Development of a Model for Assessment of Irrigation Management Performance and application to Hetao Irrigation District in the Yellow River basin

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1. Introduction

IMPAM (Irrigation Management Performance Assessment Model) is a model that is being developed by the authors to simulate water movement and calculate water balance in irrigation areas. IMPAM can be a tool for the assessment of management performance procedures in irrigation areas which strongly affects water balance of in irrigated areas, as well as it can provide important information for simulations of river runoff basin and regional climate.

In addition, IMPAM can simulate water balance after change in water management. Water conservation is one of the most important current concerns in managing irrigation areas throughout the world, and several trials to improve irrigation performance through modification of water management (both physically and operationally) are being pursued. However, changing water management practices can cause unexpected changes in water balances and often bring unintended side effects. For example, modification of a channel system to reduce seepage may produce a drop in groundwater levels, disadvantaging farmers who depend on groundwater (Roost, 2002). It is important therefore to have techniques to predict changes in water balance caused by changes in irrigation management procedures, as well as to assess the present water balance of an irrigated area, to look for problems and suggest how they can be ameliorated.

2. Development of IMPAM

2.1 Scope of IMPAM

To assess and compare water management procedures, the appropriate scale of operation for study would appear to be that which covers the system from farm-block to irrigation district, as the effects of different water management procedures should appear most clearly at this scale; accordingly, this is the scale at which the IMPAM system has been designed to operate. Several earlier water balance models have been developed, but their scales are either too wide or too narrow to describe the effects of management changes on the water balance. Thus, the PODIUM (IWMI, 2000) model simulates the balance of demand and supply at scales ranging from regions to whole countries, and take into consideration socio-economic factors as well as agriculture. The scope of these models is too large; detailed hydrological processes are ignored, and they are therefore not suited to the assessment of irrigation management procedures. On the other hand, models like SWAP and HYDRUS include very precise calculation of the one-dimensional water balance in a farm plot, considering physical aspects of soil water movement. For an irrigation district the water balance often depends more on the physical characteristics of the irrigation system, its operation rules, the cropping pattern and distribution of land use practices etc., than on the water balance of individual farm plots. For example, the water balances of irrigation districts in the Ningxia Autonomous Region (Weining and Qingtongxia IDs) and Hetao ID (Inner-Mongolia Autonomous Region) in the Yellow River basin (Figure 1), China, are quite different, especially in the ratio of drain water to intake water (Figure 2 (a) and (b)). Such difference should be mainly because of differences in the characteristics of these irrigation districts such as operational procedures, physical structures, etc., which cannot be described by one-dimensional water balance models. However, these important components of the water balance of irrigated areas are included in the IMPAM system.

