Final
Deliverable 3

Optimization Model for National Water Master Planning: Design and Documentation

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1. Executive Summary

This report describes GTZ project terms of reference (TOR) and how the project addresses them. Project product exceeds GTZ TOR requirements, because the product is a result of collaborative funding from GTZ and USAID. USAID desired that Jordanian Ministry of Water and Irrigation (MWI) be better able to employ systems analysis in national water management. GTZ requested development of an optimization model to enhance current National Water Master Plan (NWMP) software and planning abilities.

The resulting Optimization Module (OM) uses mathematical optimization to determine the best combination of flows from water sources to water demands for the water balancing, allocation, and transfer functions of the NWMP. With input from MWI, the OM has been tested using quasi-hypothetical subsystems representative of Jordanian conditions.

The OM differs from the NWMP in that the OM can be applied to all of Jordan or to any discrete portion (subsystem). OM requires all relevant data for the physical system or subsystem being addressed. Because the OM rigorously optimizes the entire flow path from water source centers (SCs) to demand centers (DCs) it requires additional data beyond NWMP requirements.

OM is designed to address important present and future NWMP-related needs. For clarity in OM development and use, this project developed and recommends some modified and additional terminology and data. An important example concerns NWMP Allocation module table T_DC_S. That table controls which water Resource Types (ResTys) and water conveyance method a water user type (Demand_Type) in a Demand Center (DC) can be allocated.

The current NWMP T_DC_S table combines both infrastructural and management reasons together. In the T_DC_S table, a restriction preventing flow might be used either because there is no pipe connecting a DC_Demand_Type combination with a particular water type, or the restriction might mean that the government does not want the DC_Demand_Type combination to use that type of water (even though a physical connection might exist).

An NWMP user cannot tell what reason a particular T_DC_S entry signifies. This mixing of infrastructure- and management-related reasons in the same table impedes software use. The mixing makes it more difficult for MWI to rapidly answer questions such as, ‘how can MWI minimize adverse impact on other users if providing water to a proposed new user?’

Proposed is a clear distinction between limits on water flows that are due to infrastructural reasons versus those due to management reasons. An infrastructural upper limit on flow might be the carrying capacity of the pipeline conveying water from a source to a Transfer System node. A management upper limit might be the sustainable groundwater extraction from an aquifer.

It is suggested that the current NWMP be modified to have two separate T_DC_S tables, one for infrastructure-related and one for management-related reasons. In addition to enhancing NWMP utility, these two tables can help guide OM input data formulation.

Concise definition of flow restriction reasons allows increased optimization detail. Rather than optimizing merely down to the NWMP DC level, it is now appropriate to optimize down to the level of an NWMP DC_Demand_Type combination. This ability presumes a new DC definition within OM—a DC definition that is equivalent to a combination of NWMP DC and NWMP Demand_Type.

It is recommended that water losses currently treated as distinct demands within the NWMP, be included with the demands of the water users (DCs). Loss of water due to a DC's water use is a function of how much water is delivered to the DC. Assumedly, a DC pays for all water delivered to it, including water that is lost after the DC receives the water. Management realism and simulation accuracy are maintained if water losses are computed simultaneously with water delivery.

It is recommended that OM be applied to a larger representative Jordanian subsystem than is used here, and that MWI be intimately involved in preparing and approving the employed data. Validity of future OM-computed optimal strategies will depend upon the validity of the input data. It is strongly recommended that critical NWMP data validity be confirmed before being input for non-testing OM optimization.

The report poses long-term development questions for MWI leader consideration. For some possible courses of action, the report contains recommendations concerning making OM easier for MWI to use, and gaining stakeholder buy-in for MWI-developed optimal planning strategies.

2. Project purpose and Terms of Reference

GTZ contracted with AHT, a German consulting company, to develop the National Water Master Plan (NWMP) database and model for the Jordanian Ministry of Water and Irrigation (MWI). The NWMP model is intended to aid water planning efforts by the National Water Master Planning Directorate (NWMPD). It is especially to help achieve water use sustainability thru careful management. It is intended to eventually address water planning at several Balancing Levels (BLs). Example BLs are administrative, socioeconomic, groundwater basin-related, and watershed-related.

The NWMPD has primarily applied the NWMP model for planning at the administrative Balancing Level, wherein each national governorate is a Balancing Unit (BU). Figure 2.1 shows Jordanian governorates.

The NWMP model has many components (modules or sub-modules) and performs numerous functions, including projecting annual water demand and availability for different weather conditions and development scenarios. An NWMP goal is to help determine how to best satisfy water needs at water Demand Centers (DCs), using water from Supply Centers (SCs). Figures 2.2 and 2.3 show Jordanian DCs and SCs, respectively.

NWMP components help determine: how to convey water thru a TransFer (TF) system; and how to allocate water to different BUs and Demand Centers. Within the NWMP model, water can be conveyed thru TF system. All other water moves via Local Distribution (LD). A different LD system exists in each BU.

The TF system includes individually identified pipelines and other means of transferring water to specified DCs within the BU providing the water, and to DCs in other BUs. Figure 2.4 shows TF segments (lines), points of connection between segments, and segment end points. Here, all TF points are termed 'nodes'. An 'end' node is connected to only one TF segment, and can either receive water entering the TF system, or discharge leaving the TF system, but not both. An 'internal' node is the junction between two or more segments.

The NWMP was developed initially as a data base application. Its purposes and uses expanded with time. Although performing many hydrologic simulations, it does not have detailed simulation abilities for computing all realistic flows within the TF system or from DC to SC. It does not include mathematical optimization. AHT and others have concerns that MWI has not validated all NWMP inputs.

The subject project was developed to provide capabilities additional to those of the NWMP. From the Terms of Reference (TOR), this project is to:

● "In close collaboration with MWI and GTZ, develop a draft prototype Optimization Module (OM). OM will emphasize volumetric approaches, and will use mathematical optimization to help determine:

- how much flow should go in each direction at pipeline branches.

•where best to send water from existing and future supply locations to existing and future demand centers.

•where it is best to develop new water wells and supplies and link them with the existing and future network."

● Apply to hypothetical area

3. Project accomplishments

Partially due to complementary USAID support, the draft prototype OM model reported here does much more than is required by the GTZ TOR. To illustrate such additional capabilities, for the activity of determining flows that should go through TF pipelines, here are compared current NWMP capability, TOR requirement, and OM ability:

●The currently used NWMP Transfer Module requires much manual iteration to obtain a flow strategy for one time period. Resulting flows might exceed physical conveyance limits—meaning the strategy might not be physically realistic or feasible.

●The TOR requests accurately computed and constrained volumetric balances for optimal transfer thru national Transfer (TF) system.

