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Research Report

The IIMI Water Balance Framework: A Model for Project Level Analysis

C.J. Perry

International Irrigation Management Institute

Research Reports

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C. J. Perry

International Irrigation Management Institute
PO Box 2075, Colombo, Sri Lanka

The author C. J. Perry is the Coordinator of Research at the International Irrigation Management Institute.

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Summary

The water balance for an irrigation project is a complex set of inflows, outflows, consumptive use, and recycling of water. When changes in cropping patterns, management regimes, or infrastructure are made, they disturb existing balances. The water balance must be fully understood to properly anticipate the chain of impacts resulting from interventions such as canal lining.

The IIMI water balance framework (IWBF), which is in Excel, is an easy-to-use computer model for analyzing the utilization of water from surface irrigation and rainfall within an irrigation project. The framework allows explicit definition of losses to seepage, operational losses, and efficiency of field application. Recycling of water through pumping from drains and from groundwater is allowed, and the resulting water balance is presented, showing flows to groundwater, outfalls from drains, and consumptive use of crops and other evaporative uses. The model permits a simple validity check of basic assumptions to ensure approximate internal consistency. Where such consistency cannot be demonstrated, either through this model or a more complex formulation, the impact of changes in management or infrastructure cannot be predicted.

The data on which the proposed water balance model is based are often reasonably well known or assumed to be known. Usually, losses in canals and watercourses have been measured, and amounts of rainfall and effective rainfall, water use by crops, and the volume of pumping from groundwater and drains are also known within reasonable limits. If these data are not known, and reasonable assumptions do not allow computation of a credible balance, the first priority in project design—or where interventions are planned—is additional study.

The model is based on a simple gross water balance. The elements of that balance include the most common set of known or assumed data for an irrigation system—canal inflows; operational, evaporative, and seepage losses; rainfall; crop consumptive use; and recycling of groundwater and drainage flows. The model has been constructed as a workbook (consisting of five worksheets) in Microsoft Excel version 5.

Even with sound field data, the IWBF may sometimes be inadequate to the type of analysis required—if precise accounting of the soil moisture status is needed, if lateral flows are significant, or if water quality issues are important. But in most cases, the level of detail and scope of analysis that the model provides will be sufficient to shed light on the interactions among the components of the water balance—for example, the relative importance of rainfall, surface deliveries and pumped supplies to crop consumption. In all cases, this model provides a convenient initial analytical approach.

The IWBF accounts for two *inflows* of water (surface-delivered supplies and rainfall), four *outflows* (crop evapotranspiration, nonbeneficial evaporation/evapotranspiration, drainage runoff, and net flows to groundwater). These elements are interlinked through seepage from channels and irrigated fields, the disposition of rainfall between runoff, infiltration, and evapotranspiration, and two modes of *transfer* (pumping from groundwater and pumping from drains).

The user must consider the appropriate level of disaggregation, spatially and temporally. Considerations include the purpose of the analysis, selection of physically appropriate boundaries, and avoidance of significant “boundary” effects by choosing the right scale for the analysis.

A single irrigation project may be taken as a whole. But in a large project where deliveries, cropping patterns, or groundwater conditions vary, it may be appropriate to disaggregate the project into distinct areas. Similarly, it is usually appropriate to separate seasons if rainfall and cropping patterns differ sharply from one season to the next. The IWBF allows simultaneous analysis of three agricultural seasons, with different data for each season (except, of course, project size). The model then produces individual seasonal analyses as well as summary tables for the year.

For each season, the model produces a set of three tables. The first traces the flow of water to the field as irrigation water is delivered via canals and watercourses; it also traces associated flows to groundwater and drains. At the field level, rainfall is integrated into the supplies, together with water pumped from drains and groundwater to compute the basic water balance. The second table shows the sources, and disposition of water in both depth terms (as is commonly used for reporting consumptive use and rainfall) and volume terms (as is commonly used for reporting flows). The third table summarizes sources and uses of water. A separate set of three tables consolidates the seasonal data on an annual basis.

This report includes documentation of the underlying formulas in the worksheet on which the analysis is based and gives a simple example of employing the model to examine the impact of an investment in improved infrastructure.

The analysis provided by the IWBF is of primary interest to those involved in designing irrigation projects, formulating improvements to existing infrastructure, or revising operational rules. Managers of irrigation projects will also find the analysis useful as a basis for interpreting issues such as water use efficiency and identifying the primary causes and effects of water imbalances—long-term rises and falls in the water table.

The IIMI Water Balance Framework: A Model for Project Level Analysis

C. J. Perry

Introduction

Understanding the water balance at project or command level is a prerequisite to analyzing the operation of an irrigation system and its performance. The relationship between various sources of water (rainfall, canal supplies, and pumping from groundwater and drains), and uses (crop consumption, drainage outflows, and rises or falls in the water table) are complex, and sometimes counterintuitive.

