type IDSTRM with a minus sign]

{leave the following fields blank if the hydrologic state option is not being used}

3. DEMR(J,1) [node J demand priority for average state]
4. DEMR(J,2) [node J demand priority for dry state]
5. DEMR(J,3) [node J demand priority for wet state]

Record #8B: [Format (10X,11I5)]

{this record is entered only if IALLY = 1; i.e., no hydrologic state option}

1. J [demand node]

2. DEMR(J,1) [node J demand priority for year (or 12 week season) 1]

3. DEMR(J,2) [node J demand priority for year (or 12 week season) 2]

11. DEMR(J,10) [node J demand priority for year (or 12 week season) 10]

{if simulating more than 10 years (or 12 week seasons), place remaining demand priorities in up to 11 remaining fields of additional records}

RECORD #9: Imported or Transbasin Inflows

Record #9A: [Format (10X,I5)]

1. IMP(I) [import node number for Ith import node]

{repeat for I=1,...,IMN}

Record #9B: [Format (20X,I10,12F4.0)]

1. IMPRT(I,K) [annual (or 12 week seasonal) inflow to Ith import node during year K]

2...13. DIMP(I,J,K) [monthly (or weekly) fractional distribution of inflows for each month (or week) I=1,...,12, i.e.,

$$\sum_{I=1}^{12} DIMP(I,J,K) = 1.0$$

{repeat this record for years K=1,...,NYEAR}

RECORD #10: Hydrologic State Information

{if IALLY=1, bypass this record, i.e., hydrologic state not considered}

Record #10A: [Format (10X,9I5)]

1. NSRS [number of reservoirs for which the hydrologic state will be computed $\leq$ 10]

2... 9. JESVOL(I) [actual node numbers of the I=1,...,NSRS reservoirs included in hydrologic state computer allowed for hydrologic state computations; no more than 10 reservoirs allowed for hydrologic state computations]

Record #10B: [Format (10X,2F10.0)]

1. AVRGLO [parameter x_1 in equation 10]

2. AVRGHI [parameter x_2 in equation 11]

RECORD #11: Units Conversion [Format (10X,3F10.0)]

{if any of the following parameters are set to any real number $\leq$ 0., it is assumed that the corresponding flow units are units of the user specified storage volume per month (or week). If, for example, inflow units are input in cfs, but volume is in acre-feet, then set CONINF=60. MODSIM3 will then multiply all the inflows in cfs by 60., which converts them to acre-feet/month. A similar conversion can be used for any demands that are input, using CONDEM. For flows computed by the model, it may be desired to convert from storage units per time period back to, say, cfs. If storage is in acre-feet, then set CONFLO = 60. MODSIM3 will then divide the flows by CONFLO, which converts them to cfs in the output.}

1. CONINF

2. CONDEM

3. CONFLO [link flow capacities are also governed by CONFLO]

RECORD #12: Reservoir Operating Rules [Format (10X,I5,5X,2I5,124.0]

Record #12A: {skip this record if IALLY=1}

1. J [reservoir node member $\leq$ NRES]

2. OPRPH(L,J) [reservoir priority or rank (between 1 and 99) at target storage for hydrologic state L]

3. OPRPL(L,J) [reservoir priority or rank at minimum storage for hydrologic state L]

4. OPRR(L,J,1) [ratio of target storage and maximum storage (fraction) for month (or week) 1 and hydrologic state L]

15. OPRR(L,J,12) [ratio of target storage and maximum storage (fraction) for month (or week) 12 and hydrologic state L]

{repeat this record for each hydrologic state: L=1 (average); L=2 (dry); L=3 (wet)}

{repeat this group of records for each reservoir J=1,...,NRES}

*Skip to RECORD #13

Record #12B: {assuming no hydrologic state computation}

1. J [reservoir node number ≤ NRES]

2. OPRPH(L,J) [reservoir priority or rank (between 1 and 99) at target storage for year (or 12 week season) L]

3. OPRPL(L,J) [reservoir priority or rank (between 1 and 99) at minimum storage for year (or 12 week season) L]

4. OPRR(L,J,1) [ratio of target storage and maximum storage (fraction) for month (or week) 1 and year (or 12 week season) L]

for month (or week) 12 and year (or 12 week season) L]

{repeat this record for years (or 12 week seasons) L=1,...,NYEAR}

{repeat this group of records for each reservoir J=1,...,NRES -- does not have to be done in strict order}

RECORD #13: Link Capacities and Costs

Record #13A: [Format (10X,I5)]

1. NVAR [number of links with capacities that change during the year or season; e.g., due to icing, etc.]

*If NVAR=0, Skip to Record #13D

Record #13B: [Format (10X,3I5,10X,I10,F10.0,I5)]

1. L [link number]

2. LNODE(L,1) [origin node for link L]

3. LNODE(L,2) [terminal node for link L]

4. CMIN(L) [minimum capacity of link L]

5. XLCF(L) [fraction of the flow entering link L which is lost due to seepage in link L]

6. COST(L) [unit cost of flow in link L; negative cost represents benefit, such as for hydropower generation; must be integer]

Record #13C: [Format (8X,12I6)]

1. CMAXV(L,1) [maximum capacity of link L during month (or week) 1]

12. CMAX(L,12) [maximum capacity of link L during month (or week) 12]

{repeat Records #13A and #13B for NVAR links}

*If NVAR=NL, Skip to RECORD #14

Record #13D: For Links with Constant Maximum Capacity [Format (10X,3I5, 2I10,F10.0,I5)]

1. L [link number]

2. LNODE(L,1) [origin node for link L]

3. LNODE(L,2) [terminal node for link L]

4. CMAX(L) [maximum capacity of link L]

5. CMIN(L) [minimum capacity of link L]

6. XLCF(L) [fraction of the flow entering link L which is lost due to seepage in link L]

7. COST(L) [unit cost of flow in link L]

{repeat Record #13D for (NL-NVAR) links}

RECORD #14: Return Flow Calculations

{Skip this record if IRTN=0}

Record #14A: [Format (10X,2I5)]

1. NEQU [number of nodes where return flows accrue $\leq$ 5;

2. NLAGS [number of time lags $\leq$ 6]

Record #14B: [Format (8F10.0)]

1. A(I,J) [regression coefficients for return flows to the Ith return flow node, for J=1,...,LAGS, where LAGS=2*NLAGS + 2. Note: The ordering should be (i) the constant term, (ii) the current ditch diversions (which contribute return flows to node I), (iii) all remaining lagged diversions (t-1),(t-2), ...,etc., (iv) lagged return flows (t-1),(t-2),...,etc.]