●The draft prototype OM:

- provides simultaneous mathematical optimization of all flows in all time periods, thru TF and Local Distribution (LD) systems from Source Centers (SCs) to Demand Centers (DCs), with or without prioritized allocation;
- computes accurate volume balances;
- satisfies all input limits on flow capacities and directions;
- satisfies all input limits on water takings from SCs, Resource Types (ResTys) and BU water resources;
- satisfies all input limits on water delivered to DCs;
- allows individual optimization time periods of one year, or other duration;
- allows multiplying objective function unsatisfied demand values by linear coefficients to provide simple economic optimization ability;
- provides marginal values or shadow prices identifying tight constraints and indicating the expected magnitude of objective function improvement resulting from relaxation in a tight constraint (such as a pipe segment that restricts flow);
- can be applied to all or part (a subsystem) of Jordan, if all necessary data is input.

Other cautionary observations concerning the existing NWMP Balancing and Allocation simulator are that it:

●seems to omit comprehensive simulator definition of:

•sets of sources and demands, and their connections with LD and TF water conveyance systems

•flow variables

•governing equations (volume balance or continuity)

●performs balancing or transfer only one time period (one time step) at a time

●uses input-specified groundwater pumping rates for each period in the allocation module-- modeler decides how much enters TF system. The rest is conveyed via LD.

●includes ambiguous water conveyance--Additional (AD) resource used locally feeds into 'virtual' TF system

●employs different levels of detail in the NWMP sub-modules dealing with water Transfer and water Allocation.

The subsequent Project Approach section briefly describes mathematical optimization as applied in OM. Here, in this section, it is sufficient to state that the developed OM addresses or rectifies the above concerns by using two coupled mathematical optimization sub-models developed specifically for this project. These are:

●Balance and Transfer (BandT), sub-Model #1.

- •Develops a water balancing and transfer strategy that minimizes sum of products of individual DC unsatisfied demands multiplied by linear coefficients;
- • If linear coefficients are economics-based, BandT performs simple economic optimization by minimizing economic impact due to unsatisfied demand.

●Balance, Allocation, & Transfer (BAT), sub-Model #2.

- •Minimizes unsatisfied demand;
- •Performs four sequential optimizations, allocating water in the order of Jordanian national priority: 1) MUNicipal, 2) INDustrial, 3) TOUristic, 4) IRRigation;
- •Assures that as many needs of higher priority demands are met as possible, before allocating to lower priority demands;
- •For special cases per specific input, allows allocating water to lower priority users, while allocating to higher priority users (such as to allow IRRigation to receive treated wastewater while water is being allocated to higher priority users that produce the raw wastewater);
- • Allows adjusting lower and upper bounds on flow to assure that particular sectors receive at least, or no more than, specified amounts of water.

Other project accomplishments involve clarification or definition of terms needed for national water management optimization. This was necessary to best correlate NWMP and OM inputs and outputs. The most important new nomenclature is presented in the section entitled Selected OM Nomenclature, Inputs and Optimized Outputs.

4. Project approach

The OM solves BandT and BAT mathematical optimization problems, each of which is defined using variables, constraint equations, upper and lower bounds (limits) on their values, and an objective function (OF). Both the BandT and BAT sub-modules use mathematical optimization to calculate an optimal water management strategy (set of flow values) for a posed optimization problem.

The OF is an equation—such as the total for all time periods, of the sum of all unsatisfied water demands at all Jordanian water demand centers. During optimization, OM calculates a set of flow values that causes the smallest possible total value of the OF (i.e. the least unsatisfied total demand possible).

OF variables are the unsatisfied demands of each DC in all time steps. Other variables whose values the OM computes include all flows from SCs thru LD and TF to DCs, total water taken from each SC and provided to each DC, losses, and other flows or volumes of interest.

Variables within the OF also exist in volume balance equations that are inter-related with flow equations describing the entire modeled physical system, and with equations describing management preferences. The equations fully describe the optimization problem (OP) posed by the OM user. An optimal solution computed by the OM is the mathematically optimal water management strategy for the posed optimization problem. Such a strategy includes, for all time periods, the optimal flows leaving all water source centers and flows eventually reaching all water demand centers.

The OM uses objective functions of minimizing total weighted or un-weighted unsatisfied water needs. To minimize total unsatisfied water needs, it computes how to optimally send water from water sources to water users located in the same and different Balancing Units (BUs). Although any type of Balancing Layer can be used, all examples tested so far have used administrative Governorates as the Balancing Layer.

The OM uses two optimization sub-modules consecutively: (a) Balancing and Transfer (BandT), and (b) Balancing, Allocation, Transfer (BAT) sub-modules. Both sub-modules route water from Source Centers (SCs) to Demand Centers (DCs). In that process, water flows through either clearly defined Transfer (TF) system, or less-defined Local Distribution (LD) system.

The following tactical goals shaped OM development, and potential future uses. The OM is intended to and can:

- Support integrated water management and investment planning
  - Address total water path from sources to demands
  - Include complete applicable water balance and continuity equations
  - Help identify good new pipeline sizes and locations
  - Consider economic factors within optimization
- Identify additional needed data.

The OM was written during this project in the Generalized Algebraic Modeling System (GAMS) language. GAMS is a high level programming language. GAMS itself does not contain any flow variables or equations. The task of writing OM in GAMS included defining all OM parameters, variables, flow and continuity equations, and input and output statements. Writing the OM model in GAMS is conceptually analogous to writing a model in C++ or VBA.

GAMS can be downloaded from the GAMS corporate website. As downloaded without cost, it includes the GAMS compiler, a programming environment (GAMSIDE), and optimization problem solvers. That version can solve simple problems that a user formulates in the GAMS language.

Solving substantive problems such as the example reported here requires purchasing a GAMS license. After a GAMS license is obtained, the OM can be run on a computer that has GAMS and the GAMS license installed.

5. Selected OM nomenclature, inputs, and optimized outputs

5.1 Nomenclature

Adopting several nomenclature conventions aided draft OM development and helps application for different situations. A Glossary is found in the OM program documentation appendix. Immediately relevant terms include:

●Time step or time period is a period of assumedly steady flow. NWMP was designed to consecutively address a fixed number of five-year periods. OM simultaneously optimizes for a user-input number of periods, computing optimal steady flows that can differ for each period.

●Planning period or planning horizon is the total duration of all OM-addressed time steps.

●Source Center (SC) names begin with an 's'. Otherwise an OM SC name can be the same as an NWMP water service center. An SC should be the lowest level of water source that is optimized. In some cases, a group of wells will be considered a single SC.

●TF node names begin with 'n'. Otherwise, a node name is the same in OM and NWMP.

●DC names begin with a 'd'.
•After the leading 'd', each DC name has four numbers. These digits are to be identical or almost identical to the current NWMP DC number (if the current NWMP number has fewer than 4 digits, zeroes are placed before the current number).
•After the four-digit number is a three-alpha abbreviation of a Demand_Type. Current NWMP practice is that an entity termed a Demand Center (DC), can have up to four Demand_Types (MUNicipal, INDustrial, TOUristic, and IRRigation). For example, Figure 4.1 shows that the current DC 7 has water users of all four Demand_Types.
•OM employs a modified Demand Center (DC) definition. Each OM DC has only a single Demand_Type. Thus the OM might employ up to four DCs in the place of each current NWMP DC. For example, instead of the single previous DC 7, the OM would use four new DCs (Fig. 4.1): d0007MUN, d0007IND, d0007TOU, and d0007IRR.
•A DC should be the lowest level of water user that is optimized in the OM. To date, this lowest level is determined by the detail in the NWMP table T_DC_S. That table states which types of ResTy-Convey combinations a particular water user can access.

