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Linking GIS and water resources management models: an object-oriented method

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Abstract

Many challenges are associated with the integration of geographic information systems (GISs) with models in specific applications. One of them is adapting models to the environment of GISs. Unique aspects of water resource management problems require a special approach to development of GIS data structures. Expanded development of GIS applications for handling water resources management analysis can be assisted by use of an object oriented approach. In this paper, we model a river basin water allocation problem as a collection of spatial and thematic objects. A conceptual GIS data model is formulated to integrate the physical and logical components of the modeling problem into an operational framework, based on which, extended GIS functions are developed to implement a tight linkage between the GIS and the water resources management model. Through the object-oriented approach, data, models and users interfaces are integrated in the GIS environment, creating great flexibility for modeling and analysis. The concept and methodology described in this paper is also applicable to connecting GIS with models in other fields that have a spatial dimension and hence to which GIS can provide a powerful additional component of the modeler's tool kit.

Keywords: GIS; Object-oriented method; Water resources modelling

1. Introduction

1.1. GIS and analytical models

GIS is a general-purpose technology for handling geographic data in digital form. Its abilities include: preprocessing data into a form suitable for analysis, supporting spatial analysis and modeling directly, and postprocessing results (Goodchild, 1993). GISs offer a spatial representation of water resource systems. A GIS can bring spatial dimensions into the traditional water resource data base, and it has the ability to present an integrated view of the world. This is accomplished by combining various social, economic and environmental factors related to spatial entities of a water resources problem and making them available for use in a decision-making process (Csillag, 1996). In particular, the visual display capacity of GISs compliments the user interface of water resources models, allowing the user to take more complete control of data input and manipulation. Sophisticated graphical user interfaces can provide user-defined triggers, which allow the user to dictate how features will respond to environmental changes, and to construct rules to control the modeling process (Crosbie, 1996).

For water resources problem solving, both a spatial representation of the system and an insight into water resource problems are necessary. GIS can represent the geo-referenced characteristics and spatial relationships of systems, but predictive and related analytical capacities are more useful and necessary for solving complex water resources planning and management problems (Walsh, 1992). In order to take advantage of GISs to improve water resources planning and management, it is an attractive idea to link GISs with traditional mathematical models. Densham and Goodchild (1989) presented an approach to develop spatial decision sup-

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port systems (SDSS) to integrate spatial data and modeling capacity into an operational framework by linking a DSS and a GIS. Walsh (1992) and Leipnik et al. (1993) provided a comprehensive discussion on the potential for extending GIS applications in water resources. Other related studies include Nyerges (1993), Watkins and McKinney (1995), Fedra (1996), Keller and Strapp (1996), McKinney and Tsai (1996), Watkins et al. (1996), and Sample et al. (2001). In particular, for general issues in GIS-based modeling, Miles and Ho (2001) discussed the limitations, alternatives, and context of GIS as a burgeoning tool proliferating in civil engineering. The authors summarized the benefits of using GIS as a supplement to engineering modeling, and promoted awareness of the issues related to GIS-based modeling.

There are several strategies for coupling an environmental model to a GIS. These can range from a loose to a tight coupling. A loose coupling is where data are transferred between models and GIS, and each has separate database management capabilities and systems. A tight coupling is where data management in the GIS and model are integrated and they share the same database (Fedra and Kubat, 1996; Djokic and Maidment, 1993). The tightest coupling is an embedded system, in which modeling and data are embedded in a single manipulation framework (Densham and Goodchild 1989; Crosbie, 1996; McKinney and Tsai, 1996; Reitsma 1996; Fedra and Jamieson, 1996).

1.2. Object-oriented methods to link GISs and models

Object-oriented methods are promising for tight coupling of GISs and environmental models (Ye et al., 1996; Reitsma et al., 1994; Fedra, 1996; Crosbie, 1996). The idea behind these methods is that the world can be perceived as consisting of objects that interact in various ways (Crosbie, 1996). Object-oriented representations of the world consist of spatial objects and thematic objects. Spatial objects represent real world entities, with both geographical and physical, environmental and socio-economic attributes (see Table 1 for spatial objects in river basin systems). Thematic objects represent methods and topics relevant to the spatial objects. Methods are functions for describing or exploring relationships between spatial objects, for example, flow balance in a reservoir. Topics, which are identified through user interactions, are tasks to be completed or objectives to be reached, for example, water supply target of a reservoir. Thus, models and GIS functions can be viewed as methods applied to topics. The integration of models and GIS functions then becomes a pragmatic question of choosing a method to perform a task on the selected objects (Fedra, 1996).

Many applications of the object-oriented method have been reported in the water resources literature. Reitsma et al. (1994) presented an object-oriented method applied in the Power and Reservoir System Model (PRSYM, CADSWES, 1993). Physical entities in a river basin were defined as objects, and each object contained all of the information necessary to determine its state and to communicate with other objects. User's functions, which were defined as external objects, allow users to directly access the objects. PRSYM provides flexible and rapid construction of modifiable river-simulation models based on a set of primitive water and information objects.

Fedra and Jamieson (1996) described an object oriented information and decision support system for river basin management, called *WaterWare*. Three classes of objects were defined in *WaterWare*: *RiverBasinObjects*, representing real world entities; *NetworkObjects*, representing abstraction of the real world entities; and *ScenarioObjects*, representing model oriented scenarios of *NetworkObjects* that are partially derived from, and linked to, the *RiverBasinObjects*. These objects and various analysis functions can be manipulated within a common interface designed in a multi-media framework, and information for decision support is therefore translated through the interface.

Tisdale (1996) applied an object-oriented analysis to south Florida hydrologic systems, and showed that this methodology could organize system information well. Conceptual models were developed to identify system components and their attributes, and to simulate interrelations between objects. These models were combined to characterize the overall structure, behavior, and functionality of hydrologic systems.

A 'map-centric' and object-oriented system was developed by Ye et al. (1996) which provided map-based surface/subsurface water flow simulation modeling capability. This system was applied to simulate surface and subsurface flow in the Niger River Basin of West Africa.