Interventions in one aspect of system infrastructure or operation will usually have impacts beyond the direct, "first round" effect. All too frequently, proposed interventions that will significantly affect the components of the water balance—lining canals, expanding conjunctive use, changing canal schedules, or introducing drainage systems or new cropping patterns—are considered or implemented without analysis of the water balance and the likely effects of the intervention.

Similarly, irrigation is described as "inefficient" at the field or project level, while virtually no water leaves the river basin because "losses" in one place are recaptured, and consumed, downstream. A proper understanding of the water balance, which identifies sources, uses, and reuses of water, will clarify such situations.

Such an analysis is of primary interest to those involved in the design of irrigation projects or in the formulation of improvements to existing infrastructure or operational rules. Managers of irrigation projects will also find the analysis useful for interpreting issues such as water use efficiency and identifying the management or investment interventions to improve efficiency or influence the sustainability of their projects by controlling undesirable trends in the water table.

The appropriate degree of sophistication in formulating a water balance depends on the purpose of the analysis and on the complexity of the system. If the purpose is to design a groundwater control system or a flood disposal system or to understand the effects of surface water quality and quantity and soil salinity and sodicity, detailed and specialized modeling may be required.

The model proposed here, the IIMI Water Balance Framework (IWBF), is based on a simple gross water balance. The elements of that balance include the most common set of known or assumed data for an irrigation system—canal inflows; operational, evaporative and seepage losses; rainfall; crop consumptive use; and recycling of groundwater and drainage flows. The model has been constructed in Microsoft Excel version 5 as a workbook consisting of five worksheets (see Annex A).

The framework presented here is not designed to meet specialist needs. Rather it is intended for more general or diagnostic purposes including:

- understanding and quantifying the main factors in the water balance
- identifying linkages between sources, uses, and reuses
- estimating project water consumption as a basis for defining actual losses, the efficiency of water use, and the productivity of water

- analyzing the potential impact of interventions

This simple gross balance approach also provides insights into related issues such as salinity. Another paper in this series (Kijne 1996) addresses the issue of the sustainable irrigated area under known conditions of water quality, using information generated by the IWBF. It is important to note that when the available data and assumptions for a project fail to produce a credible balance within the IWBF, understanding of the water balance is limited, and interventions should be delayed until better information is found. At a minimum, application of this model will identify parameters that should be investigated in more detail.

The IWBF differs from CROPWAT (Smith 1992), CRIWAR (Bos, Vos, and Feddes 1996), and the CERES series,[1] which compute crop water consumption at plant, field, and project levels, as well as appropriate irrigation scheduling. CROPWAT and CERES also have yield prediction options. These models produce information that is one element of the project-level water balance, namely, seasonal crop demand.

Other models, such as SHE[2] and the various HEC models,[3] provide analysts with a far more powerful array of tools than is available in the IWBF. They address the timing of interactions among elements in the hydrological system at the water basin level, water quality, and many other issues. But the data requirements, computational power, and training needs are correspondingly more complex. Often, the IWBF will provide initial insights that the analyst may judge adequate to fulfill the intended purpose. Where the IWBF falls short, its purpose, which is first to encourage analysts to actually attempt to derive water balance, will have been fully achieved if the analyst is persuaded to move on to a higher-order model.

Conceptualization of the IIMI Water Balance Framework

The IWBF accounts for two *inflows* of water (canal-delivered supplies and rainfall), four *outflows* (crop evapotranspiration, nonbeneficial evaporation / evapotranspiration, drainage runoff, and net flows to groundwater). These elements are interlinked through seepage from channels and irrigated fields; the disposition of rainfall among runoff, infiltration, and evapotranspiration; and two modes of *transfer* (pumping from groundwater and pumping from drains).

In total, there are 11 elements in the system, each with potential linkages to the other 10. For example, rainfall on irrigated land can contribute to crop consumption, nonbeneficial evapotranspiration (NBET), flows to groundwater, and runoff to drains. The runoff to drains can, in turn, be pumped back for further irrigation, partially lost to groundwater, and pumped again for irrigation from groundwater. In the Excel workbook, the user specifies each interaction in the most commonly used terms (percentage of losses from canals, effective rainfall percentage, etc.) and can thus include or exclude any interaction.

The model evaluates 31 of the possible interactions. Figure 1 shows the 31 interactions with the source identified in the left column and the destination or use in the row heading.

[1] For example, Jones and Kinry 1986.

[2] Système Hydrologique Européen—see Abbott et al. 1986.

[3] United States Corps of Engineers, Haestad Methods Civil Engineering Software, Waterbury, Connecticut, USA.

FIGURE 1.
The 31 components of the IWBF.