It is recommended that the current NWMP be modified to have two separate T_DC_S tables, one for infrastructure-related and one for management-related reasons. These two tables, can then correctly guide input data formulation for the OM.

Some of the above recommended name changes are optional. If they prefer, OM users can omit the leading 's', 'n', or 'd' in above terms. Also, if a user wants to treat each DC as if all the DC's water users can obtain water from the same combinations of

Resource Type and Conveyance, the other above DC nomenclature change is not necessary.

However, if a user wants OM to optimize to the same detail as is found in the T_DC_S of the NWMP of September 2007 (that NWMP was released after this project began) the substantive DC name change should be used. That will allow different Demand_types of an NWMP DC to access different combinations of Resource Type and conveyance method (ResTy_Convey combos).

● Infrastructure- and management-based limits on flow

•Infrastructural reasons refer to capabilities or restrictions of the physical system. An infrastructural upper limit on flow might be the carrying capacity of the pipeline conveying water from a source to a Transfer System node.

•Management reasons refer to non-infrastructural reasons. A management upper limit of total groundwater pumping from a BU might be the sustainable groundwater extraction rate for the BU. An example upper limit on how much water should be delivered to a DC might be 85% of projected demand—if MWI wanted to use that assumption while developing a strategy.

●DC water demand.

•NWMP. How much water a DC:

□historically has used (without including water losses), or

□will want in the future (without including water losses) for assumed weather and development situations.

●DC water need.

•OM. How much water is actually needed in order to maintain an appropriate level of activity.

●Upper bound on water delivered to a DC.

•OM. Within an OM optimization problem, the maximum amount of water allowed to reach a DC.

●Lower bound on water delivered to a DC

•OM. Within an OM optimization problem, the minimum amount of water required to reach a DC.

● Water conveyance systems

•NWMP. Employs TransFer (TF) system and 'virtual' transfer system. Other conveyance is assumed to be by Local Distribution (LD) system.

□ TF system is solely as defined in files T_points and T_lines. Other conveyance connections are handled thru database links. TF system can transport water only thru TF segments and can release water in different BUs than it originated in.

□ LD system can only convey water within the BU in which the water originates.

•OM. Requires that all water be conveyed by either clearly defined TF system, or more amorphously defined LD system. There are no hybrids.

□ TF system. To be included in the TF system, a conveyance system requires clear identification of all hydraulic connections between SCs and conveyance segments, and all connections between conveyance segments and DCs.

□ LD system can only convey water within the BU in which the water originates.

●BU Subject water

•OM. A BU's Subject water resources are those waters that are first available either for conveyance via LD within that BU, or for entry to a TF within that BU. Subject water does not include water that can be transferred into a BU via the TF from outside the BU. Subject water includes all addressed water Resource Types (ResTy):

□renewable groundwater (GW),
□Reservoir Safe yield (RS),
□surface water Base Flow (BF),
□Treated Waste-Water (TW),
□ADditional resources (AD), including desalinized water, peace-treaty water, non-renewable groundwater, and any other special cases.

•OM. All subject water of a BU is either assigned to a particular Conveyance method or is unassigned.

●Assigned Water.

•OM. Subject water of a BU that is assigned to a particular Conveyance method or is unassigned.

□Water assigned to LD system, termed LD water, is used within the providing BU.

□Water assigned to TF system is termed TF water (or TR water to be in harmony with NWMP). TF water must flow thru TF and will exit TF either within or outside of the BU at which it entered. TF water will be used in the BU in which it exits the TF system. If used outside the providing BU it is an external transfer. If used inside the providing BU it is an internal transfer.

●Unassigned Water.

•OM. Subject water of a BU that not assigned to LD or TF conveyance. Unassigned water will not be allocated or used.

●Allocated Water.

•NWMP. Water given to a DC or combination of DC and demand type (not counting losses due to distribution or use).

•OM. Water given to a DC or combination of DC and demand type. It is best if water given to a DC includes losses caused by its use. For example:

□Assume a DC that only receives water from one TFout node.

□Water that the DC should receive (including losses resulting from use) should not exceed the DC's water need (without including losses) + losses (computed via a function relating losses to DC water need).

□ OM could be used to consider losses as distinct demands, but it would be a serious mistake to do that. When managers determine the water flow to deliver to a particular DC, that flow includes water that will be lost by DC use. Assumedly, a DC would pay for all the water it receives, including the losses the DC allows to happen after receipt.

5.2 OM inputs and optimized outputs

5.2.1 For a study area or physical system

A study area or system can be all or part of Jordan. In each time period, OM requires and computes the following, respectively.

●Known or computed directly from inputs:
- •Total available water of each Resource Type (ResTy: GR, BF, RS, TW, AD)
- •Total water demand (need) of each Demand_Type (MUN, IND, TOU, IRR)

●Optimized output:
- •Total water assigned to LD or TF flows
- •Total unassigned water
- •Total water reaching each Demand Center_Demand Type (DCDT) combo
- •Total satisfied and unsatisfied demand

5.2.2 For a Balancing Unit (BU)

For each Balancing Unit, or governorate, in each time period, OM requires and computes, respectively:

●Input:
- •Upper limits on water that can be taken from each ResTy for infrastructure-based reasons.
- •Upper limits on water that can be taken from each ResTy for management-based reasons.

OM combines the limits to select the lowest upper limit due to each infrastructure and management reasons.

●Optimized:
- •Water taken from each Resource Type (ResTy = GR, BF, RS, AD, TW)
- •Water from each Resource Type assigned to:
  - □each Source Group for LD water
  - □each TFin node for TF water
- •Available water of each Resource Type that is unassigned (not assigned to LD or TF distribution).

5.2.3 For a Source Center (SC)

For each SC, OM input and optimized output, respectively, are:

●Input:
- •Upper limits on water that can be taken from the SC due to infrastructural reasons.
- •Upper limits on water that can be taken from the SC due to management reasons.

OM combines the above two sets of limits, and uses the lower value for each SC.