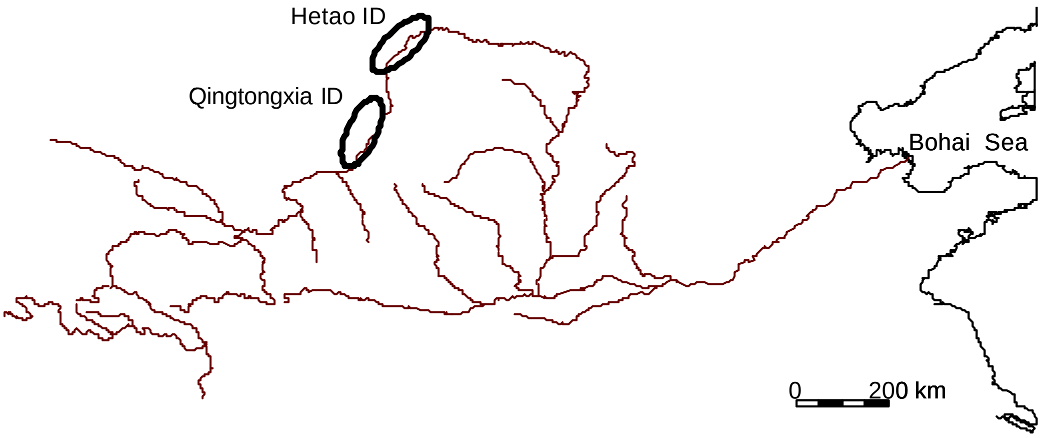

Figure 1. Hetao and Qingtongxia Irrigation Districts

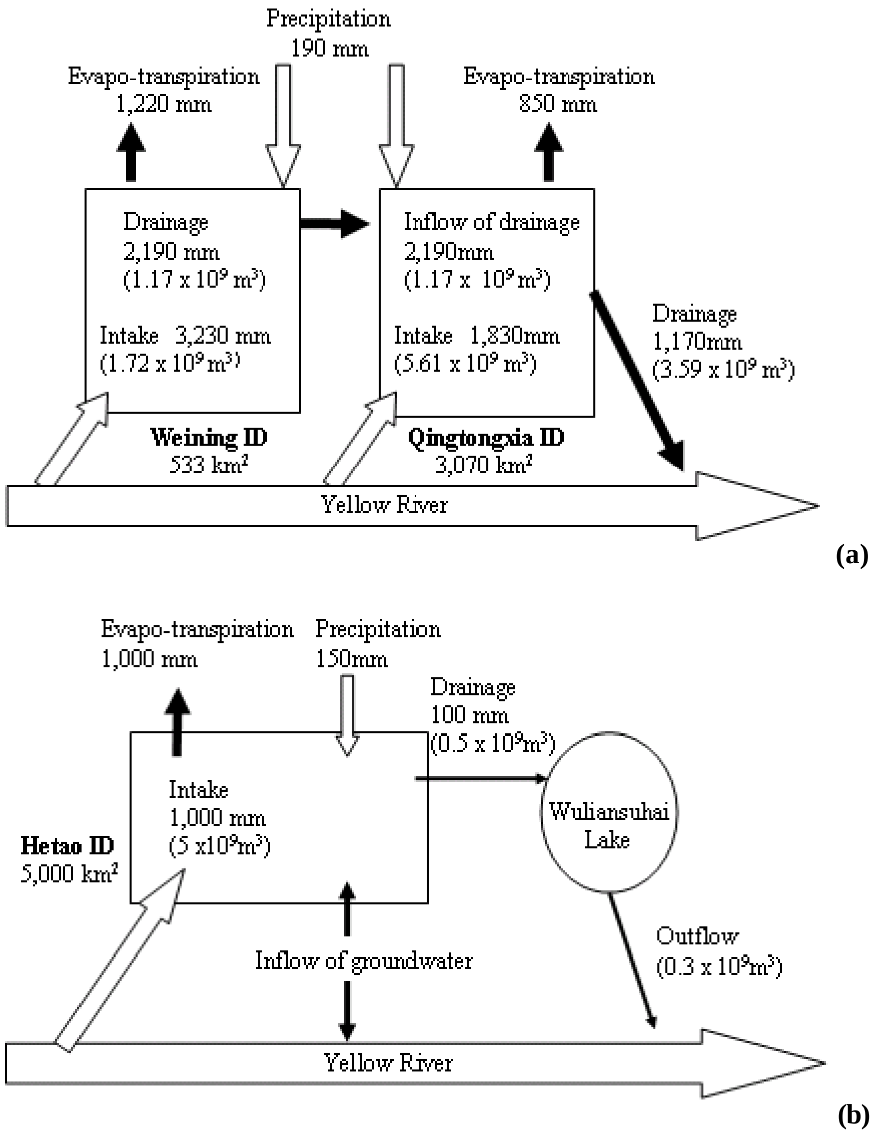

Figure 2. Water balance of Irrigation Districts in Ningxia (a) and the Hetao Irrigation District (b)

2.2 Structure of IMPAM

Use of IMPAM for simulations of water balance, including the district-scale components described above, requires several kinds of dataset, as indicated in Figure 3. IMPAM combines four modules (Water Distribution Module (WDM), Drainage Reuse Module, Spatial Water Balance Module (SWM), and Farm Water Balance Module (FWM)) (Figure 4), to simulate complicated water dynamics in irrigated areas.