To: From:	Canal	Water-course	Drain	Field	Crop	Rain on irrigated area	Rain on unirrigated area	Ground-water	NBET	Pump (ground-water)	Pump (drain)
Canal		1	2	—	—	—	—	3	4	—	—
Watercourse	—		—	5	—	—	—	6	7	—	—
Drain	—	—		—	—	—	—	8	9	—	10
Field	—	—	11		12	—	—	13	14	—	—
Crop	—	—	—	—		—	—	—	—	—	—
Rain on irrigated area	—	—	15	—	16		—	17	18	—	—
Rain on unirrigated area	—	—	19	—	—	—		20	21	—	—
Groundwater	—	—	22	—	—	—	—		—	23	—
NBET	—	—	—	—	—	—	—	—		—	—
Pump (groundwater)	—	—	24	—	25	—	—	26	27		—
Pump (drain)	—	—	28	—	29	—	—	30	31	—	

Application of the IWBF—A Worked Example

This section describes the approach the model takes, allowing potential users to judge the extent to which it will meet specific needs, and explains how to apply the model (annex B contains cell-by-cell definitions of the formulas in the IWBF).

The user must first decide the appropriate spatial and temporal parameters. Considerations include the purpose of the analysis, the selection of physically appropriate boundaries, and ensuring that the scale chosen for the analysis is consistent with avoiding significant "boundary" effects.

A single large irrigation project may be taken as a whole. But in a large project where deliveries, cropping patterns, or groundwater conditions vary, it may be appropriate to disaggregate the project into distinct areas. Similarly, it is usually appropriate to separate seasons if rainfall and cropping patterns vary sharply. The IWBF allows simultaneous analysis of three seasons, with different data for each season (except, of course, project size). The model then produces individual seasonal analyses as well as summary tables for the year.

For ease of exposition, the following description traces the data and analysis for a single season.

Data are entered by the user into the data block (fig. 2). The gray cells are those into which data can be entered. All cells except those into which data are entered are locked to prevent accidental erasure or modification. Figure 2 includes a sample set of data, presented as a basis for describing the analysis.

The data analyzed represent conditions in the fresh groundwater areas of the Indo-Gangetic plains of northern India for the winter season. Surface water is adequate for only about 30 percent of the command, and groundwater use is significant. The project area is 10,000 hectares, with seasonal rainfall of 100 millimeters and surface supplies equivalent to 300 millimeters over the entire command.

FIGURE 2.
The data worksheet with data entered for one season.

	B	C	D	E	F	G	H
2	Title			Winter			Total
3	Area	ha	10,000			10,000	project area
4	Irrigation intensity	%	55			55	irrigated cropping intensity
5	Canal inflow	000 m^3	30,000			30,000	surface water supply
6	Operational losses	%	10			10	canal inflows surplused to escapes
7	Canal seepage	%	25			25	canal inflow lost to seepage in canals
8	Watercourse seepage	%	27			27	inflows lost to seepage in watercourses
9	Field efficiency (surface)	%	70			70	field deliveries from watercourses used by crop
10	Irrigation losses to runoff	%	10			10	field losses going to drainage
11	Drain seepage	%	10			10	drain flows lost to seepage
12	Losses to NBET	%	30			30	losses (except runoff) going to NBET
13	Rainfall	mm	100			100	rainfall
14	Effective rain (irrigated)	%	70			70	rainfall used by crop
15	Effective rain (unirrigated)	%	50			50	rainfall on unirrigated area to evapotranspiration
16	Rain to runoff	%	20			20	noneffective rainfall going to drains
17	Pump recovery (groundwater)	%	110			110	flows to groundwater recovered through pumping
18	Pump recovery (drains)	%	10			10	flows to drains recovered through pumping
19	Field efficiency (pump)	%	80			80	pumped field deliveries used by crop

In defining the data, the common terminology for “losses” is used, partly because these are terms and data with which field practitioners are familiar. The important ongoing redefinition of these terms, either as components of effective efficiency (Keller and Keller 1995) or as consumed, recoverable and nonrecoverable fractions (Willardson, Allen, and Frederiksen 1994) helps to clarify the interactions specified here, and in turn, the analysis produced by the IWBF provides a clear basis for identifying the components of these redefined concepts of efficiency. In the descriptions that follow, traditional terminology is used. Thus canal seepage is described as a loss, although the model allows recapture of such losses through groundwater pumping. The data may be summarized as follows:

Cell D2 ***Title***

Used to designate the project, season, or other information.

Cell D3 ***Area***

The physical command area of the project (or subproject)—the maximum area that could be irrigated in a season in the absence of constraints on water or other inputs.

Cell D4 ***Irrigation intensity***

The proportion of the *area* that is irrigated from surface water or groundwater, or both, in the period under analysis. The irrigated area is equal to the *area* multiplied by *irrigation intensity*. Taking the data in figure 2 as an example, the irrigated crop area for the season would be 5,500 hectares (10,000 * 55%). No differentiation should be made between area irrigated from surface water and area irrigated through pumping from groundwater or drains.