●Optimized:
- •Water going to (assigned to) each:
  - □Source Group for LD water
  - □Source Group for TF water

□TFin node for TF water
•Available water that is unassigned (not assigned to LD or TF distribution

5.2.4 For a Demand Center (DC)

For each DC in each period, inputs and optimized outputs are, respectively:
●Input:
•Upper limit on water that can be provided to the DC due to infrastructural reasons.
•Upper limit on water that can be provided to the DC due to management reasons.
OM compares the two values for each DC, and uses the lower values as the upper bound on water delivered to the DC during optimization.
●Optimized output:
•Water received from each Resource Type (GR, BF, RS, AD, TW) thru Local Distribution (LD)
•Water received from the TF system thru each TFout outflow node
•Unsatisfied demand (globally minimized)

5.2.5 For a TF segment

●Input:
•Upper limit on water that can flow thru the segment during a time period.
•Seepage coefficient (proportion of entering flow that is lost during passage due to seepage).
●Optimized output:
•Water entering the TF segment
•Seepage loss during transit
•Water exiting the TF segment thru the TF system (exiting flow value does not include seepage loss)

5.3 Sample results

MWI/NWMPD proposed a hypothetical Jordan-based study system for testing OM. To increase realism, the proposed hypothetical subsystem evolved into what is termed system HJ61E. Figures 5.1 and 5.2 show the northern and southern parts of the system, respectively. Subsystem HJ61E is appropriate for this part of the report. OM documentation addresses an even more complex subsystem HJ61H.

Figures 5.1 and 5.2 do not show node, SC and DC index numbers. If visible, one would see that some index numbers used here do not correspond to any in the NWMP. For this hypothetical problem, index numbers of nine thousand or more (9XXX) indicate purely hypothetical elements needed to depict the problem closely to what was proposed.

Developing software to allow GIS-based visualization was not required by this project. It would be part of a user interface should one be developed. That ability could place on maps the optimal flow rates determined by the model, as well as model inputs and other outputs.

BandT and BAT optimization models were run for this subsystem, assuming two time periods. Utilized flows are per year, so we will refer to them as volumes. Upper bounds on water taken from sources and water delivered to DCs were the same for each period. This caused answers to be the same in both periods, except as noted below. Data was kept simple so that results could be individually checked, and easily understood.

All loss coefficients (linear proportions of conveyed flow that is lost due to seepage) were 0.0 in value. Thus the flow leaving one location and going toward a second location, equaled the flow reaching the second location. If loss coefficients differ from zero, the two flows are unequal. For a real problem, the loss coefficients would either come directly from the NWMP, or would be computed from NWMP-reported seepage.

Values used here are MCM. Management desires to provide 10 MCM per period to each of 26 DCs (or 260 per period; 520 total). Each 10 MCM is the upper bound on how much water can be delivered to a DC.

Nine combinations of Resource Types and Balancing Units (i.e. 9 BU_ResTy combinations) exist. The upper limit on water that can be provided by each BU_ResTy is 10 MCM per period. Thus, a maximum of 90 MCM can be provided per period (maximum of 180 MCM total).

There must be at least 170 MCM unsatisfied demand per period (260-90), or 340 MCM total for two periods (520-180). If there is more unsatisfied demand than that, there is either seepage loss or unassigned water. Because there is no seepage loss in this example, any difference results because water is not assigned. This is demonstrated below.

Figures 5.3-5.5 show selected BandT output (edited for conceptual clarity). Figure 5.3 emphasizes optimization problem statistics, unsatisfied demand and demand. Figure 5.3a shows that this small problem had 708 equations that were solved simultaneously during optimization. The objective function value is 380 MCM. That is the sum of all unsatisfied demands occurring during two periods, multiplied by a coefficient of 1.0. Because 380 exceeds the 340 MCM computed above, we know there is unassigned water.

Figure 5.3b shows the unsatisfied demands for each governorate using DCs in this problem. Ajloun has 30 MCM per period, Aqaba, Al Balqa, and Irbid have 30, 30, and 100 MCM, respectively. Figure 5.3c identifies the unsatisfied demand of each DC. Figure 5.3d shows the demand per BU--the sum of demands of all DCs in the BU. For a real problem, demand values would come from an STP table. Each DC's demand value is used as the upper bound (due to management reasons) on how much water can be delivered to the DC.

Figure 5.4 focuses on available Subject water of different Resource Types (ResTys) in each governorate (indices are BU.ResTy). Figure 5.4a shows the upper bound on how much water of each ResTy can be taken per period. For a real problem and renewable resources, the upper limits would be the sustainable rates from STP tables. For AD nonrenewable groundwater, the upper bound would be provided by MWI.

Figure 5.4b shows that 20 MCM per period of available Subject water is not assigned to either TF or LD conveyance…meaning it cannot be used. For Amman governorate (AM), the 10 MCM of renewable groundwater is unassigned because its SC is not connected to the TF system, and no employed DC is in AM BU (Fig 5.3d). (If there were a DC in Amman governorate, in order to use the renewable groundwater (GR) via LD, the T_DC_S table would have to permit it).

Figure 5.4b also shows that BU MN has 10 MCM of unassigned water. That results because there is insufficient pipeline capacity to bring that water to the DCs having unsatisfied demand. Here all TF segments have an upper bound (due to infrastructural reason) of 30 MCM. If the north-south pipeline flows full in a segment, no more water can be sent from the South toward Irbid. For a real problem, such an occurrence would indicate the need for increased conveyance capacity. As shown in the users instructions, marginal values (shadow prices) can be used to estimate a priori how much improvement to expect from increasing pipe capacity, and where the increase is needed.

Figure 5.4c shows how much water each BU_ResTy (Balancing Unit-Resource Type) combination provides for assignment to a conveyance method. Figure 5.4d shows how much water each Source Center provides per period. Because of the TF capacity restriction, not all BU MN water is needed. In period 1 MN provides 10 MCM of AD water from SC sNG001, but in period 2 MN provides 10 MCM of GR water from SC sK3006. Via upper or lower bounds, the OM user can force OM to take water from the same SC in both periods, or can force a particular blend of water from both SCs.

Figure 5.5 details optimal TF-related flows. These are flows that are sent from SCs toward the TF, enter it, move thru it, exit it, and then reach receiving DCs. To illustrate, the first line of Figure 5.5a shows the flow that leaves SC sSW001 and flows toward TF node n1. The first line of Figure 5.5b shows the flow departing TF node n119 and flowing toward DC d0007MUN (the municipal demand part of NWMP DC 7).

Between the TFin at which water enters the TF, and the TFout where it leaves the TF, water flows through the TF. The first line of Figure 5.5c quantifies the flow departing node n1 and flowing toward node n9002. Figure 5.5d shows that the identical amount reaches node n9002.

The above sample illustrates the level of detail computed and provided by OM. Additional inputs and outputs are presented in the software documentation.

6. Conclusions and recommendations

The developed OM software:
● computes accurate and mathematically optimal water management strategies for tested representative situations.
● is suitable for use on stand-alone computer, and is potentially suitable for web-based application.
● requires additional data beyond that used by NWMP (needed to accurately represent flow from water sources all the way to demand centers).

Issues that MWI is asked to consider addressing are:
● determine which of the current NWMP functions, if any, OM should completely replace, and a desirable schedule for the replacement
● determine whether OM's long-term source of data is to be NWMP or an alternative, such as the Water Information System (WIS).
● determine whether, in addition to individual computer use, web-based running of OM is desirable, and the proposed platform (refer to below paragraph on building stake-holder support).
● identify important NWMP output data and summaries that OM should also provide
● identify qualified MWI individuals to collaborate with Dr. Peralta, and to confirm validity of Jordanian input data for OM.
● separate current NWMP allocation module table into two different T_DC_S tables, one for infrastructure-related and one for management-related reasons. In addition to enhancing NWMP utility, these two tables are needed for OM input data formulation.
● determine how to document input data validity for future OM optimization runs. This is necessary in order to build stake-holder confidence and increase likelihood that optimal strategies are followed nationally.