Many challenges are associated with the integration of GISs with models in specific applications. One of them is adapting models to the environment of GISs. Unique aspects of water resource management problems require a special approach to GIS data structure and expanded development of GIS applications for handling water resources management analysis in a GIS. In this paper, we apply an object-oriented method develop a tight link between a GIS and a water resources management model for optimal water allocation in river basins. Research issues addressed in this paper include: (1) how to represent the data and functions of a water resources management model as spatial and thematic characteristics in a GIS; (2) how to integrate problem definition, data manipulation and analytical functions in a GIS environment; and (3) how to implement the model formulation and result analysis taking advantage of a GIS's spatial capabilities. These issues are addressed in this paper by: (1) formulating a conceptual model that integrates data, model and user interactions in a GIS

Table 1
Attributes of the spatial objects

Classes of spatial objects	Attributes	
	Geo-referenced characteristics/spatial relationships	External information
River reaches	From and to nodes, shape and length/upstream and downstream reach(es) and reservoirs, out and in-canals and in-collectors, intercepted demand sites and aquifers, associated hydropower stations and treatment plants.	Rainfall drainage, committed flows for political, environmental, recreational, and other purposes, seepage rate, and water quality requirements.
Reservoirs	Shape and area/in and out-reaches, in and out-canals and in-drainage collectors, intercepted demand sites and aquifers, associated hydropower stations and treatment plants.	Storage, topographic relations, rainfall drainage, committed release for downstream uses, maximum allowed release for flooding control, maximum allowed and minimum required level, evaporation, seepage, and water quality requirements.
Canals	From and to nodes, shape and length/in—treatment plants, in—rivers, in—reservoirs, intercepted demand sites, and intercepted aquifers.	Capacity and distribution loss.
Drainage collectors	From and to nodes, shape and length/in—demand-sites, out—rivers, out—reservoirs, and out—aquifers.	Capacity and distribution loss.
Aquifers	Shape and area/contained or intercepted rivers, reservoirs, canals, drainage collectors, and demand sites.	Hydraulic conductivity, yield coefficient, maximum allowed water table, pumping capacity, and water quality requirements.
Treatment plants	Coordinates, in-drainage collectors, associated rivers, canals, and aquifers.	Treatment/disposal capacity, water quality requirements
Demand sites	Shape and area/contained/intercepted rivers, canals, reservoirs, and aquifers, and out-drainage collectors.	Water rights, water demands, water distribution and use infrastructure.
Hydro. stations	Coordinates, reservoirs or rivers in proximity	Information with the reservoir or river reach that is associated with the hydropower station, power generation capacity and efficiency.

environment; and (2) developing a prototype linkage between a GIS and a water resources management model.

2. Object-oriented representation of a river basin system

Regional water allocation, generally considered at the river basin scale, is a decision making problem based on the physical and socio-economic conditions in the basin. As discussed here, a river basin system includes three components: (1) source components, such as rivers, canals, reservoirs, and aquifers; (2) demand components, including offstream uses for irrigation, industrial and municipal water supply, and instream uses, such as hydropower generation and ecological water use; and (3) intermediate components, including drainage collectors, treatment plants, and water reuse and recycling facilities. To analyze a river basin system, we model it as a node–link network, with nodes representing all source, demand and intermediate components, and links representing the spatial relations between the nodes. There are two kinds of links: natural links, e.g., a link between two consecutive river nodes; and engineered links, which represent the water supply-demand relations, e.g., a link between a reservoir and a demand site. For regional water allocation, mathematical models, including simulation and optimization models, can be constructed based on this network representation (Loucks, 1996).

2.1. Case study—Kashkadarya Basin, Central Asia

The river basin used as a case study in this paper is the Kashkadarya River basin, which is a sub-basin of the Amudarya River basin in the Aral Sea region of Central Asia. This is a well-known region where intensive irrigation and inappropriate water management has caused tremendous environmental and ecological problems (decay of the Aral Sea, once the fourth largest inland lake in the world). Fig. 1 shows a digitized map of the basin (McKinney et al., 1997). A major canal, the Moscow canal, diverts water from the Kashkadarya River to Mosk, an irrigation region outside of the basin. Since the local water in the basin is not sufficient for water supply, another major canal, the Kashi Canal, diverts water from the Amudarya River to the Kashkadarya River basin. There are several reservoirs in this basin, the major ones include the Chmik Reservoir on the Kashkadarya River, and the Talim reservoir on the Kashi Canal. These reservoirs can fully control the normal natural inflow (McKinney et al., 1997). Although the