Record #14C: [Format (5X,2I5)]

1. NDNEQU(I) [the number of demand nodes which contribute return flows to the Ith return flow node; the total diversions will be used in the regression]
2. JRTFT(I) [the actual node number of the Ith return flow node]

Record #14D: [Format (5X,15I5)]

1. IRTFF(I,1) [the actual demand node number of the first demand which contributes return flows to node JRTFT(I)]
2. IRTFF(I,2) [the actual demand node number of the second demand node which contributes return flows to node JRTFT(I)]

   (etc.) -- up to IRTFF(I,NDNEQU(I))

Record #14E: [Format (5X,12I6)]

1. IDIVL(I,J) [total ditch diversion observed contributing return flows to node JRTFT(I) for period zero minus J]
2. IRTL(I,J) [observed return flows at node JRTFT(I) for period zero minus J]

{complete this record for J=1,...,NLAGS}

*{Repeat Records #14B, #14C, #14D, and #14E for all I=1,...,NEQU.}

Following the data file read by Subroutine CARDS, MODSIM3 reads inflow, demand and evaporation data for all system nodes one month (or week) at a time. It is assumed that the user has read this information onto a disk file (either sequential or random access read). For the current version of MODSIM3, the read statement is set up for disk file 52, with the starting record set at the user specified number KAPE1 (which is input in Record #4 of the CARDS input), is:

For all storage nodes JK=1,...,NRES:

```
READ(52'KAPE1,END=121)U(JK),DEMON(JK),EVAP(JK).
```

And for all nonstorage nodes JK=NRES+1,...,NJ

```
READ(52'KAPE1,END=124)U(JK),DEMON(JK)
```

where

U(JK) = inflows to node JK during the current month (or week)

DEMON(JK) = demans at node JK during the current month (or week)

EVAP(JK) = evaporation rate for current month (should be in units consistent with the ACTAB table in the CARDS input.

B. Example Problem for MODSIM3 (Ponder River Basin)*

The hypothetical Ponder River basin is shown in Figure 22. Historically, the Dry Ditch Irrigation Co. has had little opportunity to divert Ponder River water during the irrigation season because of their very junior water rights. The City of Fort College, however, possesses senior water rights, plus No Right reservoir and Bandit ditch and therefore has been able to meet demands with little difficulty. A recent flood has damaged the Fort College intake facilities thereby limiting a direct river diversions to 500 acre-feet per month. Fort College officials are concerned that future demands may not be met due to the reduced capacity. One possible method to meet the Fort College demand would be to exchange water with the Dry Ditch Co. The Dry Ditch Co. owns a portion of Toothless Reservoir. Fort College officials would like to use MODSIM3 to assess the feasibility of an exchange between the Dry Ditch Co. and the City of Fort College.

1. Ponder River input data.

Month	Native Streamflow (ac. ft)	Bandit Ditch (Import) (ac. ft)	Dry Ditch Co. (Demand) (ac. ft)	City of Fort College (Demand)
1	600	0	0	500
2	600	0	0	500
3	600	0	0	500
4	500	0	500	600
5	200	500	1000	1000
6	200	500	2000	1500
7	200	500	4000	2000
8	200	500	2500	2000
9	500	500	500	1500
10	600	0	0	600
11	600	0	0	500
12	600	0	0	500
Average	5400	2500	10,000	11,700

* Developed by Andrew Pineda.

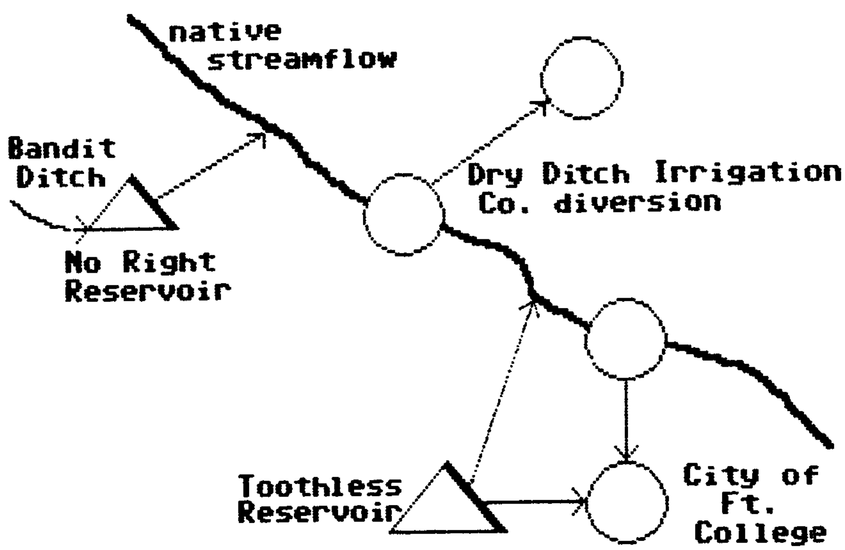

Figure 22. Hypothetical 'Ponder River Basin'.

2. Channel loss is reported to be about 5% of the total flow above the Dry Ditch Co. diversion.

3. Reservoir Data:

	No Right	Toothless*
Max. storage	6000	10,000
Min. storage	0	0
Starting storage	4000	0

*The Dry Ditch Co. owns shares in Toothless Reservoir up to a maximum of 10,000 shares. (1 share = 1 ac. ft). These shares will be shown as a credit from the Dry Ditch Co. to Fort College.