The following actions would enhance OM and prepare MWI for making OM production runs as needed.
● augment OM so it can produce important outputs and summaries identified above
● apply OM to a larger representative Jordanian subsystem, using real data, and ensure MWI is intimately involved in preparing or approving employed data.
● develop pre-processing utilities to aid organizing input to OM. This will reduce inadvertent input data errors. It would include automatic data retrieval from NWMP or alternative approved data source.
● evaluate OM interface options
● develop a graphical user interface (GUI) to aid OM use by MWI personnel, and to display output
● demonstrate application to a hypothetical problem containing all Jordanian directorates using assumed data. This will provide data helpful in predicting run duration for large problems.

A strategic OM implementation goal is to help gain stakeholder buy-in for MWI-led national water planning. Achieving this goal is aided by letting stakeholders outside MWI also use OM within an appropriate process. Such a procedure would:

●allow stakeholders to change appropriate optimization problem variable bounds and assumptions, without harming the model core;
●be transparent and accessible to many, especially if OM is a web-based application;
●include a documented procedure for reaching consensus on some bound and assumption changes, and for reporting changes in assumptions for optimization runs.

To increase the likelihood that Jordan will follow (implement) water management strategies developed by MWI, MWI should:
● adopt a unified procedure (see above paragraph) to encourage stakeholder acceptance, especially buy-in to Lower & Upper bounds in support of transparent water resources management decisions. Note that if this will involve web-enabled OM use, a web implementation procedure is needed.
● present to stakeholders, the adopted procedure developed above. Obtain from them the list of desired outputs, and recommendations on input changes.
● modify procedure as appropriate to build long-term support and commitment for MWI-led national water planning.

Figures

Figure 2.1 Jordan Governorates (derived from NWMP)

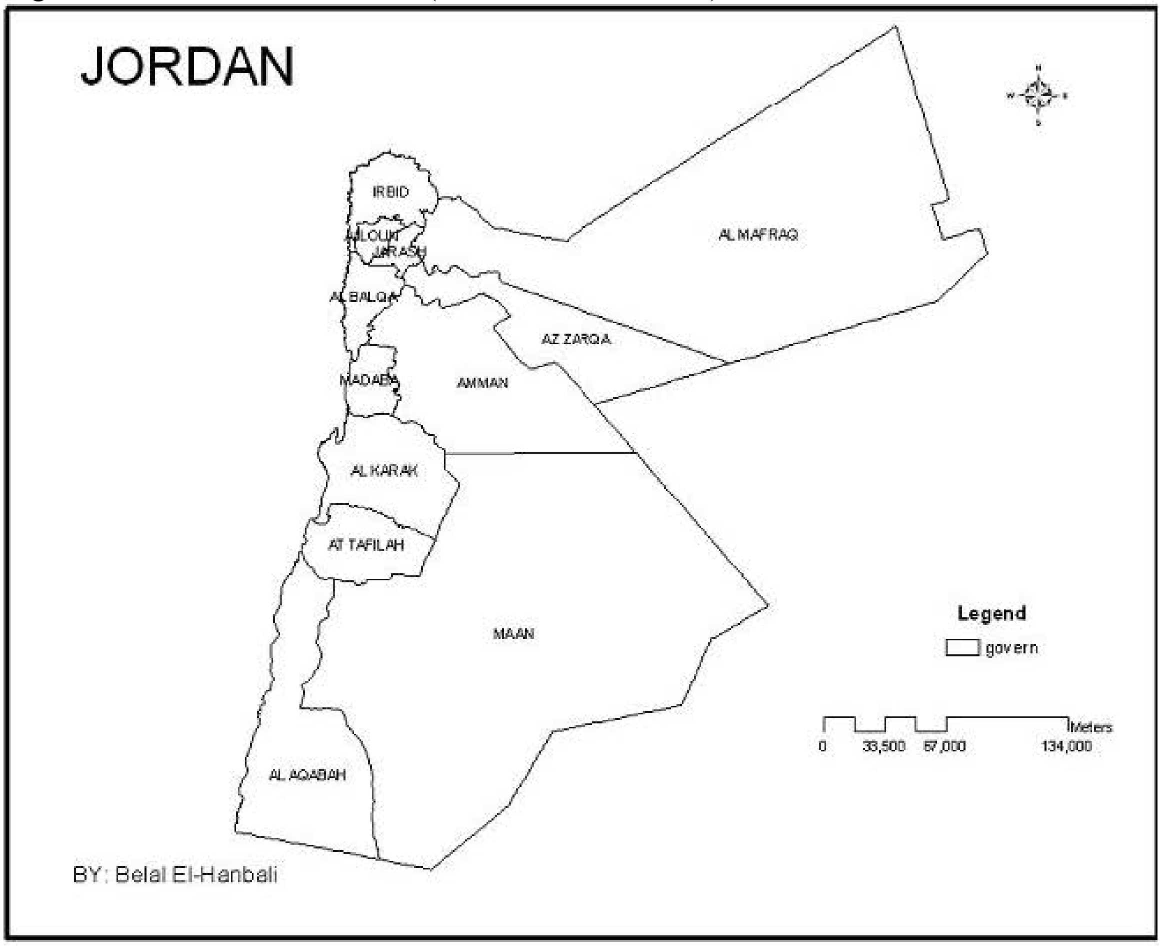

Figure 2.2 Jordan NWMP Demand Centers (derived from NWMP)