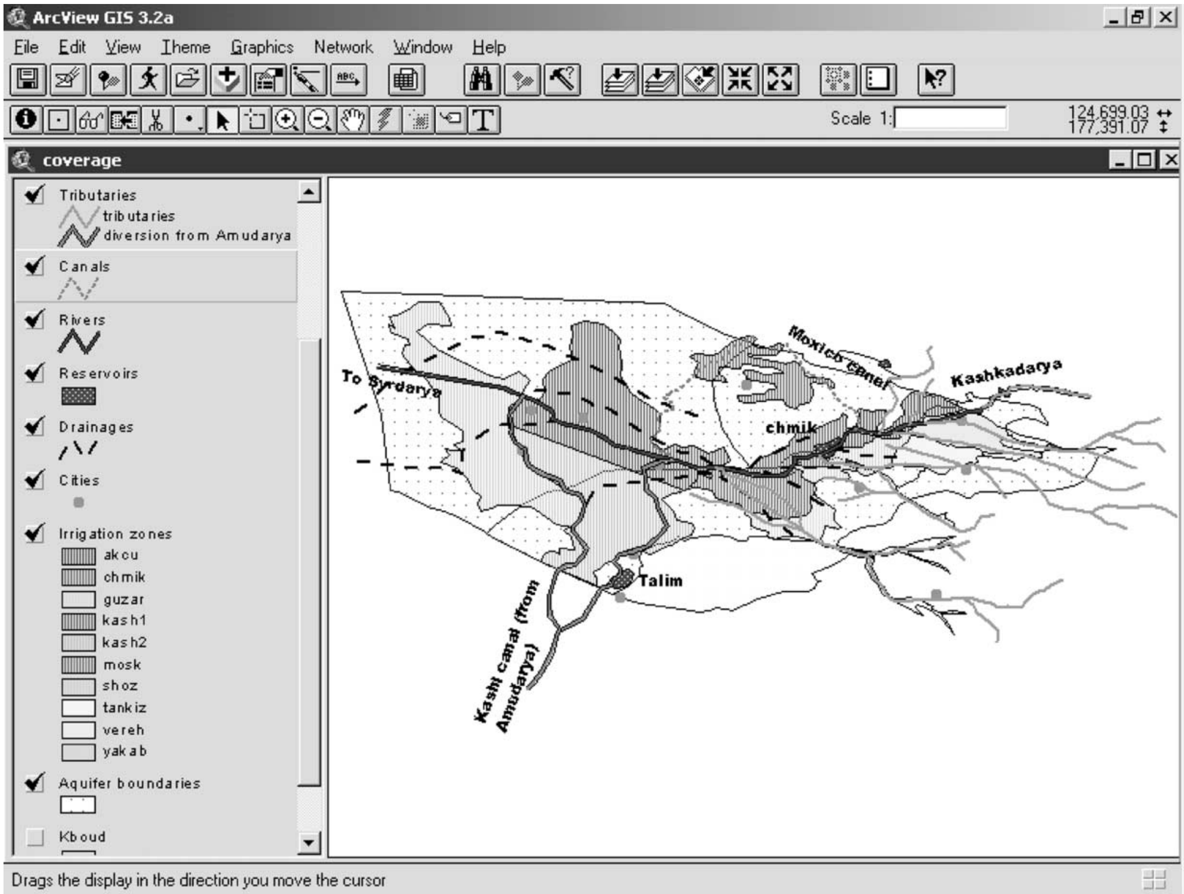

Fig. 1. Digitized Kashkadarya River basin map in Central Asia.

water demand is supplied mainly from surface water, groundwater in several aquifers in the basin also plays a role in water supply. There is intensive irrigated agriculture in the basin, and irrigation is the major part of the total water demand in the basin. Fig. 1 shows a number of demand sites, which are delineated according to the administrative districts and irrigated area distribution (McKinney et al., 1997). Within these demand sites, besides the water supply canals, there are drainage water collector canals that collect drainage from the irrigation fields and send it back to rivers. The semi-arid climate and intensive irrigation have created two typical problems in the basin: water quantity shortage and salinization. Our primary research purpose was to develop an efficient water allocation tool to aid in the resolution of the problems in this basin. However, in this paper, we illustrate the object-oriented GIS modeling concept and its application to the Kashkadarya basin.

2.2. Spatial objects—physical representation

For the case study, the river basin components include (Fig. 1):

- River reaches,
- Canals,
- Drainage collectors,
- Reservoirs,
- Groundwater sources (aquifers),
- Water treatment plants,
- Water demand sites, including agricultural, municipal, and industrial sites, and
- Hydropower stations.

These components are represented as polygon, arc, or point coverages in a GIS (see Table 2). We define each of these components as a *class* of spatial *objects*. They are stored in vector format and they can be visually displayed in the GIS. Various spatial relationships, e.g., proximity, adjacency, interception, and containment, between these entities, can be identified by overlaying these coverages in the GIS (ESRI, 2000).

Corresponding to each spatial object, there are two types of attributes. The first are geo-referenced characteristics, such as coordinates, length of lines, and area or perimeter for polygons, and spatial relationships between objects. A GIS can derive these types of attributes. The second are external information associated with spatial features, including physical, socio-economic and environmental data. For the purpose of modeling water

Table 2
Types of nodes and derivation methods

Node type	Coverage type	Derivation method
River reaches	Arc	Taking the central point of a arc as a node
Canals	Arc	Taking the central point of a arc as a node
Drainage collectors	Arc	Taking the central point of a arc as a node
Reservoirs	Polygon	Taking the central point of a polygon as a node
Aquifers	Polygon	Taking the central point of a polygon as a node
Treatment plants	Point	Taking the point as a node
Demand sites	Polygon	Taking the central point of the polygon as a node
Hydropower stations	Point	Taking the point as a node

allocation in a river basin, Table 1 shows the major attributes for the objects described above.

2.3. Thematic objects—logical representations

Three classes of thematic objects are defined for modeling river basins: (1) a node–link network (NetworkObj), (2) physical laws and management policies, which are defined as control objects (ControlObj), and (3) mathematical models for specific analysis (ModelObj). These are discussed below.

2.3.1. NetworkObj—logical representation of SpatialObj

A node–link network is a bridge between the real world and mathematical models. The network is defined as a class of thematic objects (nodes and links) that can be derived from spatial relationships in the GIS. In the network, the spatial objects (physical entities) are treated as nodes, and the spatial relations between the physical entities (see Table 1) are treated as directed arcs (links). For example, a tributary may intersect a demand site, which can be visually seen on a river basin map; while in the network view, this relation is represented as a link (arc) from the tributary to the demand site. This link indicates that the tributary may supply water to the demand site. As a demonstration, Fig. 1 shows the map of the case study and Fig. 2 shows the network derived from that map.

In the river basin network, both node and link objects inherit characteristics from the spatial objects. However, they inherit different attributes. Node objects inherit georeferenced characteristics and other external information, while the link objects inherit spatial relationships between objects, such as proximity, adjacency, intersection, and containment. This is further illustrated in the network derivation described later.

2.3.2. ControlObj—physical laws and management policies

The physical laws that govern spatial objects in the real world, and the management policies that control the operation of a river basin system and water allocation in a basin, are defined as a separate class of thematic objects. Since this class represents natural and anthropogenic controls, they are called control objects (ControlObj). The physical relations considered in the case study include:

- Water flow balance (FlowBal),
- Constituent (salt) mass balance (ConstBal),
- Hydropower generation as a function of flow release and reservoir level (HydrpGen),
- Topographic characteristics of reservoirs (TopolRel), and
- Physical bounds on storages, flows and diversions (PhyBnd).

The management policies include:

- Institutional rules for reservoir and aquifer operations,
- Committed flow for recreational, environmental and ecological uses,
- Water allocation among demand sites, and
- Water quality requirements.

The attributes of the control objects (ControlObj) include the physical relations and management constraints, as well as policy bounds for some state and decision variables. All attributes of the control objects are associated with a physical entity (node object). The form of these attributes is presented below in the description of the model objects.