Cell D5 ***Canal inflow***

Surface water delivery at the canal head for the period of analysis (season, year, etc.) in thousands of cubic meters. Note that surface deliveries may be pumped from a river or other source. However, elsewhere in the model, “pumped” supplies refer to internal recycling of flows from groundwater and drains.

Cell D6 ***Operational losses***

The proportion of *canal inflow* that is released through escapes,[4] and hence to drains, expressed as a percentage of canal inflow. These losses are assumed to occur at the canal level, not in watercourses. If such losses also occur at the watercourse level, they should be included in the estimate of operational losses for canals. Losses at the watercourse level may be recaptured through pumping from drains.

Cell D7 ***Canal seepage***

The proportion of *canal inflow* that goes to seepage. Such losses may be recovered through pumping from groundwater.

Cell D8 ***Watercourse seepage***

The proportion of watercourse inflow that is lost to seepage. Such losses may be recovered through pumping from groundwater.

Cell D9 ***Field efficiency (surface)***

The proportion of water arriving at the field from canals that is used in evapotranspiration in the course of the growth of the crop. Conventionally, this value includes evaporation of moisture from the wetted field surface.

Cell D10 ***Irrigation losses to runoff***

The proportion of field losses that goes to drains. This value is different from rainfall-related runoff (Cell D16), and will depend on the irrigation technology. It may often be zero in water-short commands with less than 100 percent irrigation intensity.

Cell D11 ***Drain seepage***

The proportion of flows in drains lost to seepage. This value may be different from the value used for canal or watercourse seepage. Drains are usually low-lying and often in areas with a relatively high water table, tending to reduce seepage. Nonbeneficial evapotranspiration from rainfall on unirrigated land is accounted for separately (see below).

Cell D12 ***Losses to NBET***

The proportion of seepage and field losses that is evaporated by weeds or trees or directly from the surface, excluding those evaporation losses that are conventionally accounted (in programs such as CROPWAT) as part of crop demand. Residual losses go to groundwater (surface runoff is already accounted for through D10).

Cell D13 ***Rainfall***

Total depth of rain during the analysis period.

Cell D14 ***Effective rain (irrigated)***

The percentage of rain falling on irrigated land that is used for crop transpiration. That portion of the rainfall that is not used by the crop goes to runoff, NBET (from weeds, trees along canals, or evaporation directly from the surface), or groundwater in accordance with specified ratios.

Cell D15 ***Effective rain (unirrigated)***

The proportion of rain falling on unirrigated land that is lost through evapotranspiration. This value may be different from the corresponding value for the irrigated area. If no rain-fed cropping is practiced, this rainfall will be entirely nonbeneficial (which is how it is accounted for in the model).

Cell D16 ***Rain to runoff***

The proportion of rainfall that is not used by the irrigated crop and goes to surface drainage as runoff.

Cell D17 ***Pump recovery (groundwater)***

The proportion of surface and rainfall losses to groundwater that is recovered through pumping. If the value in cell

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[4] This occurs when, for example, rainfall causes a sharp fall in demand for irrigation water.

D17 is set to 100 percent, the water table will remain at a constant level. Setting it at less than 100 percent results in a drainable surplus to groundwater and a rising water table. The estimated value will depend upon water quality, installed capacity, and aquifer conditions. If the volume of pumping is known (from survey data or estimates), the value given in D17 can be adjusted so that the computed volume matches the known volume.

Cell D18 ***Pump recovery (drains)***

The proportion of surface and rainfall runoff to drains that is recovered through pumping. If the volume of such pumping is known (from survey data or estimates), the value in D18 can be adjusted so that the computed volume matches the known volume.