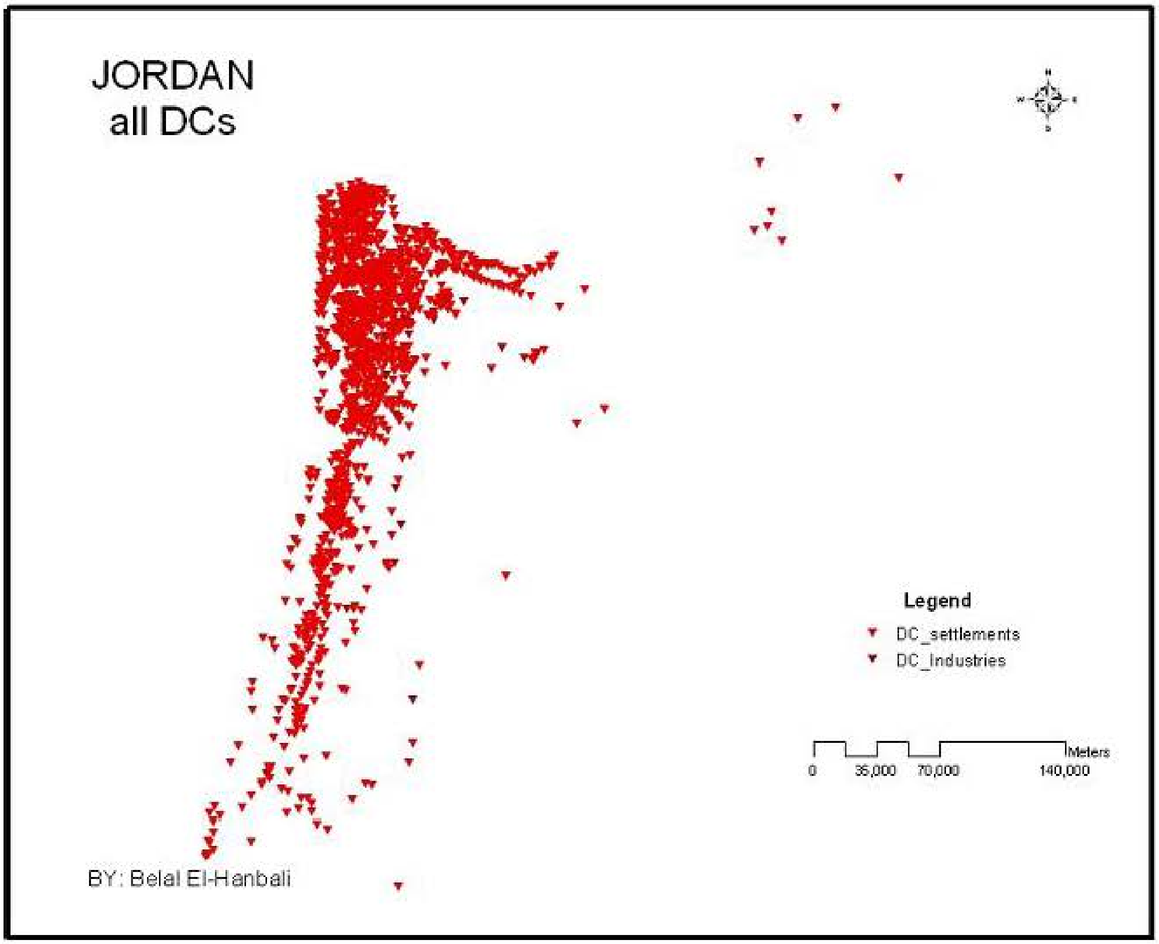

Figure 2.3 Jordan NWMP Source Centers (derived from NWMP)

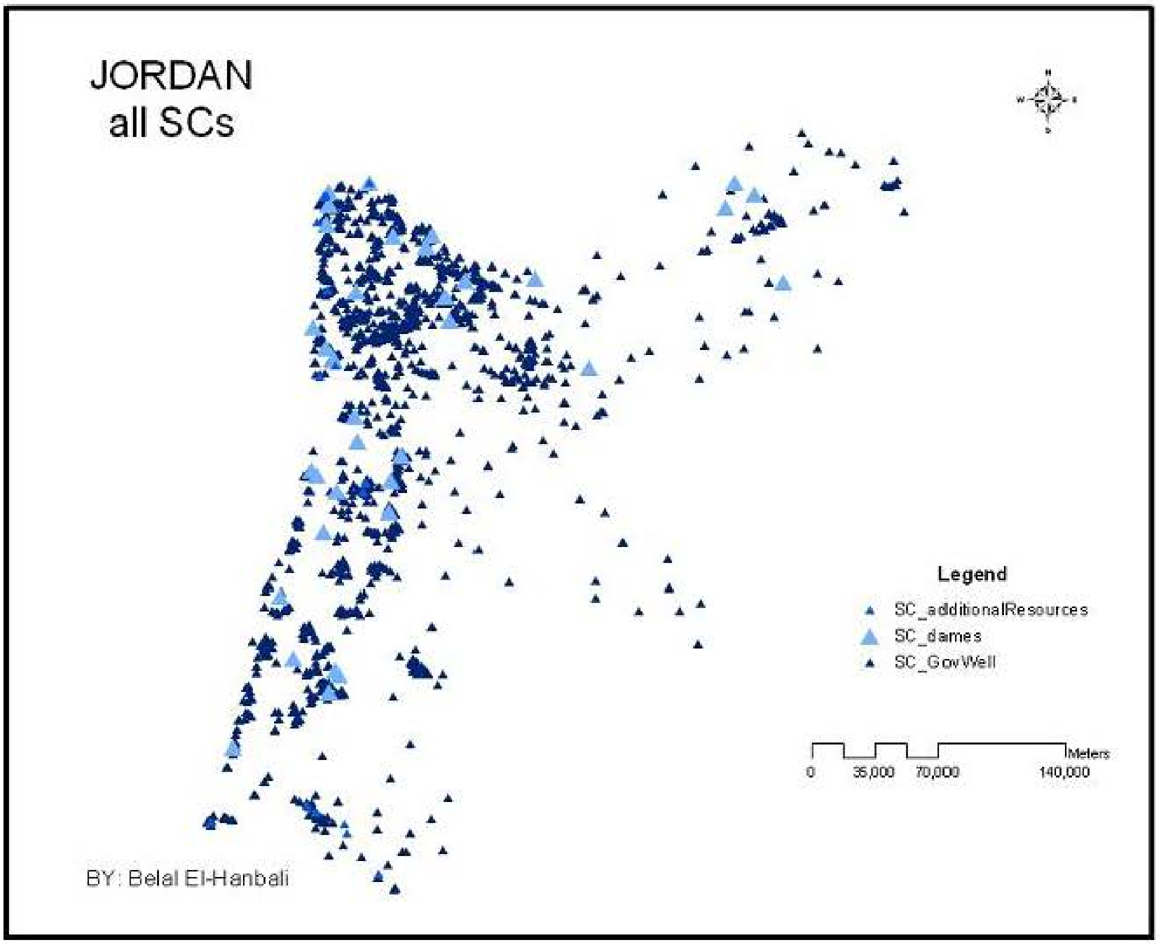

Figure 2.4 NWMP Transfer (TF) system segments and nodes (derived from NWMP)