The functions of the four modules are as described below.

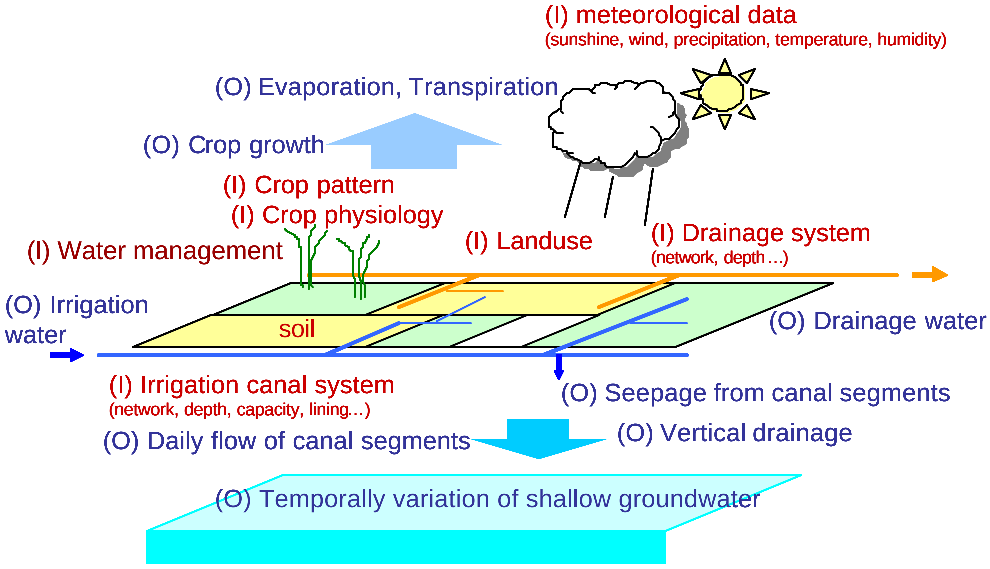

Figure 3. Input (I) and output (O) of IMPAM (Entrée (I) et rendement (O) d'IMPAM)