2.3.3. Systematic integration of NetworkObj and ControlObj—ModelObj

The aggregation of the network objects and the control objects forms the third class of thematic objects, the model objects (ModelObj). Following the structure of a general modeling system (Brooke et al., 1988), a model object is comprised of four classes of objects: ***SETS*** (basic building blocks, corresponding to the indices in the algebraic representation of models), ***DATA*** (fixed constants or input data), ***VARIABLES*** (decision and state variables of the river basin systems), and ***EQUATIONS*** (relations that govern the processes or policies in the basin). In this object-oriented method, a model is defined as a set of inquiring schemes acting on an abstracted representation of the river basin (NetworkObj) and based on physical laws and management policies (ControlObj). These schemes allow us to

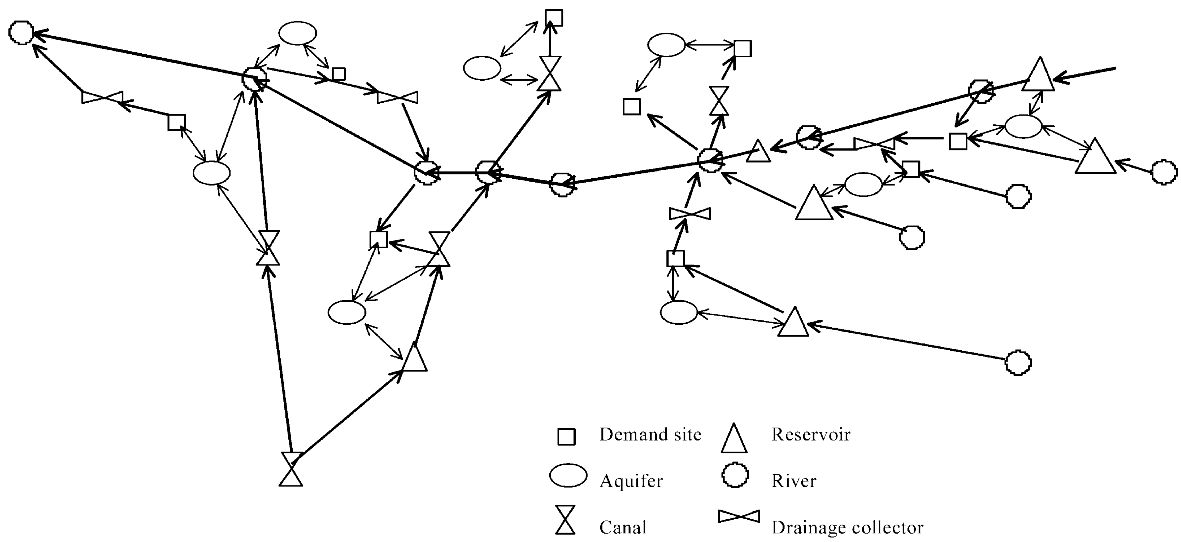

Fig. 2. Network derived from the basin map.

perform optimization or simulation modeling to analyze specific issues in water allocation.

A generic formulation of an optimization model for water allocation analysis in a river basin is presented here to illustrate the model objects, as well as the relationships between the model objects and the network and control objects. A full formulation of the model is given in McKinney et al. (1997). The model considers multiple objectives as listed below. Modeling relationships include the physical relationships and management constraints listed above related to the ControlObj.

SETS

$t \in T \subset$ ***SETS*** $\subset$ **ModelObj**, index of time periods.

n, n_1, $n_2 \in$ ***SETS***, inherited from **Nodes⊂NetworkObj**. indices for spatial objects (see Table 1 for a list of the spatial objects).

(n_1, n), (n, n_2), $(n_1, n_2) \in$ ***SETS***, inherited from **Links⊂NetworkObj**. For example, (n_1, n) is a link from node n_1 to node n (see Table 3 for a list of the links).

DATA

$Q_0(n, t) \in$ ***DATA*** $\subset$ **ModelObj**, **n** $\in$ **Nodes** (rivers, reservoirs or aquifers). Source of water from: rainfall drainage to rivers or reservoirs, or groundwater recharge.

$C_0(n, t) \in$ ***DATA*** $\subset$ **ModelObj**, $n \in$ **Nodes** (rivers, reservoirs or aquifers). Source of salt concentration in $Q_0(n, t)$.

$WD(n, t) \in$ ***DATA*** $\subset$ **ModelObj**, $n \in$ **Nodes** (demand sites). Water demand.

$WR(n, t) \in$ ***DATA*** $\subset$ **ModelObj**, $n \in$ **Nodes** (demand sites). Water right.

$k(n) \in$ ***DATA*** $\subset$ **ModelObj**, $n \in$ **Nodes** (hydropower stations). Hydropower generation efficiency.

$pgc(n) \in$ ***DATA*** $\subset$ **ModelObj**, $n \in$ Nodes (hydropower stations). Power generation coefficient when a station is a river node, and power is assumed to be linear with flow through the river node,

$tw(n) \in$ ***DATA*** $\subset$ **ModelObj**, $n \in$ Nodes (hydropower stations). Tail water level.

w_i, $(i=1, \ldots 4) \in$ ***DATA*** $\subset$ **ModelObj**. Weights for multiple objectives.

VARIABLES

$Q(n, n_2, t) \in$ ***VARIABLES*** $\subset$ **ModelObj**. Flow variables, including flows through river reaches, reservoir releases, water diversions and groundwater pumping to demand sites.

$S(n, t) \in$ ***VARIABLES*** $\subset$ **ModelObj**. Storage variables, for n $\in$ Nodes (aquifers and reservoirs), we may set $S(n, t)=0$ for rivers, canals, or drainage collectors.

$C(n, t) \in$ ***VARIABLES*** $\subset$ **ModelObj**. Constituent concentration variables.

$H(n, t) \in$ ***VARIABLES*** $\subset$ **ModelObj**, **n** $\in$ **Nodes** (reservoirs). Reservoir water head.

$P(n, t) \in$ ***VARIABLES*** $\subset$ **ModelObj**, **n** $\in$ **Nodes** (hydropower stations). Hydropower generation.