4. Area-Capacity tables:

	Area (acres)	Capacity (ac. ft)
No Right	0	0
	100	2000
	200	4000
	300	6000
Toothless	0	0
	200	4000
	400	6000
	600	10000

5. Evaporation: (ft per month)

Month	No Right	Toothless
1	-.05	0
2	-.02	0
3	.01	0
4	.04	0
5	.14	0
6	.22	0
7	.27	0
8	.35	0
9	.28	0
10	.17	0
11	.06	0
12	.01	0

6. River, canal, pipeline limitations:

(a) Releases from No Right reservoir are limited to 500 ac. ft per month for months 1 through 4, and 10 through 12 (reduced winter flow).

(b) Maximum capacity from river to Fort College is 500 ac. ft per month.

7. Other operation criteria:

(a) City of Fort College demand is senior to Dry Ditch Co.

(b) The following criteria for Toothless Reservoir will control the amount of exchanged water.

Toothless Reservoir Contents (ac. ft)	1 Fort College	2 Dry Ditch	3 No Right	4 Toothless
0-1500	high priority	high priority	release to 1 and 2	release to 1
1500-2500	high priority	low priority	release to 1	release to 1
2500-10000	low priority	low priority	no releases	release to 1

8. <u>Demand and Storage priorities</u>:

Toothless Reservoir Contents (ac. ft)	Demand		Storage	
	Fort College	Dry Ditch Co.	No Right	Toothless
0-1500 (dry)	10	40	80	80
1500-2500 (avg)	10	40	30	80
2500-10000 (wet)	10	40	5	80

*Note that if in the 'avg' state, No Right reservoir will not release to the Dry Ditch Co. demand, but will release to Fort College if native streamflow is not adequate.

<u>Network Setup</u>

Figure 23 shows the network configuration for this hypothetical problem. The numbering of nodes and links is governed by the following.

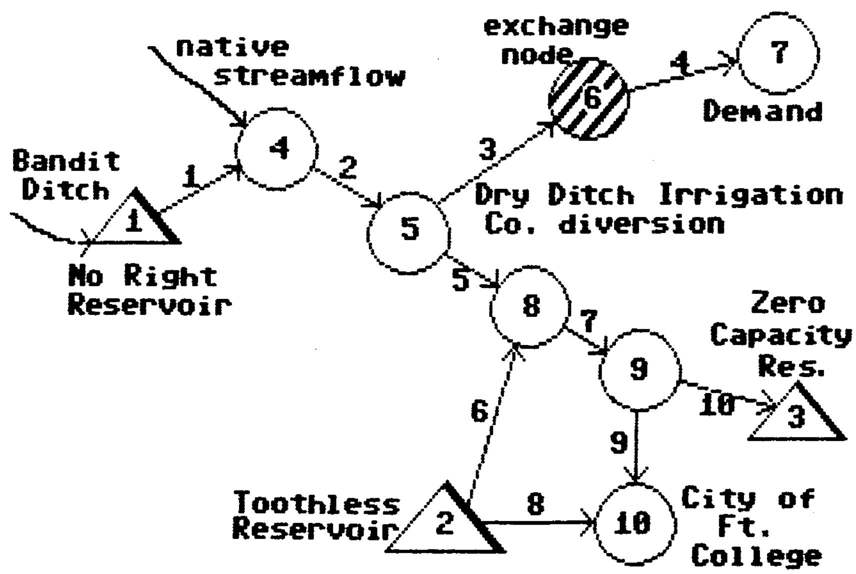

Figure 23. Network Configuration for Ponder River Example

1. Number the reservoirs first
2. Number nonstorage nodes next
3. Number links (designate links 9, 10 as 'pump links')

Note the location of node 5 as the exchange node. Any flow in link 3 will be credited in reservoir 2 (Toothless). Location of node 5 also prevents 'double' accounting of water that is released from 1 to demand at node 4. Link 2 will have a channel loss coefficient of 0.05 assigned to it. Reservoir 3 is designated as a zero capacity reservoir to spill excess water left in system.

The input data file for this example problem is shown in Table 3.

Analysis of Results

Table 4 gives the output from MODSIM3 for this example problem. An organized presentation of the input data is first given. This is followed by a monthly accounting of the operation of each reservoir in 12 month groups. An accounting of each exchange and demand node is included for each month showing inflows, outflows, demands, and shortages. Notice that no demand is shown for demand node 6 since it is actually an exchange node. This information is followed by a matrix giving the flows entering each link and channel losses for each month.

1. Note the exchange that occurred between Fort College and Dry Ditch Co.
2. Had the exchange not occurred, Fort College would have had a shortage of 5700 ac. ft rather than a shortage of 878 ac. ft (11,700-500x12). The Dry Ditch Co. would have experienced a shortage of 10,500 ac. ft if the exchange was not possible.
3. Note that the 'hydrologic' state stayed in the 'dry' state throughout the simulation, since the hydrologic state is determined prior to any exchange.