Cell D19 ***Field efficiency (pump)***

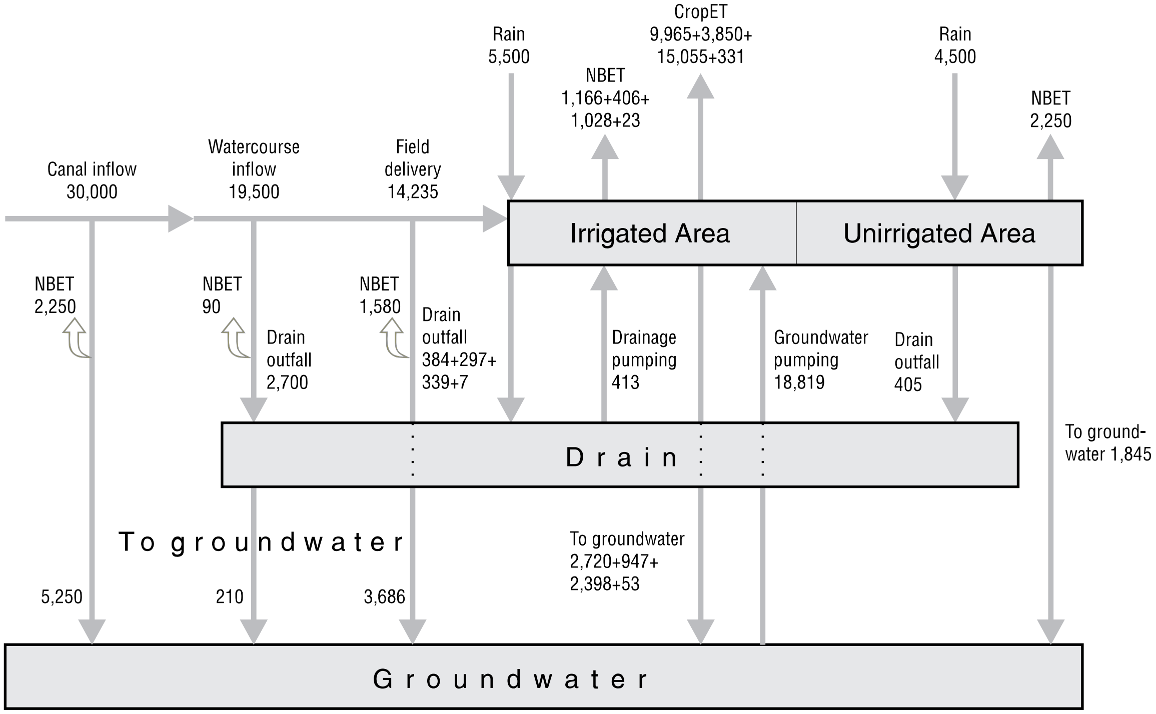
The proportion of deliveries from pumping of groundwater and drain pumping that is used by the irrigated crop. The residual is lost to NBET (from weeds, trees along canals, or evaporation directly from the surface) or to groundwater in accordance with specified ratios. These losses may differ from the corresponding value for surface deliveries because of the better control of the latter.

Figure 3 shows one of the three seasonal worksheets containing the water balance values computed on the basis of the data shown in the data block (fig 2). Figure 4 is a schematic flow diagram of the results shown in figure 3.

FIGURE 3.
Portion of a worksheet showing the water balance computed from data in the data block worksheet.

	Season: Winter Table 1: Water balance	Surface water	Rainfall			Pumping	
			Irrigated	Unirrigated	Total	Groundwater	Drains
					000 m^3		
25	CANAL INFLOW	**30,000**					
26	*Operational losses*	3,000					
27	Drain outfall	2,700					
28	NBET	90					
29	To groundwater	210					
30							
31	*Seepage*	7,500					
32	NBET	2,250					
33	To groundwater	5,250					
34							
35	WATERCOURSE INFLOW	**19,500**					
36	*Seepage*	5,265					
37	NBET	1,580					
38	To groundwater	3,686					
39							
40	FIELD DELIVERY	**14,235**	**5,500**	**4,500**	**10,000**	**18,819**	**413**
41	*Crop use*	9,965	3,850		3,850	15,055	331
42	*Losses*	4,271	1,650		6,150	3,764	83
43	Drain outfall	384	297	405	702	339	7
44	NBET	1,166	406	2,250	2,656	1,028	23
45	To groundwater	2,720	947	1,845	2,792	2,398	53

FIGURE 4.
Schematic flow diagram of the water balance shown in figure 3.



Calculations

Canal inflows are traced through canals and watercourses to the field. The losses specified in the data block are accounted for at each stage. In the example (fig. 3), operational losses to drains (cell D26) are 10 percent (cell D6) of canal inflows.[5] Seepage losses from drains (D11) are 10 percent, so that the net flow in the drain is 2,700,000 cubic meters (D27). Of the 300,000 cubic meters of seepage losses from drains, 30 percent (D12) goes to NBET (D28), with the residual going to groundwater.

Canals lose 25 percent of inflows to seepage (from cell D7), which is further allocated between NBET and water going to groundwater. The residual canal flow (30,000,000 – 3,000,000 – 7,500,000 = 19,500,000 m^3) arrives at the watercourse level, and further seepage losses within the watercourse are computed and allocated to arrive at the final delivery of surface supplies to the field level (D40).

At the field level, the calculations become more complex because supplies to the field come from watercourses (D40), as outlined above, rainfall (E40 and F40), and pumping from groundwater and drains (H40 and I40, respectively).

Rainfall on irrigated land contributes to crop use (cell E41, based on cell D14), the residual going to runoff (E43) and NBET (E44) in accordance with the ratios specified in the data block (D16 and D12, respectively), with the residual going to groundwater (E45).

[5] Cells numbered from 2 to 19 are shown in the table in figure 2, and cells numbered from 25 to 45 are shown in the table in figure 3.

FIGURE 5.

Portion of a worksheet showing sources and allocation of water.