EQUATIONS

Objective function $\in$ ***EQUATIONS*** $\subset$ **ModelObj**

$$\text{Maximize } w_1 \cdot Z_1 - w_2 \cdot Z_2 - w_3 \cdot Z_3 + w_4 \cdot Z_4$$

where Z_1=ratio of water delivery to water demand at demand sites, Z_2=maximum water deficit over all time periods, which is minimized in the objective function

Table 3
Types of links and derivation methods

Link type	Coverage type	Derivation method
River–River; River–Canal; Drain. collector–River; Canal–Canal; Canal–River	Arc–Arc	If the from-node of arc 1 is *within a distance* (*proximity*) to the to-node of arc 2, these two points are recognized as to be at the same position, and a link is made from the central point of arc 1 to that of arc 2.
River–Aquifer; River–Reservoir; River–Dem. site; Canal–Dem. site; Canal–Reservoir; Canal–Aquifer; Drain. collector–Aquifer	Arc–Poly	If an arc intercepts with a polygon (*interception*), and the to-node of the arc is within the polygon (*containment*) or within a distance to the polygon (*adjacency*), then a link is made from the central point of the arc to the central point of the polygon. However, if the polygon is an aquifer, only the first condition is required, since the flow direction can be either way.
Aquifer–River; Aquifer–Canal; Reservoir–River; Reservoir–Canal; Dem. site–Drain. collector	Poly–Arc	If a polygon intercepts with an arc (*interception*), and the from-node of the arc is within the polygon (*containment*) or within a distance to the polygon (*adjacency*), then a link is made from the central point of the polygon to the central point of the arc. If the polygon is an aquifer, only the first condition is required.
Demand site–Aquifer; Aquifer–Dem. site; Reservoir–Aquifer	Poly–Poly	If polygon 1 intercepts with or within polygon 2 (*interception* or *containment*), then a link is made between the central point of polygon 1 and that of polygon 2. The direction of the link can be either way.
Treat. plant–River	Point–Arc	If a point is within a distance (*adjacency*) to an arc, then a link is made from the point to the central point of the arc.
Drain. collector–treatment plant	Arc–Point	If the to-node of an arc is within a distance (*adjacency*) to a point, then a link is made from the central point of the arc to the point
Treat. plant–Reservoir; Hydro. station–Reservoir	Point–Poly	If a point is within a distance (*adjacency*) to a polygon, then a link is made from the central point of the polygon to the point. If the point represents a hydropower station, then the link represents an association, instead of a flow link

by a negative weight. Z_3=maximum water deficit over all the demand sites, which is minimized in the objective function by a negative weight, and Z_4=ratio of hydropower power generation to power demand. Mathematical definitions of these objective items should be referred to McKinney et al. (1997). The objective function is defined as:
Constraints⊂***EQUATIONS***⊂**ModelObj**

- Flow balance (FlowBal) for node n

$$S(n,t)-S(n,t-1) = Q_0(n,t) + \sum_{n_1 \to (n_1,n)} Q(n_1,n,t) - \sum_{n_2 \to (n,n_2)} Q(n,n_2,t)$$

- Constituent (salt) balance (ConstBal) for node n

$$S(n,t)\cdot C(n,t)-S(n,t-1)\cdot C(n,t-1) = Q_0(n,t)\cdot C_0(n,t) + \sum_{n_1 \in (n_1,n)} Q(n_1,n,t)\cdot C(n_1,t) - \sum_{n_2 \in (n,n_2)} Q(n,n_2,t)\cdot C(n,t)$$

- Hydropower vs. flow release and reservoir level (HydrpGen) for hydropower generation node n

$$P(n,t) = \{k(n) \sum_{n_2 \in (n_1,n_2)} Q(n_1,n_2,t)\{[H(n_1,t) + H(n_1,t-1)] - tw(n_1)\}/2 \quad \forall n_1 \in Nodes(reservoirs) k(n)\cdot pgc(n)\cdot \sum_{n_1 \in (n,n_1)} Q(n_1,n_2,t), \quad \forall n_1 \in Nodes(rivers)$$

- Reservoir surface area vs. elevation (TopolRel)

$$S(n,t) = f(H(n,t)) \qquad n \in Nodes\ (reservoirs)$$

where f is a polynomial function.

- Physical bounds (PhyBnd) on Q, S, C, P, e.g., storage capacity and water withdrawal capacity.
- Policy bounds (PolBnd) on Q, S, C, P, e.g., maximum allowed water diversion by water right, minimum instream flow for environmental purposes, and water quality standards.

Attributes for the model objects include the attributes inherited from the network objects and attributes derived from the network objects which are illustrated in the following. Additional attributes for the model objects are the "grammar features", in other words, how each of the model objects can be described in special codes that can be complied by a model solver. We describe this in the section on model generation.

2.4. A conceptual data model integrating spatial and thematic objects

An object-oriented data model portrays objects and relationships between objects. It represents some state of affairs that exists within the problem domain. It is the result of a conceptual analysis of that problem domain. This analysis is mapped onto a set of graphical or linguistic conventions, and is able to faithfully represent the characteristics and complexity of the phenomena.

Fig. 3 shows a data model framework illustrating the relationships between classes SpatialObj, ModelObj, NetworkObj, and ControlObj. Interactions between the object classes and the system user are also shown. The diagram depicts several types of relationships: inheritance (generalization), aggregation (composition), and association (Rumbaugh et al., 1991). Inheritance or generalization illustrates the "is-kind-of" relationships and allows for a progressive refinement of classes from the more general to the more specific. Super-classes define more general aspects which subclasses inherit and further define additional, more specific characteristics and behavior. Aggregation represents the "is-composed-of" relationship: a class includes objects from other classes. Association represents a structural relationship between classes, and an aggregation is a strong form of association.

NetworkObj is a specific representation of SpatialObj. Nodes in NetworkObj inherit spatial entities and associated attributes. Links in NetworkObj inherit spatial relationships between the spatial entities (see Table 2). ControlObj is associated with NetworkObj, i.e., each object in ControlObj, e.g., a physical relation or a management constraint, must be associated with some physical entity, e.g., a node, in NetworkObj. For example, a flow balance equation is associated with a reservoir, a river reach, or an aquifer. Some classes of objects in ModelObj are generated from network objects, with ***SETS*** (model elements and structure) inherited from nodes and links of NetworkObj, and ***DATA*** generated from the attributes of nodes. Equations (***EQUATIONS***) in ModelObj are composed (aggregated) from physical relations and management constraints in ControlObj. Variables (***VARIABLES***) are prescribed and incorporated in ModelObj. Both ***EQUATIONS*** and ***VARIABLES*** are associated with NetworkObj, for example, a flow variable $Q(n, n_2, t)$ has two physical domains with physical entities n and n_2, and a flow balance equation (member of ***EQUATIONS***) must be associated with a physical entity (e.g., a reservoir) and the connections between that entity and others.

User interactions (requests) during model generation are incorporated in all classes of objects. User interactions and inter-relationships between various classes of objects are further illustrated in the implementation of model generation below.