Table 3. Data input file for "Ponder Basin" example

```
CONTROL OPTIONS     1    1    0    0    0   10        1.10
EXAMPLE PROBLEM     PONDER RIVER BASIN (EXCHANGE)
PARMETERS     10    3   10    8    1    3    3 1984   1    0    1    1
OUT3 PARM      0    1    1   -1    0    1    0
NO RIGHT       1      6000         0      4000        3
TOOTHLES       2     10000         0         0        2
RES NO 3       3         0         0         0        1
NODE 4         4
NODE 5         5
EXCH           6
D D CO.        7
NODE 8         8
NODE 9         9
FTCOLLEG      10
NO. PAIRS      4
AR-CAP1        1         0         0       100     2000      200     4000
                       300      6000
AR-CAP2        2         0         0       200     4000      400     6000
                       600     10000
AR-CAP3        3         0         0         0        0        0        0
                         0         0
DEMAND    6 -2  1  1  1
DEMAND    7  0 40 40 40
DEMAND   10  0 10 10 10
IMPORT         1
YEAR1                     2500    0    0    0    0  .2  .2  .2  .2  .2    0    0    0
SUBSYSTEM      1    2
AVERAGE ST        .15        .250
FACTORS             0           0         0
ANNUAL OPR     1          80   301.001.001.001.001.001.001.001.001.001.001.001.00
ANNUAL OPR     1          80   801.001.001.001.001.001.001.001.001.001.001.001.00
ANNUAL OPR     1          80    51.001.001.001.001.001.001.001.001.001.001.001.00
ANNUAL OPR     2          80   801.001.001.001.001.001.001.001.001.001.001.001.00
ANNUAL OPR     2          80   801.001.001.001.001.001.001.001.001.001.001.001.00
ANNUAL OPR     2          80   801.001.001.001.001.001.001.001.001.001.001.001.00
ANNUAL OPR     3          80   800.000.000.000.000.000.000.000.000.000.000.000.00
ANNUAL OPR     3          80   800.000.000.000.000.000.000.000.000.000.000.000.00
ANNUAL OPR     3          80   800.000.000.000.000.000.000.000.000.000.000.000.00
NVARKS         1
LINK           1    1    4                 0             0    0
CVMAX        500  500  500   500  6000  6000  6000  6000  6000   500   500   500
LINK           2    4    5      6000       0          .050    0
LINK           3    5    6      6000       0             0    0
LINK           4    6    7      6000       0             0    0
LINK           5    5    8      6000       0             0    0
LINK           6    2    8      6000       0             0    0
LINK           7    8    9      6000       0             0    0
LINK           8    2   10      6000       0             0    0
LINK           9    9   10       500       0             0    0
LINK          10    9    3      6000       0             0    0
```

Table 4. MODSIM3 output for "Ponder Basin" example

```
RIVER BASIN SIMULATION PACKAGE:                    PROGRAM MODSIM - COLORADO STATE UNIVERSITY
          EXAMPLE PROBLEM    PONDER RIVER BASIN (EXCHANGE)

              NUMBER OF NODES =    10             NUMBER OF RESERVOIRS =  3
              NUMBER OF LINKS =    10          NUMBER OF RIVER REACHES =  8
 CALENDAR YEAR OPERATION STARTS = 1984        NUMBER OF YEARS TO SIMULATE =  1
        NUMBER OF DEMAND NODES =    3              NUMBER OF SPILL NODES =  3
RESERVOIR OPR RULE OPTION(KAPE4) =    0            NUMBER OF IMPORT NODES =  1

 CHANNEL LOSSES WILL     BE CONSIDERED
 CHANNEL LOSS TOLERANCE =     1.100

 RETURN FLOWS WILL NOT BE CALCULATED
```

NODE NO.	NODE NAME	CAPACITIES MAXIMUM	CAPACITIES MINIMUM	CAPACITIES STARTING	SPILL RANK
1	NO RIGHT	6000	0	4000	3
2	TOOTHLES	10000	0	0	2
3	RES NO 3	0	0	0	1
4	NODE 4				
5	NODE 5				
6	EXCH				
7	D D CO.				
8	NODE 8				
9	NODE 9				
10	FTCOLLEG				

Table 4. continued

RIVER BASIN SIMULATION PACKAGE: PROGRAM MODSIM - COLORADO STATE UNIVERSITY

EXAMPLE PROBLEM PONDER RIVER BASIN (EXCHANGE)

SYSTEM CONFIGURATION

LINK NO.	FROM NODE	TO NODE	MAX. CAPACITY	MIN. CAPACITY	LOSS COEFFICIENT	COST
1	1	4	VARIES MONTHLY	0	0.0	0
2	4	5	6000	0	0.050	0
3	5	6	6000	0	0.0	0
4	6	7	6000	0	0.0	0
5	5	8	6000	0	0.0	0
6	2	8	6000	0	0.0	0
7	8	9	6000	0	0.0	0
8	2	10	6000	0	0.0	0
9	9	10	500	0	0.0	0
10	9	3	6000	0	0.0	0

Table 4. continued

```
RIVER BASIN SIMULATION PACKAGE:              PROGRAM MODSIM - COLORADO STATE UNIVERSITY
              EXAMPLE PROBLEM    PONDER RIVER BASIN (EXCHANGE)

NODE NO.  1       YEARLY IMPORT =        2500
                  MONTHLY IMPORT DISTRIBUTION:  0.0  0.0  0.0  0.0  0.20 0.20 0.20 0.20 0.20 0.0  0.0  0.0

SUB-SYSTEM OF RESERVOIRS      2

"AVERAGE" DEFINED AS BETWEEN  15.0, AND  25.0 PERCENT FULL OF SUBSYSTEM

FACTORS
     MULTIPLY LINK CAPACITIES BY   1.000
     MULTIPLY INFLOWS BY .......    1.00
     MULTIPLY DEMANDS BY .......    1.00
```

Table 4. continued

RIVER BASIN SIMULATION PACKAGE: PROGRAM MODSIM - COLORADO STATE UNIVERSITY

EXAMPLE PROBLEM PONDER RIVER BASIN (EXCHANGE)

DEMAND RANKING FOR AVG,DRY,WET CONDITION

NODE NO.	AVG	DRY	WET
6	1	1	1
7	40	40	40
10	10	10	10

Table 4. continued

RIVER BASIN SIMULATION PACKAGE: PROGRAM MODSIM - COLORADO STATE UNIVERSITY

EXAMPLE PROBLEM PONDER RIVER BASIN (EXCHANGE)

DESIRED MONTHLY STORAGE LEVEL (PERCENT FULL)

RESERVOIR NO.														RANKHI	RANKLO
1	AVRG	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	30	
	DRY	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	80	
	WET	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	5	
2	AVRG	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	80	
	DRY	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	80	
	WET	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	80	
3	AVRG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	80	
	DRY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	80	
	WET	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	80	

Table 4. continued

RIVER BASIN SIMULATION PACKAGE: PROGRAM MODSIM - COLORADO STATE UNIVERSITY

EXAMPLE PROBLEM PONDER RIVER BASIN (EXCHANGE)