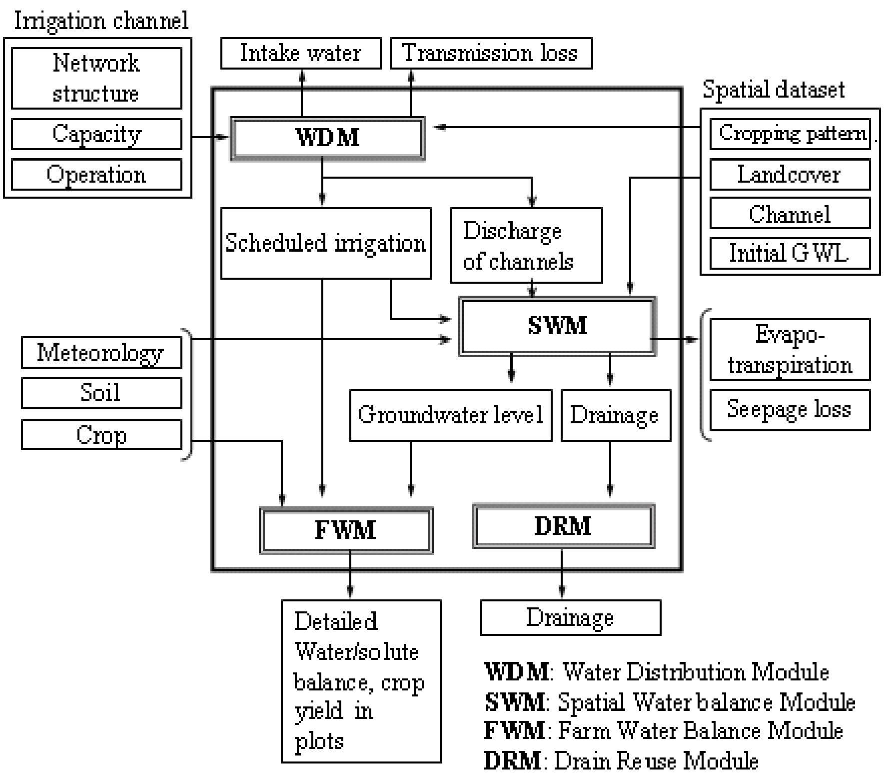

Figure 4. Framework of IMPAM

A. Water Distribution Module

The WDM calculates the daily discharge rate (m^3/s) of each irrigation channel segment, taking into account the amount of seepage loss. The main input items to this module are (i) the topological structure of the irrigation channel network, (ii) the capacity and loss rate of each channel segment, (iii) the date and amount of irrigation for each farm plot and (iv) the crop pattern, and dates of sowing and harvest. Details of dates and amounts of irrigation inputs are derived from reference tables prepared by local government, or can be calculated by the FWM (see below). If the calculated daily discharge supplied is clearly in error (for example, if calculated discharge exceeds channel capacity), channel daily discharge is calculated again after the irrigation schedules have been adjusted.

B. Drain Reuse Module (DRM)

The DRM calculates the total amount of drainage-water from an irrigated area. The layout of the drainage channel network, amount of drainage and amount of reuse of drainage-water of each plot are the main input items to this module.

C. Spatial Water balance Module

The SWM is a quasi-three-dimensional water balance model that calculates the temporal and spatial variation of groundwater levels. Vertical movement of soil moisture in unsaturated zone is governed by Richards equation and horizontal water flow in saturated zone is governed by a differential equation in this module. Meteorology, irrigation schedule, landuse-crop spatial distribution, and the irrigation-drainage channel spatial distribution database are the main input items of this module. This module takes into account evapotranspiration from land areas that are uncropped (such as saline land) and the seepage loss from irrigation channels as factors that affect the water balance. The spatial distribution of seepage from channels is calculated using the channel daily discharge calculated by the WDM. Temporal and spatial variation of groundwater levels is used by the FWM as a lower boundary condition.

D. Farm Water balance Module

The FWM calculates the water balance of each plot (whether bare or fallow) with data inputs such as irrigation schedule, meteorology, crop calendar, soil character parameters, etc. An earlier vertical one-dimensional water balance must be incorporated into this module. In a test application described below, SWAP (Soil Water Atmosphere Plant) was used. Other models, as determined by data availability, can be used to provide the required simulation precision.

3. Application of IMPAM

Appling IMPAM to a lower part of a particular administration area of the Xile secondary channel (Figure 5), Yongji-Irrigation-District in the Hetao Irrigation area, and we simulated water balance changes under three simplified conditions: first, no channel is lined, second, tertiary channels are lined, and third, all channels are lined and no seepage from channel occurs in the area.

In the study area, two tertiary channels (Xile and Nanqu) and 59 quaternary-level channels were included (**Photo 1**) It is estimated that 60% of total water intake to the district is lost as seepage from irrigation channels. The physical structure of the channel system, the frequency and amount of irrigation, the irrigated crop area in the administration area and the water intake periods suggest that the Yongji-Irrigation-District abstracts water on the assumption that about 40% of the total intake will be lost in transmission. We assumed that the ratio of seepage loss to total water intake into the simulation area is about 30%, and in addition, that the loss rate per unit channel length is the same for all channel segments. Using the WDM, we estimated the loss rate per unit channel length to be $6.0 \times 10^{-5} m^3/m/s$, and then developed an assumed rotation pattern.

In the Hetao Irrigation District, irrigation is applied four to five times a year from May to October. The last irrigation is applied after the harvest at the end of September or the beginning of October, for the following year's crop, as water demand in spring is so high that sufficient water cannot be taken from the Yellow River.