3. Implementation

To implement the object-oriented method discussed above, some extended GIS functions were developed using an object-oriented programming language within a GIS—the Avenue language designed to work with Arcview GIS (ver. 3.2) from Environmental Systems Research Institute (ESRI) in Redlands, CA. Using these functions, once a user inputs a river basin map and additional information, the GIS can extract a node–link network, accept the user's modification of the network, incorporate management policies through the user's interactions, generate a mathematical model in an optimization modeling language—the General Algebraic Modeling Language, GAMS (ver. 2.5) was used (GAMS Development Corporation, www.gams.com), run the model by calling a solver, and finally display the modeling results. Fig. 4 presents an overall procedure for these tasks, with selected GIS windows demonstrating the steps. Below, the details of two of the extended GIS functions are presented (*network extraction/update* and *model generation*), and a brief introduction of other functions is also given. The system is run with Windows NT on a Pentium III.

3.1. Network derivation/modification

Spatial relations can be used in a GIS to resolve problems that involve issues of location, such as proximity,

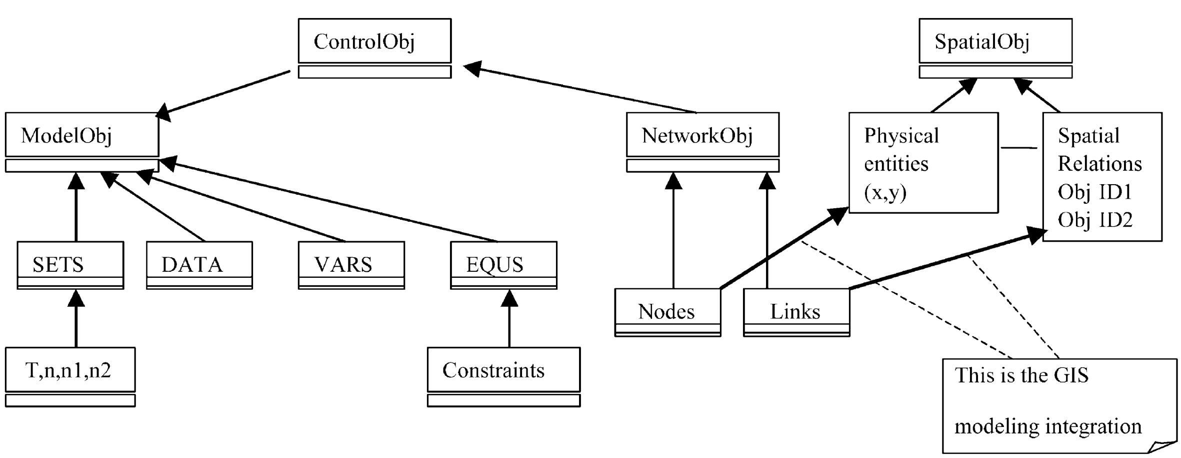

Fig. 3. A diagram for the object-oriented data model.

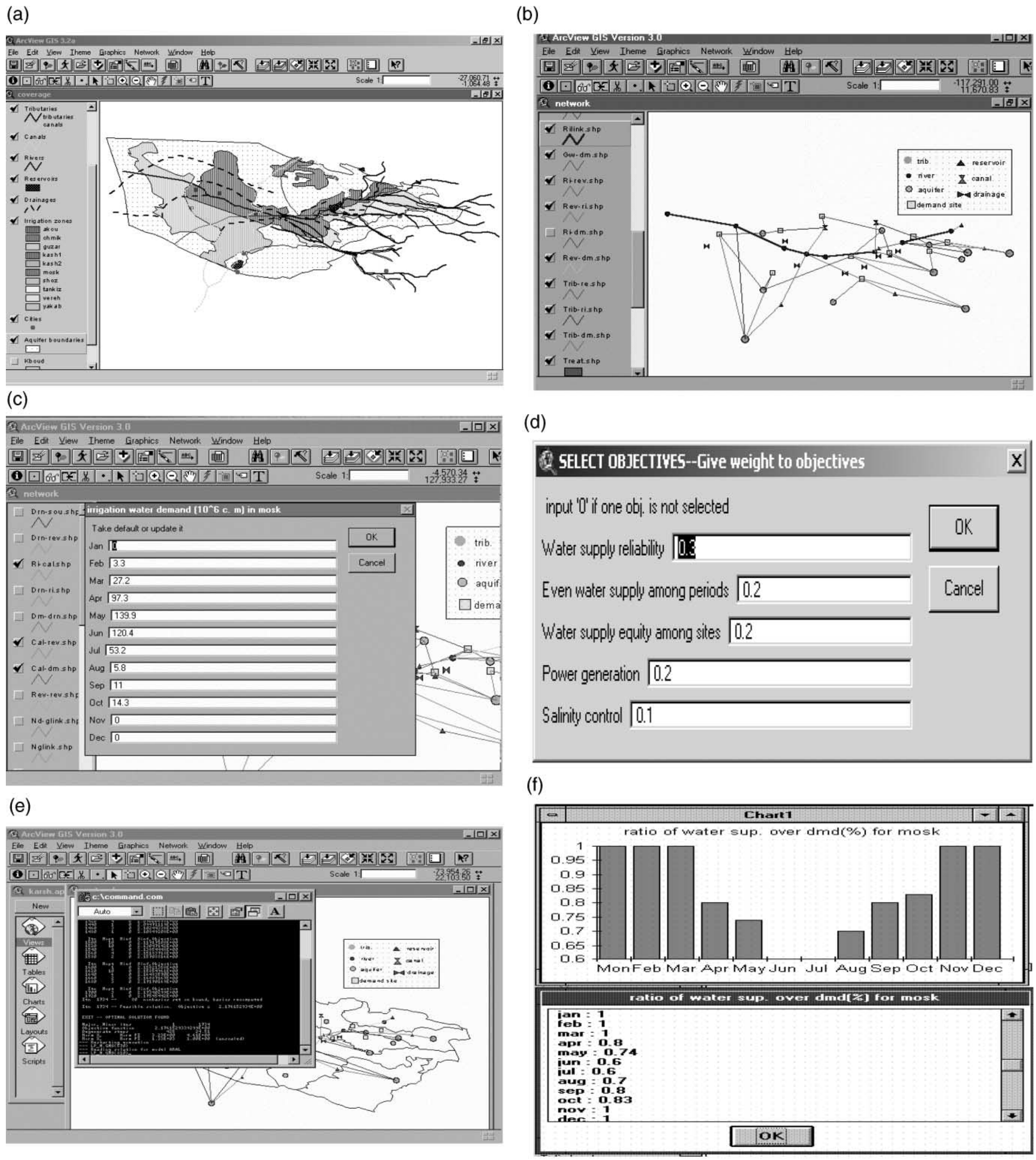

Fig. 4. (a) Prepare coverage and attributes. (b) Extract network. (c) Input/update data. (d) Interact with a user for model generation, e.g. select objective weights. (e) Generate and run GAMS model. (f) Result display.

adjacency, interception, and containment. These spatial relations are defined for a selected spatial object, the one doing the selecting, and a target spatial object, the one from which items are being selected. The network derivation procedure includes three steps: (1) searching all spatial objects and identifying them as nodes in the network; (2) transferring spatial attributes from the spatial objects to nodes, a class of network objects; and (3) searching all spatial relations between the spatial objects, and identifying them as links in the network. The types of nodes and links and their derivation methods are presented in Tables 1, 2 and 3.