RESERVOIRS AREA(AC) & CAPACITY(AC-FT) TABLES

	RESERVOIR NO. 1		RESERVOIR NO. 2		RESERVOIR NO. 3		RESERVOIR NO.
1	0	0	0	0	0	0	
2	100	2000	200	4000	0	0	
3	200	4000	400	6000	0	0	
4	300	6000	600	10000	0	0	

Table 4. continued

EXAMPLE PROBLEM PONDER RIVER BASIN (EXCHANGE)

SIMULATION YEAR 1 CALENDAR YEAR 1984

RESERVOIR NO 1 NO RIGHT MAX. CAPACITY 6000 MIN. OPERATING POOL 0

MONTH	INITIAL STORAGE	UREG INFLOWS	UPSTRM RELEASE	DEMAND	SURFACE AREA	EVAP RATE	EVAP LOSS	DWNSTRM RELEASE	SHORTAGE	PUMPED INTO	PUMPED OUT	SYSTEM LOSS	END MO. CONTENT	OPER. RULE
1	4000	0	0	0	200	-0.05	-9	0	0	0	0	0	4009	6000
2	4009	0	0	0	203	-0.02	-3	0	0	0	0	0	4012	6000
3	4012	0	0	0	201	0.01	2	0	0	0	0	0	4010	6000
4	4010	0	0	0	197	0.04	8	130	0	0	0	0	3872	6000
5	3872	500	0	0	184	0.14	26	852	0	0	0	0	3494	6000
6	3494	500	0	0	139	0.22	31	1905	0	0	0	0	2058	6000
7	2058	500	0	0	51	0.27	14	2544	0	0	0	0	0	6000
8	0	500	0	0	0	0.35	0	500	0	0	0	0	0	6000
9	0	500	0	0	0	0.28	0	500	0	0	0	0	0	6000
10	0	0	0	0	0	0.17	0	0	0	0	0	0	0	6000
11	0	0	0	0	0	0.06	0	0	0	0	0	0	0	6000
12	0	0	0	0	0	0.01	0	0	0	0	0	0	0	6000
	TOTAL	2500	0	0			69	6431	0	0	0	0		

RESERVOIR NO 2 TOOTHLES MAX. CAPACITY 10000 MIN. OPERATING POOL 0

MONTH	INITIAL STORAGE	UREG INFLOWS	UPSTRM RELEASE	DEMAND	SURFACE AREA	EVAP RATE	EVAP LOSS	DWNSTRM RELEASE	SHORTAGE	PUMPED INTO	PUMPED OUT	SYSTEM LOSS	END MO. CONTENT	OPER. RULE
1	0	0	0	0	0	0.0	0	0	0	0	0	0	0	10000
2	0	0	0	0	0	0.0	0	0	0	0	0	0	0	10000
3	0	0	0	0	0	0.0	0	0	0	0	0	0	0	10000
4	0	500	0	0	0	0.0	0	500	0	0	0	0	0	10000
5	0	1000	0	0	0	0.0	0	1000	0	0	0	0	0	10000
6	0	2000	0	0	12	0.0	0	1500	0	0	0	0	500	10000
7	500	2607	0	0	40	0.0	0	2000	0	0	0	0	1107	10000
8	1107	165	0	0	28	0.0	0	1272	0	0	0	0	0	10000
9	0	450	0	0	0	0.0	0	450	0	0	0	0	0	10000
10	0	0	0	0	0	0.0	0	0	0	0	0	0	0	10000
11	0	0	0	0	0	0.0	0	0	0	0	0	0	0	10000
12	0	0	0	0	0	0.0	0	0	0	0	0	0	0	10000
	TOTAL	6722	0	0			0	6722	0	0	0	0		

RESERVOIR NO 3 RES NO 3 MAX. CAPACITY 0 MIN. OPERATING POOL 0

MONTH	INITIAL STORAGE	UREG INFLOWS	UPSTRM RELEASE	DEMAND	SURFACE AREA	EVAP RATE	EVAP LOSS	DWNSTRM RELEASE	SHORTAGE	PUMPED INTO	PUMPED OUT	SYSTEM LOSS	END MO. CONTENT	OPER. RULE
1	0	0	0	0	0	0.0	0	0	0	70	0	70	0	0
2	0	0	0	0	0	0.0	0	0	0	70	0	70	0	0
3	0	0	0	0	0	0.0	0	0	0	70	0	70	0	0
4	0	0	0	0	0	0.0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0.0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0.0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0.0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0.0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0.0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0.0	0	0	0	70	0	70	0	0
11	0	0	0	0	0	0.0	0	0	0	70	0	70	0	0
12	0	0	0	0	0	0.0	0	0	0	70	0	70	0	0
	TOTAL	0	0	0			0	0	0	420	0	420		

Table 4. continued

EXAMPLE PROBLEM PONDER RIVER BASIN (EXCHANGE)

SIMULATION YEAR 1 CALENDAR YEAR 1984

DEMAND NODE 6 EXCH

MONTH	UREG INFLOWS	LINK INFLOWS	PUMPED INTO	TOTAL INFLOWS	DEMAND	SHORTAGE	TOTAL OUTFLOW	LINK OUTFLOW	PUMPED OUT
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	500	0	500	0	0	500	500	0
5	0	1000	0	1000	0	0	1000	1000	0
6	0	2000	0	2000	0	0	2000	2000	0
7	0	2607	0	2607	0	0	2607	2607	0
8	0	165	0	165	0	0	165	165	0
9	0	450	0	450	0	0	450	450	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
TOTAL	0	6722	0	5722	0	0	6722	6722	0

DEMAND NODE 7 D D CO.