	B	C	D	E	F	G	H	I
	Season: Winter Table 2: Sources and allocation by area		Command	Irrigated	Unirrigated	Command	Irrigated	Unirrigated
				000 m^3			mm	
50	SOURCES							
51	Diversion		30,000	22,906	7,094	300	416	158
52	Rainfall		10,000	5,500	4,500	100	100	100
53		Total	40,000	28,406	11,594	400	516	258
54	ALLOCATION							
55	*Net drain outfall*		*3,719*			*37*		
56		From surface	3,365			34		
57		From rain	768			8		
58		Drainage pumping	-413			-4		
59								
60	*Crop use*		*29,200*	*29,200*		*292*	*531*	
61		From surface	9,965	9,965		100	181	
62		From rain	3,850	3,850		39	70	
63		From groundwater pumping	15,055	15,055		151	274	
64		From drainage pumping	331	331		3	6	
65								
66	*Nonbeneficial ET*		*8,791*	*4,778*	*4,014*	*88*	*87*	*89*
67		From surface	5,085	3,322	1,764	51	60	*39*
68		From rain	2,656	406	2,250	27	7	50
69		From groundwater pumping	1,028	1,028		10	19	
70		From drainage pumping	23	23		0	0	
71								
72	*To groundwater*		*-1,711*	*-7,671*	*5,960*	*-17*	*-139*	*132*
73		From surface	13,850	9,734	4,115	119	141	91
74		From rain	3,259	1,414	1,845	28	17	41
75		Groundwater pumping	-18,819	-18,819		-164	-299	
76	*Leaching fraction at field (%)*		*19*	*16*				

Rain falling on unirrigated land does not contribute directly to irrigated crop use.[6] It goes to NBET (F44, based on the proportion specified in D12), to drainage (F43, based on D16), or to groundwater (F45).

Pumping allows transfer of water from drains and groundwater to irrigated cropping in accordance with the recovery percentages specified in the data block for each. The amount of water available for this is computed from the various relevant sources—for example, water going to groundwater is the total of those components of canal (D33), drain (D29), and watercourse (D38) seepage that go to groundwater, plus the calculated proportions of field losses (D45) and rainfall infiltration (G45) going to groundwater.

Calculations of field delivery from groundwater and drainage pumping (H40, I40) are the sum of a converging series—water is recovered from groundwater and applied to the field, and losses from this irrigation application further contribute to groundwater.

The water balance table (fig. 3) is further disaggregated in figure 5, which shows sources and disposition of water, calculated separately for the irrigated and unirrigated areas. The data are presented both in volume measures and in depth measures because analysts tend to think in terms of volumes for deliveries of water and drainage outflows and in terms of depths for consumption and rainfall.

Allocation of rainfall between irrigated and unirrigated areas is based on the pro-

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[6] But it may of course be utilized by unirrigated crops through the coefficient for effective rainfall (unirrigated), specified in the data block (fig. 2).

FIGURE 6.
Portion of a worksheet giving a summary breakdown.

	B	C	D	E	F	G	H	I
	Season: Winter		Crop Consumptive Use					
	Table 3: Summary		Direct	Pumped	Total	Drain	NBET	Groundwater
81	Diversion (000 m^3)		9,965	12,457	22,421	3,028	5,935	-1,385
82	Rain (000 m^3)		3,850	2,929	6,779	691	2,856	-326
83	Total		13,815	15,386	29,200	3,719	8,791	-1,711
84	Diversion (%)		25	31	56	8	15	-3
85	Rain (%)		10	7	17	2	7	-1
86	Total		35	38	73	9	22	-4

portion of the area irrigated. In the case of diversions, the allocation of water is based on the assumption that canals and watercourses run through all areas, so that seepage losses are distributed in proportion to the irrigated and unirrigated areas. Calculations related to field losses and pumped deliveries are confined to the irrigated area.

The leaching fraction (D76 and E76 in fig. 5) is defined as the proportion of total water entering the soil profile that goes to groundwater. The calculation is made at the field level, ignoring seepage from canals, watercourses and drains, which is localized and does not affect the salt balance in the root zone. Although the model includes no analysis of water quality (which is fundamental to determining an appropriate value for the learning fraction) users can see the source of each component of recharge and of field application (from rain, surface, or pumping). Thus they can calculate, to the extent that data are available, the likely quality of the irrigation water applied and hence estimate the adequacy of the computed leaching fraction.

The table shown in figure 6 summarizes this information to provide a quick reference of what water goes where.

Discussion

The information presented in figures 3 and 5 can be compared with other calculations and information available about conditions in the field (for example, whether the water table is rising, whether drains are frequently full, etc.). Particular points of reference are:

- Calculated crop consumption (fig. 5, cell H60, 531 mm) should be compared with calculated consumptive use from a program such as CROPWAT.
- Calculated value for effective rainfall (fig. 5, D62 and G62) should also be consistent with results from CROPWAT.
- Net flows to groundwater (fig. 5, D72 and G72) should be consistent with observations of the water table—these results show net withdrawals of 124 mm/season for the irrigated area (H72); net recharge of 132 mm/season for the unirrigated area (I72) and near balance (17 mm overdraft, G72) for the entire command.