Fig. 5 shows an example for deriving a river basin network from a GIS based on the methods listed in Tables 2 and 3. As can be seen, the aquifer intersects two river reaches, and there is flow between the aquifer and the river reaches. The reservoir is *contained* in the aquifer, and both infiltration of water from the reservoir to the aquifer and recharge of water from the aquifer to the reservoir may occur. The reservoir is linked to its upstream and downstream river reaches. Flow can be diverted from the reservoir to the demand site through a canal. The demand site intersects the aquifer, the two-way link between the aquifer and the demand site indicates that water may be pumped to the demand site, and deep percolation from the demand site may recharge the aquifer.

However, in the real world, water supply is related to physical, environmental, social and political issues, and water supply links cannot be determined only by the kinds of spatial relationships described above. Moreover, the river basin map may only represent current conditions, however, a user may also want to introduce some changes to the system for future planning purposes. For these cases, it is necessary for the user to modify or update the network for variants that do not exist in the original map. The network modification tool allows users to add or delete nodes or links, so as to build a variant network. The tool is designed as a user-defined trigger (Crosbie, 1996) with which users can build the model structure to suit their needs. When an existing node or link is deleted, the attributes associated with it are made inactive; when a new node or link is added, the user is required to input attributes associated with the new features.

3.2. Model generation

As discussed above, model objects (ModelObj) are generated from the network objects (NetworkObj), the control objects (ControlObj), as well as the user's interactions. Before we describe how the generation is implemented, we give a brief introduction to GAMS, which is linked to the GIS to compile and solve the model. GAMS is a programming language used to solve mathematical programming problems (Brooke et al., 1988). In the GAMS language, a model is composed of *sets* (modeling dimensions and elements), *data*, *variables*, and *equations* (objective function and constraints), which exactly corresponds to the forms of the model objects defined in this study. Therefore, generating a GAMS model requires composing the model parts corresponding to the model objects.

Fig. 6 shows a diagram of model generation in the ArcView GIS based on the conceptual object-oriented data model described above. Four processes are undertaken during model generation: (1) user interaction, (2) data transformation, (3) model object generation, and (4) GAMS code generation. The user interaction includes selecting a model type (linear or nonlinear), selecting objectives, specifying targets for objectives, specifying weights for the objectives, updating constraints such as water allocation and committed flows, and assigning initial values of reservoir storages, groundwater tables, etc. These inputs update the node and control object attributes, and specification of the model type.

During the process of data transformation, specific data associated with network and control objects and user interactions are transferred to various model objects.

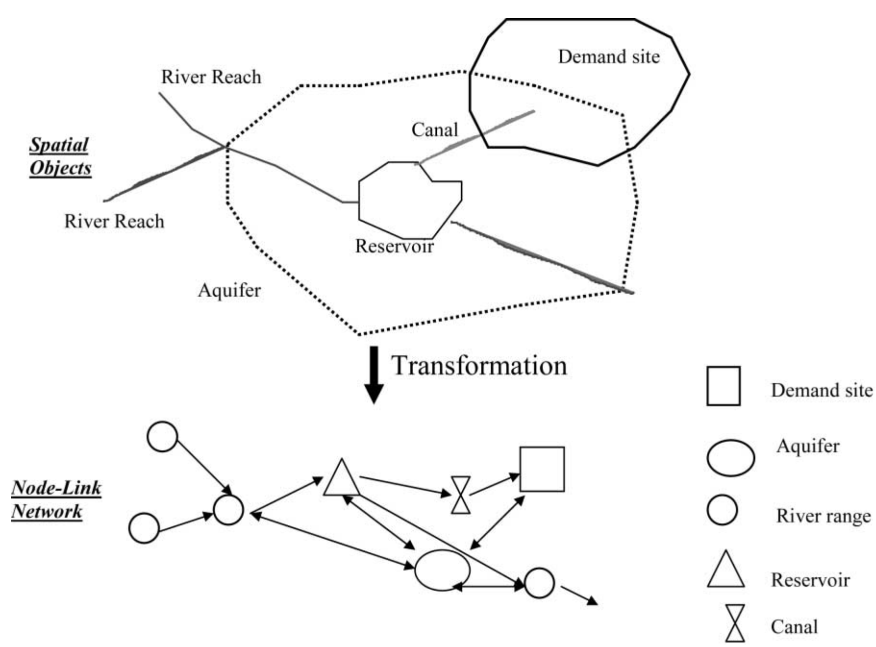

Fig. 5. A simplified example for network derivation.

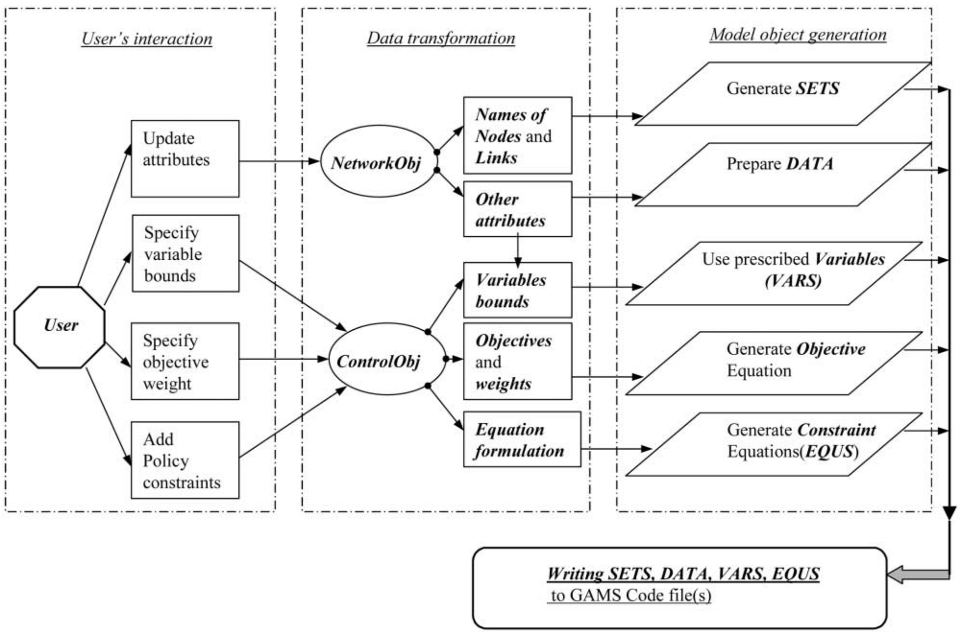

Fig. 6. Procedures for model generation in GIS.