MONTH	UREG INFLOWS	LINK INFLOWS	PUMPED INTO	TOTAL INFLOWS	DEMAND	SHORTAGE	TOTAL OUTFLOW	LINK OUTFLOW	PUMPED OUT
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	500	0	500	500	0	0	0	0
5	0	1000	0	1000	1000	0	0	0	0
6	0	2000	0	2000	2000	0	0	0	0
7	0	2607	0	2607	4000	1393	0	0	0
8	0	165	0	165	2500	2335	0	0	0
9	0	450	0	450	500	50	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
TOTAL	0	6722	0	6722	10500	3778	0	0	0

DEMAND NODE 10 FTCOLLEG

MONTH	UREG INFLOWS	LINK INFLOWS	PUMPED INTO	TOTAL INFLOWS	DEMAND	SHORTAGE	TOTAL OUTFLOW	LINK OUTFLOW	PUMPED OUT
1	0	0	500	500	500	0	0	0	0
2	0	0	500	500	500	0	0	0	0
3	0	0	500	500	500	0	0	0	0
4	0	500	100	600	600	0	0	0	0
5	0	1000	0	1000	1000	0	0	0	0
6	0	1500	0	1500	1500	0	0	0	0
7	0	2000	0	2000	2000	0	0	0	0
8	0	1272	500	1772	2000	228	0	0	0
9	0	450	500	950	1500	550	0	0	0
10	0	0	500	500	600	100	0	0	0
11	0	0	500	500	500	0	0	0	0
12	0	0	500	500	500	0	0	0	0
TOTAL	0	6722	4100	10822	11700	878	0	0	0

Table 4. continued

EXAMPLE PROBLEM PONDER RIVER BASIN (EXCHANGE)

SIMULATION YEAR 1 CALENDAR YEAR 1984

* VOLUMETRIC FLOW IN LINK *

SEASON / LINK NO.	1	2	3	4	5	6	7	8	9	10	11	12	TOTAL
1	0	0	0	130	852	1905	2544	500	500	0	0	0	6431
LOSS	0	0	0	0	0	0	0	0	0	0	0	0	0
2	570	570	570	599	999	2000	2607	665	950	570	570	570	11240
LOSS	30	30	30	31	53	105	137	35	50	30	30	30	591
3	0	0	0	500	1000	2000	2607	165	450	0	0	0	6722
LOSS	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	500	1000	2000	2607	165	450	0	0	0	6722
LOSS	0	0	0	0	0	0	0	0	0	0	0	0	0
5	570	570	570	100	0	0	0	500	500	570	570	570	4520
LOSS	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0
LOSS	0	0	0	0	0	0	0	0	0	0	0	0	0
7	570	570	570	100	0	0	0	500	500	570	570	570	4520
LOSS	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	500	1000	1500	2000	1272	450	0	0	0	6722
LOSS	0	0	0	0	0	0	0	0	0	0	0	0	0
9	500	500	500	100	0	0	0	500	500	500	500	500	4100
LOSS	0	0	0	0	0	0	0	0	0	0	0	0	0
10	70	70	70	0	0	0	0	0	0	70	70	70	420
LOSS	0	0	0	0	0	0	0	0	0	0	0	0	0

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APPENDIX
PROGRAM MODSIM3 STRUCTURE

1. Description

Program MODSIM3 is a sequential network optimization model for management of complex river basin systems. The general structure of the program is shown in Figure A.1. Each subroutine performs different tasks as explained below.

Program MODSIM [WSD100] is the core program to call other subroutines. Certain control information corresponding to Record #1 in the data input file is read here, after which control is transferred to the subroutines.

Subroutine Area [WSD912] receives a current volume for a particular reservoir as input and then performs a linear interpolation on the user input area-capacity table ACTAB for that reservoir to produce the corresponding surface area in Subroutine OPRATE.

Subroutine CHANLS [WSD913] computes channel losses in each link as a fraction flows entering the link origin node.

Subroutine CARDS [WSD914] reads all data, except system inflows, demands and evaporation rates.

Subroutine DATA [WSD916] reads one month (or week) at a time of inflow, demand, and evaporation data for all nodes from a disk file created by the user. In addition, ENTRY WSD933 is used by Subroutine OPRATE to compute the current hydrologic state.

Subroutine OPRATE [WSD916] is the major subroutine in MODSIM3. It performs the following functions (flowchart given in Figure A.2):