If field observations deviate substantially from results from the model, further refinement of the input data is needed. The model also provides a convenient framework for testing the sensitivity of results to changes in assumptions and for identifying the most sensitive linkages.

The calculated crop consumption of 531 millimeters is consistent with climatic data for a crop season of 130 to 140 days—pan evaporation varies from 3 to 5 mm/day during the winter months. The calculated groundwater balance for the area, where it is known that the water table is stable or declining, is also reasonable.

The summary table in figure 6 shows the relative importance of various water sources in crop consumptive use. Rainfall, for example, is much less important than pumped water, and almost 10 percent of available water is lost to surface runoff (comparing cell G83 with total availability, cell D53, fig. 5), indicating the scope for expanded use of this source—perhaps through artificial recharge to replenish groundwater. Recycled surface deliveries (E81) contribute significantly more to crop consumption than direct deliveries (D81).

Availability of Data and Related Analytical Issues

An approximate estimate of the water balance is a powerful tool. The data required for the analysis presented above are close to the minimum set that can be expected to provide meaningful results—indeed this was an objective in designing the IWBF. Nevertheless, several items may prove difficult to obtain or estimate. In particular, the proportions of rainfall going to consumptive use, runoff, and groundwater are difficult to assess with precision, and the extent of groundwater pumping is often poorly documented. Even in areas where power supplies to wells are metered, the dynamic interaction between pumping, local “coning” of the water table, and the relationship between power consumption and the volume of water pumped is complex. Similarly, where hours of operation are measured, the rate of delivery may vary significantly over time. In such cases, the solution is generally to be found through successive iterations around reasonable estimates. If users know how many wells there are in an area and have indications of pump size distribution and usage, then they can estimate the reasonable range of pumping and its relationship to canal deliveries.

Because consumptive use of the crop is the value analysts tend to spend most time calculating, it is the value we often know best. And we know it cannot be greater than seasonal evapotranspiration nor much less than 60 percent of seasonal evapotranspiration if the crop matures. Analysts also have a reasonable fix on effective rainfall, which cannot exceed crop evapotranspiration and must, together with the quantity of water delivered to the field through irrigation, equal or exceed the value for evapotranspiration.

With this basic data defined within known ranges, coming to a realistic water balance is not an insurmountable task, even though some of the initial estimates may be little more than informed guesses. The very nature of the system and the fact that it is a balance analysts are seeking ensure that the model has to “close” on a consistent and reasonable set of data. Where “known” data cannot be brought together within this framework, it is clear that some of the data will need to be reassessed. The power of the model is that it identifies these issues, points to the areas where uncertainties are real and important, and sometimes simply forces the analyst to move to a more sophisticated model. Such results are far preferable to continued intervention and investment without knowledge.

A number of issues will always need careful, location-specific, and perhaps season-specific, attention. Canal losses are a good example: It is assumed in the model that losses are a (specified) proportion of flows. Often, losses may be more dependent on the duration of flow than the rate, and losses will be a far higher proportion of low flows (for example while deliveries are made for domestic uses). Such attention to detail is important for assessing "efficiency" of deliveries at different times of the year. In such cases, the loss percentage can be varied by season and even selected to achieve a specific volume of losses.

A further difficult issue is assigning runoff to irrigation or rainfall (in other words, does one assume that it rained just after an irrigation, and thus the rain goes to the drains, that it rained during an irrigation, so that a mixture goes to the drains, or that it rained just before an irrigation, so that irrigation water goes to the drains?). One view[7] is that since the irrigation water is the additional input, incremental flows to drains should be charged to irrigation (in)efficiency. The model as formulated follows the middle course described above, which may fail the test of intellectual rigor, but has the advantage of recognizing the likely physical composition of the water (since over time, it will sometimes be rain, sometimes irrigation, and sometimes a mixture that goes to drains). This then allows consideration of the quality of water going to the water table and to drains.

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[7] Harald Frederiksen—personal communication.

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ANNEX A

Notes on the Use of the IWBF

General

It is assumed here that the user is familiar with or has access to the manual for Microsoft Excel. Words in italics in this annex are explained in the Excel manuals. The model is available in formats for Excel version 5 and does not readily translate into other software application because extensive use has been made of multiple *worksheets* in a single *workbook*—a feature that does not translate. The workbook occupies about 100 kilobytes of disk space. Where large numbers of situations are to be analyzed, it may be worth creating *linked* data sheets, which would each occupy only a few kilobytes, referencing the data sheet from the data cells in the main sheet. The *workbook* consists of five *worksheets*—Data, Season 1, Season 2, Season 3, and Total.