The data type, source, and destination for various data transformation paths are shown in Fig. 6. Names of nodes and links are transferred to form model objects (***SETS***), other attributes including water supply and demand data are transferred to generate model objects (***DATA***). Variables (***VARIABLES***) are prescribed according to the modeling problem, including state variables such as flow, reservoir storage, etc., and decision variables such as water withdrawal, reservoir release, etc. Attributes of node objects are used to form physical bounds for some variables, and specifications from user interactions are used to form policy bounds as described before. The objective function form and weights derived from user interaction are used to form the objective function (a member of the object class, ***EQUATIONS***). The physical relations and management constraints are transferred to form constraints (members of ***EQUATIONS***) required for the modeling problem. Fig 7 shows the algorithm used to generate the equations.

For each *class* of Nodes ⊂ NetworkObj

(For example, reservoirs, river reaches, canals, see Table 1)

For each node object in the class

Find ***equation*** *(**EQUS**) type associated with the node* ⊂**ControlObj**

(mass balance, constituent balance, topologic

relations, policy constraints, etc.)

Generate equations based the equation types

End for one class of the spatial objects

End for all classes of the spatial objects

Fig. 7. Algorithm for equation generation.

As shown in Fig. 6, different classes of model objects are generated separately. As defined before, each class of model objects has an attribute specifying the "grammar" of how a model is to be coded. The GAMS language, which is similar to commonly used programming languages, provides basic programming features, allowing users to build maintainable models that can be adapted to various analytical problems (Brooke et al., 1988). Specific programming features of GAMS are incorporated into the attributes of various model objects. These features, as well as other attributes inherited from NetworkObj, or aggregated from ControlObj, are written to the corresponding parts of the GAMS code, which can be encoded and complied by the GAMS modeling package. Fig. 8 illustrates several special features used when expressing an equation in GAMS, as well as the association with the attributes of ***EQUATIONS***, generated through the data model.

GAMS consists of a language compiler and a stable of integrated solvers (Brooke et al., 1988). When the GAMS code for an optimization model is generated, a system connection function in ArcView ("hotlink") calls GAMS within the system, and a window is opened to show GAMS solution progress (see Fig. 4, the window for "Generate and run GAMS model"). When GAMS completes execution, the system connection function writes the solution into the attribute tables of the spatial objects for further display and analysis (see Fig. 4, the window for "Display results", as an example.)

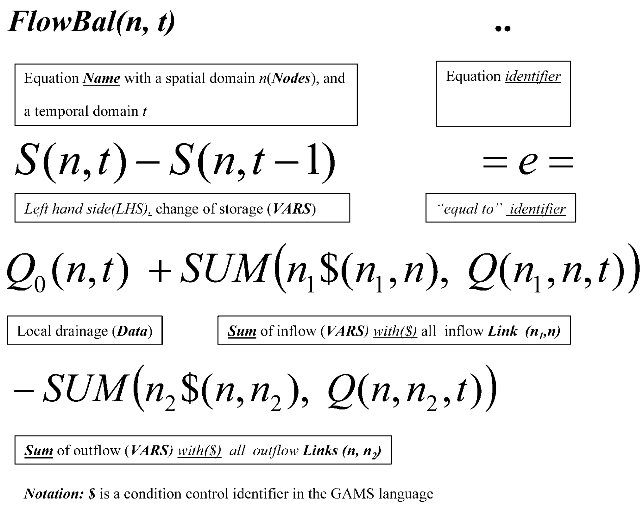

Fig. 8. GAMS features of an equation and attributes of equation objects.

3.3. Other functions

3.3.1. Data input/update

On a graphical screen showing the river basin network, the data input/update functions allow users to click on any node or link object to open a tabular window for users to input or update external information for the node or link object.

3.3.2. Visual display

Apart from the primary display capacity of the GIS, an enhanced display function can display error and help information during the execution of all the functions described above. It can also display primary data or modeling results in tables or charts, for the network objects (nodes or links) selected by the user.

4. Conclusions

A river basin is modeled as a collection of spatial objects and thematic objects, and a conceptual GIS data model is formulized to integrate the physical and logical representations of a river basin water allocation problem into an operational framework. Then based on this, extended GIS functions are developed to implement a tight linkage between a GIS and a water resources management model based on optimization. The linkage is tight because all processes, including data input/update, network generation and modification, model generation, model solution, and result analysis/display, are integrated in the environment of the GIS, and the extended GIS is enhanced by optimization capability.

Another contribution provided by this paper is a prototype development of expanded GIS applications. This includes a series of extended GIS functions to represent the spatial objects of a river basin in the GIS, and to extract/derive thematic objects related to a number of water resources management problems. In particular, the network derivation function builds a bridge, the node–link network, between the physical representation and the logical representation of the water management problem. Normally, one extracts a network based on a paper map of a river basin; in many areas, digital representations exist, and the network extraction and modification function will reduce labor and is also much more flexible for scenario analysis. Moreover, the model generation function makes it possible to generate a model based on the network extracted from the spatial representation of a river basin, combined with physical relations and management policies and user's interactions. Overall, data, models and user's interactions are integrated in the GIS environment, which creates great flexibility for modeling analysis.

Although we focus on connecting GIS with water management modeling, the concept and methodology described in this paper is general for connecting GIS with modeling capacity in other fields such as transportation systems, power delivery systems, sewer systems, truck routing, etc., and further development of the object-oriented method should be promising for those fields with phenomena that have a spatial component, and offer professionals and managers a new paradigm for decision analysis.

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