1. Sets user supplied and default limits on all system links, including artificial links.

2. Sets user supplied and default costs or priority factors on each link.

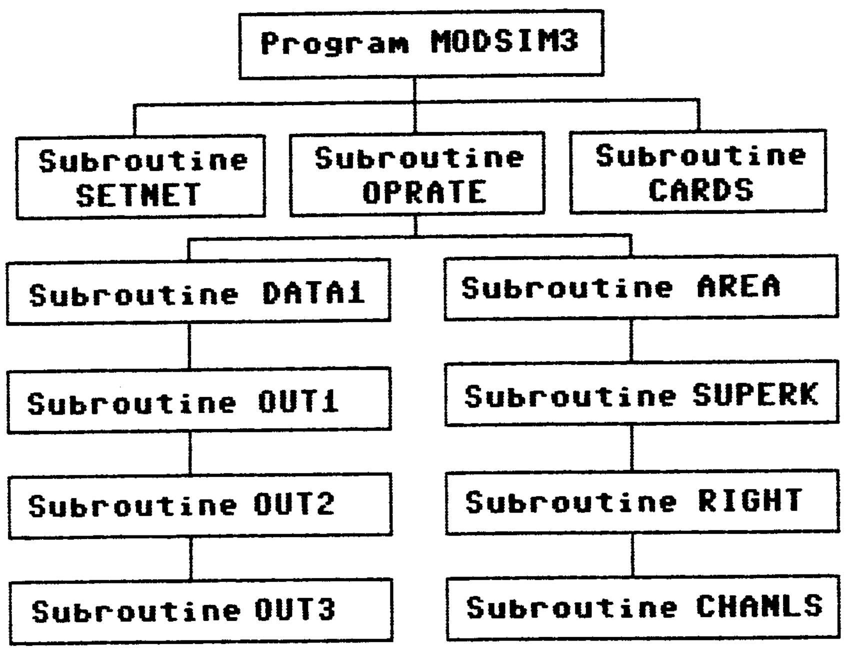

Figure A.1. Organization of Program MODSIM3

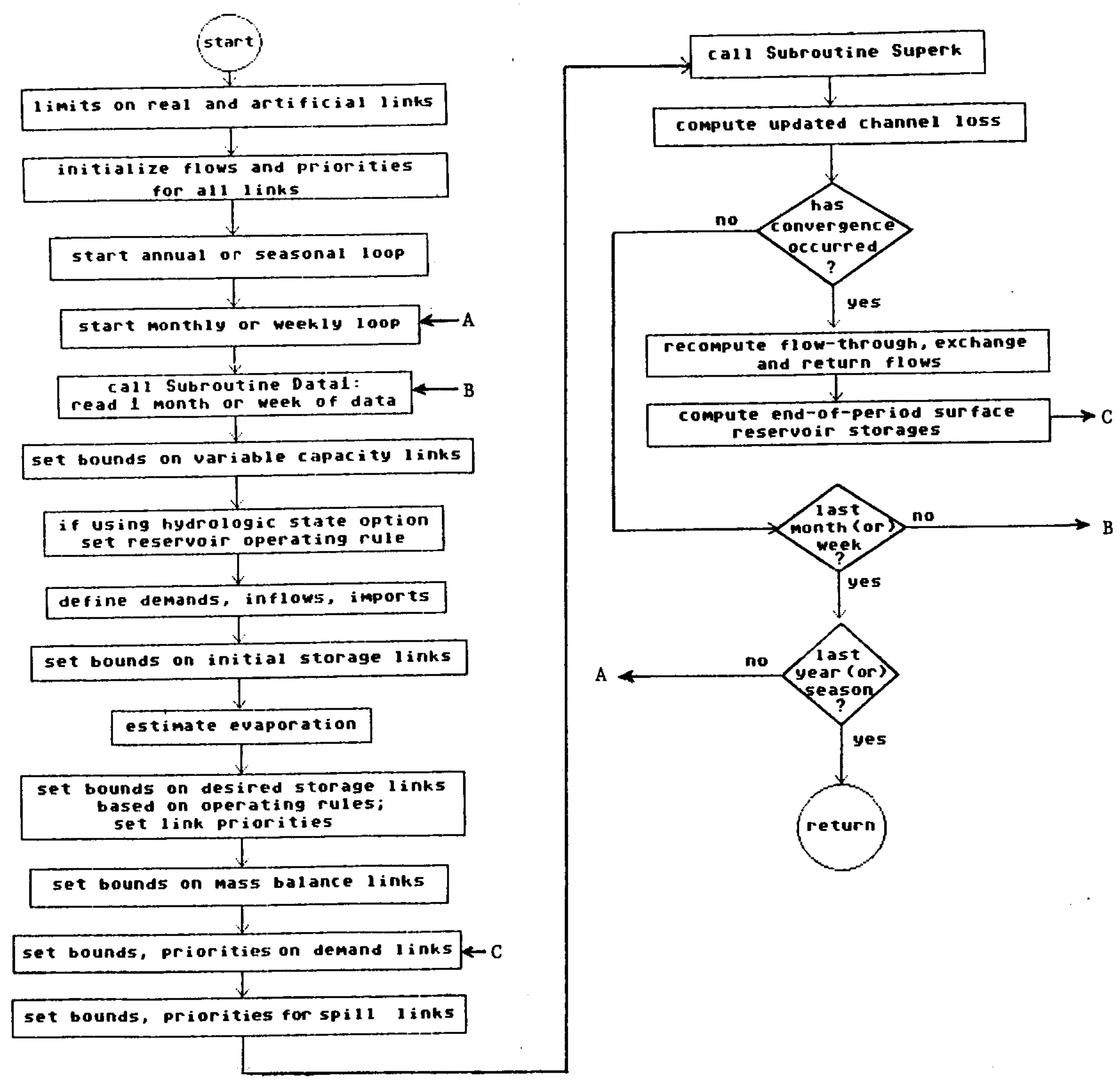

Figure A.2. Flow Chart for Subroutine OPRATE

3. Loops over each month (or week) in the simulation.

4. Determines appropriate reservoir operating targets based on user supplied information.

5. Estimates evaporation, as described in the report.

6. Calls the out-of-kilter network flow optimizing algorithm (Subroutine SUPERK).

7. Tests for convergence of channel loss flow-through demand, exchanges, and return flows, or checks if the user-specified maximum number of iterations is exceeded.

8. Sets up output information to be printed out by Subroutines OUT1, OUT2 and OUT3. This information is currently written to disk file 51.

Subroutine OUT1 [WSD917]. At the user's option, this subroutine provides an organized format for all data input.

Subroutine OUT2 [WSD918]. This subroutine provides detailed solution information on a month to month (or week to week) basis, organized in yearly (or 12 week) groupings. Output information includes actual storages, target storages (for comparison purposes), evaporation, demands, spills, releases, demand shortages, and all link flows.

Subroutine OUT3 [WSD919]. At the user's option, this subroutine prints summary information over the entire simulation period for each node and for each year (or 12 week period) over all nodes. Average and maximum link flows over the entire simulation period are also printed out.

Subroutine RIGHT [WSD920]. This subroutine performs shifting operations for the dual phase of the out-of-kiler algorithm in Program SUPERK and checks for primal or dual infeasibility. ENTRY WSD931 shifts to the left in the dual phase.

Subroutine RTFLOW [WSD921] computes return flows based on user supplied data. For each return flow node, diversions contributing to the return flow at that node are added for the current period. The subroutine also retrieves previous total diversions and places them into the regression equation, which also includes past return flow estimates.

Subroutine SETNET [WSD922] sets up the numbering system for all artificial nodes and links.

Subroutine SUPERK [WSD923]. The out-of-kilter network optimization algorithm, which is described more fully in documentation by the Texas Water Development Board (1972).

2. Variable Description

The block common usage in all subroutines is shown in Table A.1. The variable description for most block commons are in Tables A.2 to Table A.15. The user is referred to the documentation by the Texas Water Development Board (1972) for details on common block SPK.