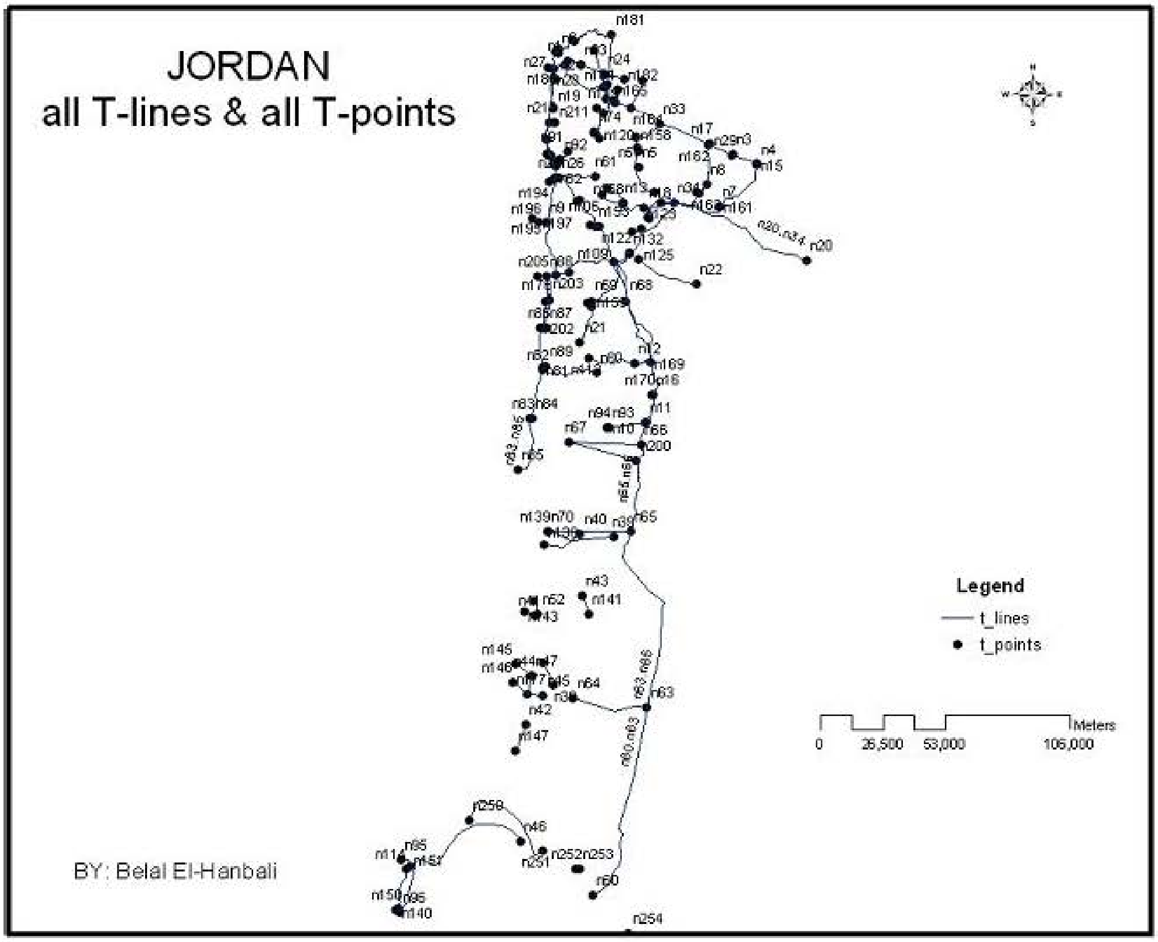

Figure 4.1 NWMP versus OM definitions of a Demand Center

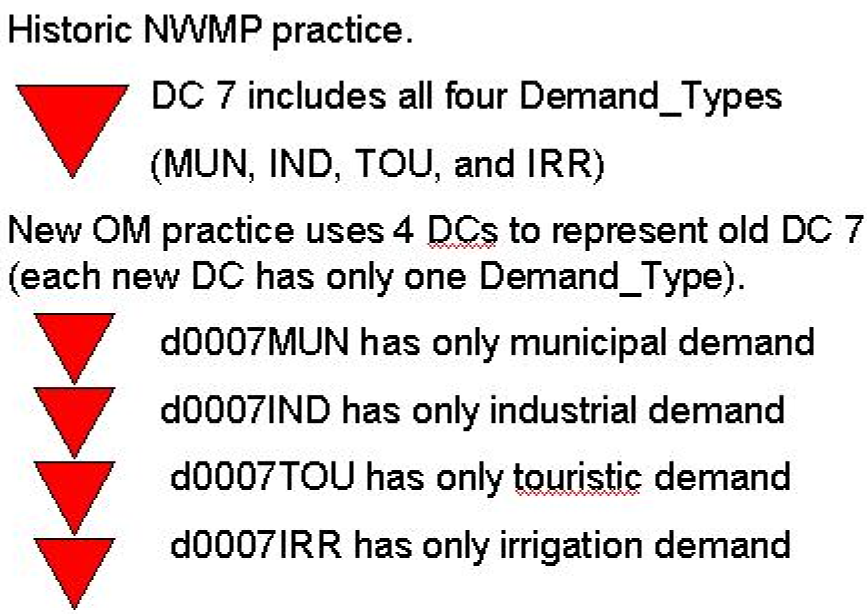

Figure 5.1 Northern part of study system HJ61E.