Land cover was separated into two classes, cropland and non-cropland, on the basis of optical examination of ASTER satellite images (Figure 6). According to the Yongji-Irrigation-District Management Office (2002), cropland occupies about 72%, close to the result from satellite image classification. To simplify the simulations, it was assumed that the remaining 28% of the area was bare soil. Corn, wheat and sunflower are mainly cultivated in this irrigation district (**Photo 2**).

The period covered by the simulation was from April 21 to October 31 (194 days), and the area was segmented into 500 x 500-m grids for simulation with the SWM.

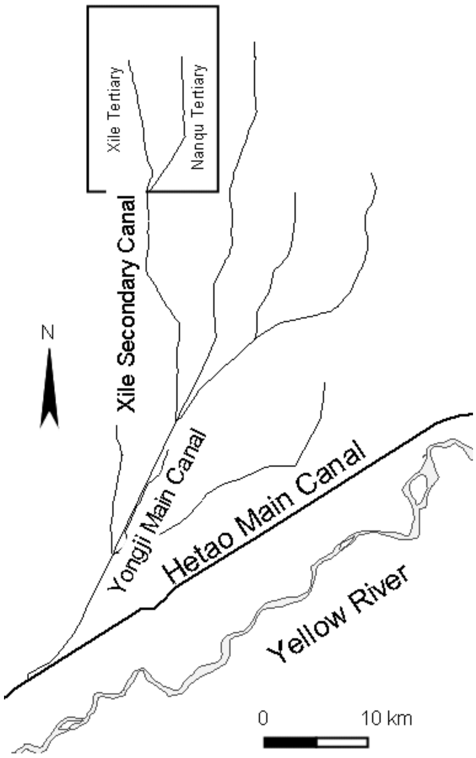

Figure 5. Simulation area

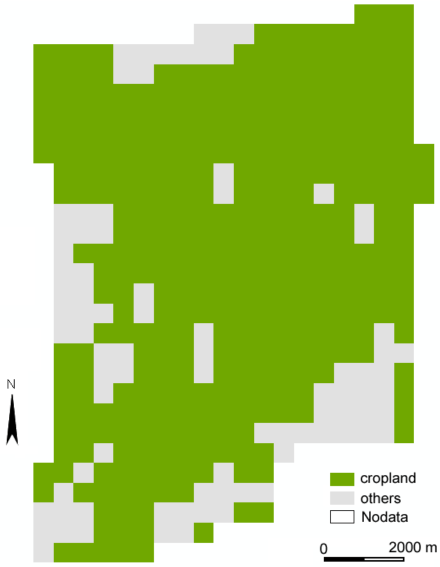

Figure 6. Land cover in the simulation area

Photo 2 Water gate on Yongji Main Canal from which Xile Secondary Canal takes off

Photo 1 Farmland in Yongji Irrigation District.

Simulation 1: Assuming 30% of total water intake is lost as seepage

In simulation 1, it is assumed that no channel is lined and 30% of intake water is infiltrates from channels into subsurface. This assumption about channel seepage is most close to an actual situation.

At the end of the simulation period, groundwater levels along the secondary and tertiary channels were found to be much higher than at the beginning (Figure 8), and waterlogging probably would have occurred in some areas. This suggests that the amount of water applied along the major channels should be reduced relative to other areas.

The fact that a large decline in groundwater level was seen mostly in uncropped areas (**Figure 6** and **7**) indicates that even in situations with soils of high hydraulic conductivity (2.5 x 10^{-6} m/s in the simulation area), horizontal water flow from irrigated cropland to neighboring non-irrigated land cannot be detected clearly in simulations if the horizontal spatial resolution is in the range of hundreds of meters.