3. Input Data

Two data files are required to run the MODSIM model.

File No. 1 stores coded data read into Subroutine CARDS.

File No. 2 stores coded data read into Subroutine DATA1 from a disk file.

4. Error Diagnostics

The problems that can occur in use of this program usually come during execution of the out-of-kilter algorithm. For example, if an infeasible solution message is obtained, the likely cause is that the user did not specify enough spill nodes, or upper and lower bounds or some of the links are too restricted. The best way to remedy these problems is to specify all surface reservoirs as spill nodes and relax some of the constraints, if possible.

Table A.2. Variable Description of Block Common ADATA.

Variable Name	Description
COST	Cost or priority associated with each link
FESIBL	A logical variable for feasibility indication
FLOW	Flow in each link
HI	Upper bound for each link
LO	Lower bound for each link
NARC	A dummy variable for the link number and also the maximum total number of links (real plus artificial)
NF	Originating node number for given link
NMAX	Number of real nodes plus five artificial nodes
NT	Terminating node number for given link
NTIME	Number of times SUBROUTINE SUPERK is called

Table A.3. Variable Description of Block Common CONFAC

Variable Name	Description
AVRGHI	Upper bound on average storage for reservoirs for which hydrologic state computed
AVRGLO	Lower bound on average storage for reservoirs for which hydrologic state computed
CONDEM	Multiplier to convert read in demands to storage units
CONINF	Multiplier to convert read in inflows to storage units
CONFLO	Multiplier to convert link capacities and flows to storage units
JESVOL	Node numbers of reservoirs in the hydrologic state subsystem
LRULE	Index for hydrologic state subsystem
NSRS	Number of reservoirs in hydrologic state subsystem

Table A.4. Variable Description of Block Common CONTRL

Variable Name	Description
KAPE4	If = 1, user reads in both OPRL and OPRH for each reservoir (otherwise 0 for constant OPRP)
KIN	Tape5 for data file read into CARDS
KOUT	Tape6 for printout file

Table A.5. Variable Description of Block Common D

Variable Name	Description
CMAXV	Maximum monthly or seasonal capacity of variable capacity links
IDSTRM	Node number to which flow-through demand accrues
ITHRU	Total flow entering a flow-through demand or exchange node
LVAR	Link number with variable capacity
NDMD	Actual node number of each demand node
NVARL	Number of variable capacity links

Table A.6. Variable Description of Block Common DEMON

Variable Name	Description
DEMON	Monthly or weekly demand read in for each node

Table A.7. Variable Description of Block Common DISK

Variable Name	Description
JFL	Record number for start of information on model output disk file 51
JFL1	Not used
JFLT	Not used

Table A.8. Variable Description of Block Common IPRINT

Variable Name	Description
IFROM	Starting year or 12 week period for detailed yearly or periodic output
IPRNT	Printout opion for link flows
ITOY	Ending year for detailed yearly output
IYLD	Not used

Table A.9. Variable Description of Block Common LDATA

Variable Name	Description
IALLY	Set to 1 if user inputs priorities for each year or season (zero otherwise)
IRTN	Set to 1 if return flows calculated (zero otherwise)
IXCLL	Total calculated channel loss
TOL	Convergence tolerance for total channel loss
XLCF	Channel loss rate for each link

Table A.10. Variable Description of Block Common LINK

Variable Name	Description
CMAX	Maximum capacity of each link
CMIN	Minimum capacity of a link
LNODE	Terminal node number for each link

Table A.11. Variable Description of Block Common LNKFLW

Variable Name	Description
LNKAFL	Monthly or weekly average link flow
LNKMX	Maximum flow observed in a link

Table A.12. Variable Description of Block Common PARM

Variable Name	Description
IMN	Number of import nodes
IYEAR	Calender year that simulation starts
NC	Number of canals
ND	Number of demand nodes
NJ	Number of real nodes
NL	Number of real links, which equals the number of river reaches plus the number of canals
NPAIRS	Number of area-capacity tabular points for each surface reservoir
NR	Number of river reaches
NRES	Number of surface reservoirs
NS	Number of spill nodes
NYEAR	Number of years or 12 week periods to be simulated
TITLE	Title for the simulation run

Table A.13. Variable Description of Block Common R1

Variable Name	Description
A	Regression coefficients for return flow equations
IDIVL	Total ditch diversions contributing return flows to a node
IRTF	Total calculated return flow at each node
IRTFF	Actual node number of demand node contributing return flow
IRTL	Return flows from previous periods
JRTFT	Actual node number of each return flow node
NDNEQU	Number of demand nodes returning flows to a node
NEQU	Number of nodes receiving return flow
NLAGS	Number of time lags in return flow regression equations

Table A.14. Variable Description of Block Common RESV

Variable Name	Description
ACTAB	Area-capacity table for each surface reservoir
DEMR	Priority of demand node, can be varied year to year or season to season
DIMP	Monthly or weekly import distribution, can be varied from year to year or season to season
EVAP	Monthly or weekly evaporation rate
IMP	Node number of import node
IMPRT	Annual import at import node
OPRPH	Priority of surface reservoir for target level storage; can vary year to year or season to season
OPRPL	Priority of surface reservoir at minimum capacity; can vary year to year or season to season
OPRR	Monthly or weekly operating rule for each reservoir
RCAP	Maximum capacity of each storage node
RMIN	Minimum capacity for each storage node
RNAME	Node name array
SP	Node number of spill node
U	Monthly or weekly unregulated inflow at each node

Table A.15. Variable Description of Block Common WRKD

Variable Name	Description
EVPT	Monthly or weekly evaporation at node
IAREA	Reservoir surface area at end-of-month or week storage
ISHTM	Monthly or weekly shortage at node
ISPIL	Monthly or weekly spill at node
START	Beginning of the month or week storage at a node
STEND	End-of-month or week storage at node
UREG	Monthly or weekly inflow at a node
USE	Monthly or weekly demand at a node