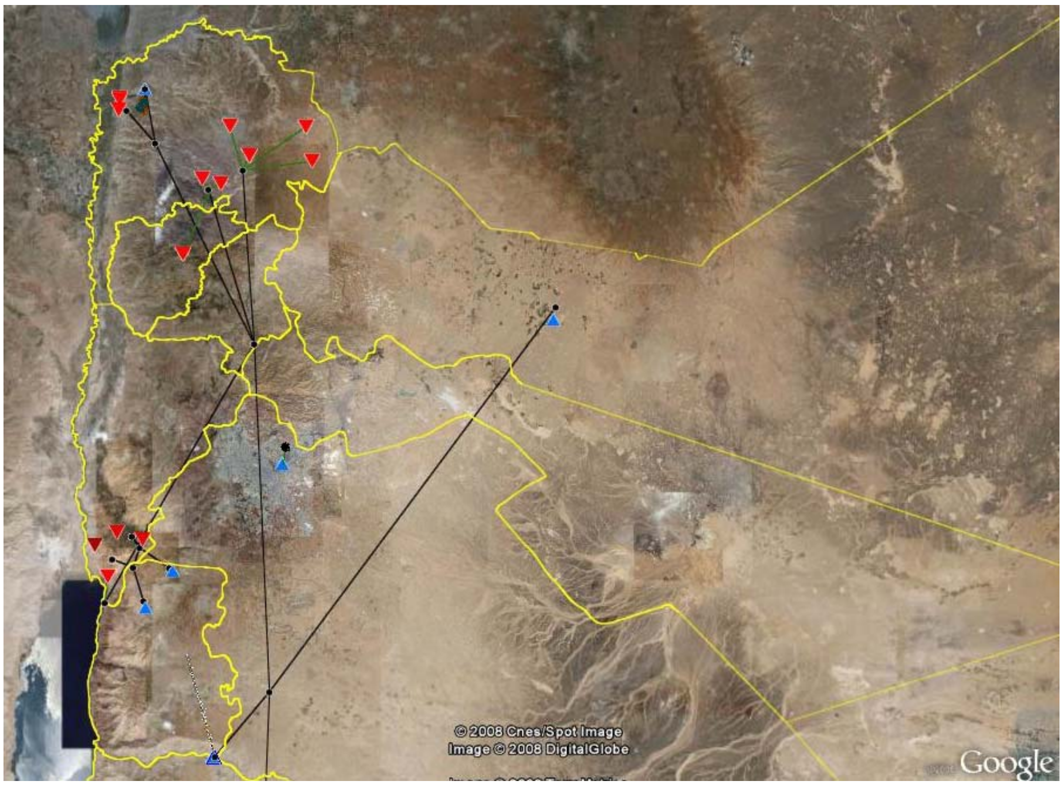

Figure 5.2 Southern part of study system HJ61E

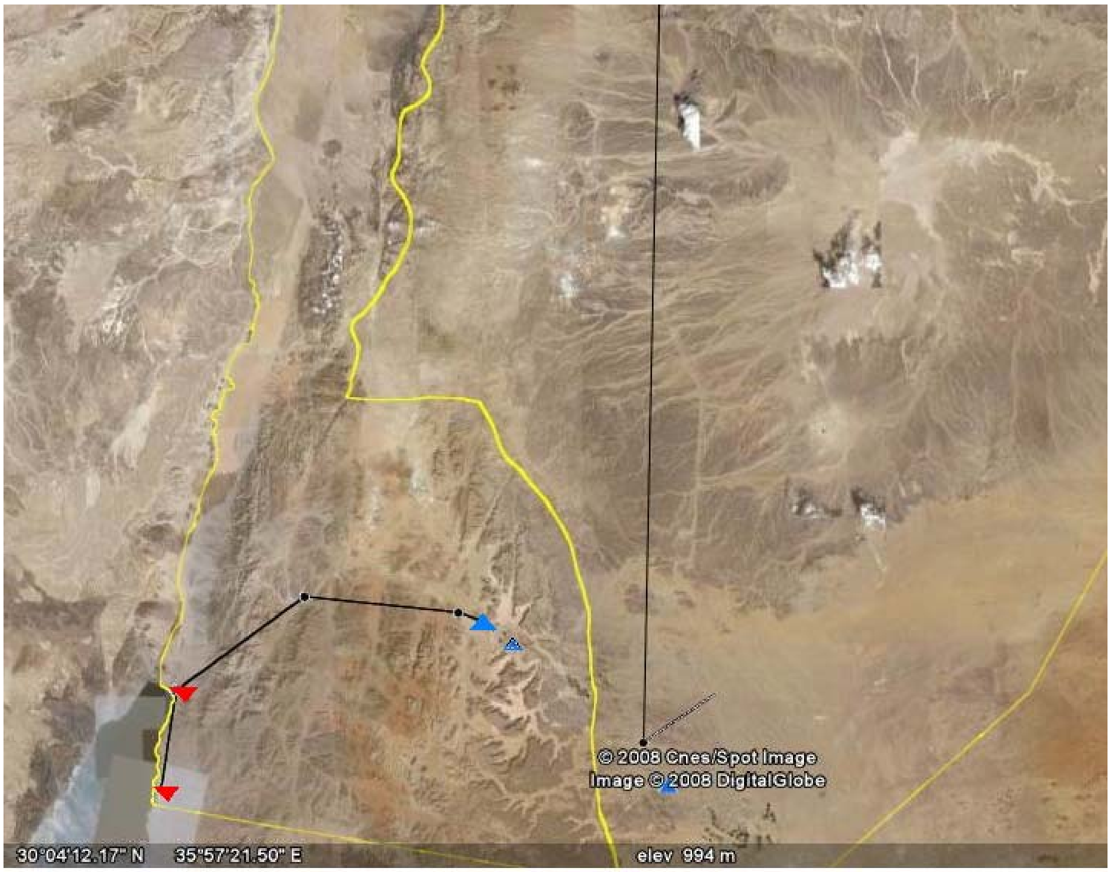

Figure 5.3 HJ61E BandT statistics, unsatisfied demand, and demand

a) MODEL STATISTICS

NUMBER OF TIME PERIODS	2
SINGLE EQUATIONS PER TIME PERIOD	354
SINGLE EQUATIONS	708
SINGLE VARIABLES	3,130
OBJECTIVE VALUE	380.0000

Total for all periods of (1.0 x DC unsatisfied demand per period)

b) (UNSATISFIED DEMAND x 1.0) PER BU PER PERIOD

	1	2
AJ	30.00	30.00
AQ	30.00	30.00
BA	30.00	30.00
IR	100.00	100.00

c) (UNSATISFIED DEMAND x 1.0) PER DC PER PERIOD (partial list)

	1	2
d0085MUN	10.000	10.000
d0572IND	10.000	10.000
d0217TOU	10.000	10.000
…		
D0013IRR	10.000	10.000

d) DEMAND PER BU PER PERIOD

	1	2
AJ	40.000	40.000
AQ	40.000	40.000
BA	30.000	30.000
IR	150.000	150.000

Figure 5.4 HJ61E BandT water Resource Type and source bounds and water takings

a) UPPER BOUND ON ResTy TAKEN PER BU PER PERIOD

	1	2
AM.GR	10.000	10.000
AQ.AD	10.000	10.000
IR.AD	10.000	10.000
IR.GR	10.000	10.000
MA.BF	10.000	10.000
MA.GR	10.000	10.000
MF.GR	10.000	10.000
MN.AD	10.000	10.000
MN.GR	10.000	10.000

b) TOTAL ResTy WATER THAT IS UNASSIGNED

	1	2
AM.GR	10.000	10.000
MN.AD		10.000
MN.GR	10.000	

c) TOTAL ResTy WATER THAT IS ASSIGNED

	1	2
AQ.AD	10	10
IR.AD	10	10
IR.GR	10	10
MA.BF	10	10
MA.GR	10	10
MF.GR	10	10
MN.AD	10	
MN.GR		10

d) TOTAL WATER TAKEN FROM AN SC

	1	2
sAL3475	10.000	10.000
sCD0046	10.000	10.000
sK3006		10.000
sNG001	10.000	
sSW001	10.000	10.000
s9002gr	10.000	10.000
sNG002	10.000	10.000
s9601	10.000	10.000

Figure 5.5 HJ61E BandT TF-related flows

a) WATER LEAVING AN SC AND FLOWING TOWARD A TF NODE

	1	2
n1 .sSW001	10.000	10.000
n4 .sAL3475	10.000	10.000
n60 .sK3006		10.000
n60 .sNG001	10.000	
n80 .sCD0046	10.000	10.000
n9496.s9002gr	10.000	10.000
n46 .sNG002	10.000	10.000
n9601.s9601	10.000	10.000

b) WATER FROM A TF NODE THAT REACHES A DC (partial list)

	1	2
n119 .d0007MUN	10.000	10.000
n165 .d0086MUN	10.000	10.000
…		
n9604.d9604MUN	10.000	10.000

c) FLOW (mn.mtn) LEAVING TF NODE 'mn' AND FLOWING TOWARD NODE 'mtn' (partial list)

	1	2
n1 .n9002	10.000	10.000
n4 .n9000	10.000	10.000
…		
n9603.n9604	10.000	10.000

d) FLOW (mn.mtn) FROM NODE mn REACHING NODE mtn (partial list)

	1	2
n1 .n9002	10.000	10.000
n4 .n9000	10.000	10.000
…		
n9603.n9604	10.000	10.000

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