Simulation 2: the secondary channels have no seepage loss

IMPAM-SWM was run assuming that the secondary and tertiary channels were completely lined, with a seepage rate of zero, and also assuming that the seepage rate from the tertiary channels was the same as in the first simulation (6.0 x $10^{-5}m^3$/m/s). The conditions for simulation 2 were the same as for simulation 1, except for differences in the loss rates of the tertiary channels. Though a decrease of transmission loss would permit a reduction in the period of rotation of irrigation, the same rotation pattern was used in simulations 1, 2 and 3 in order to evaluate the impact of physical changes in the channel system clearly.

This simulation suggested that lining secondary and tertiary channels might not produce a drastic change in the water balance (**Figures 7** and **8**). In the simulation area, seepage loss seems to occur mostly in the quaternary-level channels because of the rotation pattern. Amount of seepage loss depends on both time and length. As the capacity of each quaternary-level channel is limited, it takes a long time to distribute water to the entire irrigation area. Tertiary channels have water longer hours however total length of tertiary channels is much less than that of quaternary channels in this area. This fact suggests that capacity of quaternary channels should be increased or quaternary channels should be lined to decrease seepage losses effectively.

Simulation 3: no channel seepage loss

When we assumed that all secondary, tertiary and quaternary-level channels were completely lined and that no seepage occurs, the groundwater level was lower at the end of the simulation than at the beginning throughout the simulation area (**Figure 9**), and evapotranspiration was much less than in the case of simulations 1 and 2 (**Table 2**). To avoid reduction in crop yield from water stress, more irrigation water would have to be applied. This result suggests that reducing seepage loss may not always decrease the water intake for irrigation.

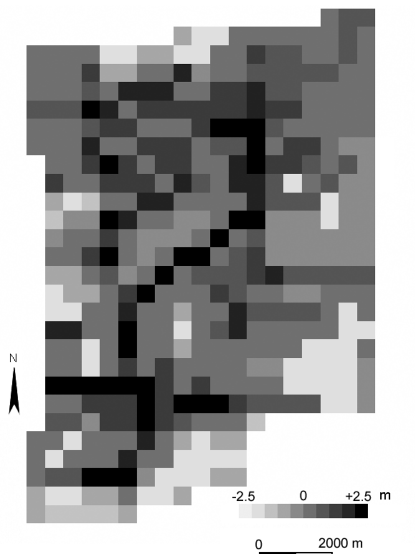

Figure 7. Changes in groundwater level (GWL) (GWL begin – GWL end) (no channel lining)

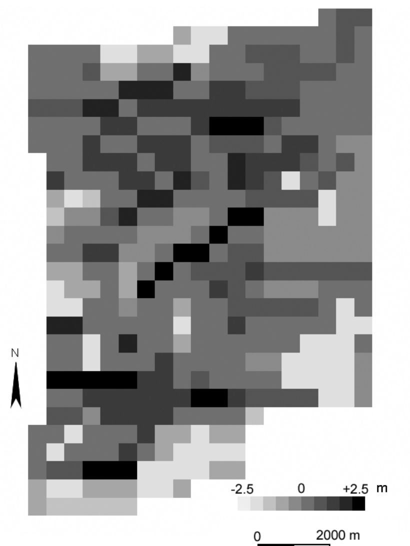

Figure 8. Changes in GWL (GWL begin – GWL end) (with lined secondary and tertiary channels)

Figure 9. Changes in GWL (GWL begin – GWL end)

Table 2. **Total evapotranspiration during the simulation period, averaged over the simulation area (mm)**

	Simulation 1	Simulation 2	Simulation 3
Canal conditions	No lining	Secondary and tertiary channels lined	All channels lined
ET (mm)	719	713	688

4. Conclusions

As shown in this paper, IMPAM can be used to estimate water balances under current management practices, and to simulate changes that would result from a proposed change in system management. IMPAM should be a useful tool for evaluating current irrigation management, and for considering how it should be modified. Now development of IMPAM is in progress. Calibration with observed data and information from management offices would improve this model.

Construction of a dam upstream on the Yellow River or modification of the channel system in the Hetao Irrigation District may change the peak of irrigation from autumn to spring. IMPAM can simulate water balance changes resulting from such changes in irrigation management.

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