Data Entry and Protection

Data may only be entered in the Data *worksheet*. The *workbook* is *protected* so that the user can only enter information into the shaded data cells. However, there is no *password*, so the user can readily *unprotect* the worksheets to see and modify formulas, but it is strongly recommended that this not be done in normal use. It is easy to accidentally erase or modify a cell, generating spurious results. On the other hand, password protection has been deliberately excluded to allow users to modify the worksheets for specific uses where the present formulation is unsuitable, to create *linked* worksheets, as suggested above to conserve disk space, or to make use of the logic of this model for other purposes. It is recommended that any alternative or additional calculations be done by creating additional *worksheets* within the present *workbook* (or separate, *linked* worksheets) so that the integrity of the present model is preserved.

Linkage to External Calculations

It may often be convenient to use this framework as part of a larger water balance (for example where there are significant additional components in the water balance, such as deliveries and withdrawals for nonagricultural uses). It is relatively easy for an experienced user of Excel to link such flows into the model, generating the associated impacts on groundwater, canal losses, etc., while maintaining the integrity of the underlying analytical framework.

ANNEX B

Documentation of the Model

The analysis is documented by defining range names that are applied to the cells in the worksheet, corresponding to the names in the data block. Thus, for example, wherever cell D7 is referenced, this is replaced by Canal_seepage. Formulas thus are of the form:

Canal_inflow (1-Canal_seepage-Operational_losses).*

This translates to=*D5*(1–D7–D6)* in the underlying worksheet. The disk version of the worksheet is in the conventional format, making it considerably smaller and faster.

FIGURE B.1.
Formulas in the worksheet.

	B C	D	E	F	G	H	I
	Season	Surface	Rainfall			Pumping	
	Table 1: Water balance	water	Irrigated	Unirrigated	Total		
			000 m³			Groundwater	Drains
25	**Canal inflow**	**Canal_inflow**					
26	*Operational losses*	*Operational_losses * Canal_inflow*					
27	Drain outfall	D26 * (1 - Drain_seepage)					
28	NBET	(D26 - D27) * (Losses_to_NBET)					
29	To groundwater	(D26 - D27) * (1 - Losses_to_NBET)					
30							
31	*Seepage*	*(Canal_inflow * Canal_seepage)*					
32	NBET	(Canal_inflow * Canal_seepage) * Losses_to_NBET					
33	To groundwater	Canal_seepage * Canal_inflow (1 - Losses_to_NBET)					
34							
35	**Watercourse inflow**	**Canal_inflow * (1 - Canal-seepage - Operational_losses)**					
36	*Seepage*	*D35 * Watercourse_seepage*					
37	NBET	D35 * Watercourse_seepage *					
38	To groundwater	D35 * Watercourse_seepage * (1 - Losses_to_NBET)					
39							
40	Field delivery	D35 * (1 - Watercourse_seepage)	Area * Rainfall * Irrigation_intensity/100	Area * Rainfall (1- Irrigation_intensity/100	Area * Rainfall/100	D1 * Pump_recovery__groundwater* H1 *Pump_recovery__groundwater* (D1 *Pump_recovery__groundwater + F1 *Pump_recovery__drains)/(1-)H1* Pump_recovery__groundwater + I1* Pump_recovery__drains))	F1 *Pump_recovery__drains+I1* Pump_recovery__drains * (D1* Pump_recovery__groundwater + F1* Pump_recovery__drains)/(1-(H1* Pump_recovery__groundwater + I1* Pump_recovery__drains))
41	*Crop use*	*D40 * Field_efficiency__surface*	*G40 * Irrigation_intensity * Effective_rain__irrigated*		*G40 * Irrigation_intensity *Effective_rain__irrigated*	*Field-efficiency__pump * H40*	*Field-efficiency__pump * 140*
42	*Losses*	*D40 * (1 - Field_efficiency__surface)*	*E40 _ E41*		*G40 - G41*	*H40 - H41*	*140 - 141*
43	Drain outfall	D40 * (1 - Field_efficiency__surface)* Irrigation_losses_to-runoff * (1 - Drain_seepage)	E40 * (1 - Effective_rain__irrigated)* Rain_to_runoff * (1 - Drain_seepage)	F40* (1 - Effective_rain_unirrigated) *Rain_to_runoff* (1 - Drain__seepage)	E43 + F43	H40* (1 - Field_efficiency__pump)* Irrigation_losses_to_runoff * (1 - Drain_seepage)	140* (1 - Field_efficiency__Pump)* Irrigation_losses_to_runoff * (1 - Drain_seepage)
44	NBET	(D40 - D41 - D43) * Losses_to_NBET	(E40 - E41 - E43) * Losses_to_NBET	F40 * (Effective_rain__unirrigated)	E44 + F44	(H40 - H41 - H43) * Losses_to_NBET	(140 - 141 - 143) * Losses_to_NBET
45	To groundwater	(D40 - D41 - D43) * (1 - Losses_to_NBET)	(E40 - E41 - E43) * (1 - Losses_to_NBET)	F40 - F43 - F44	E45 + F45	(H40 - H41 - H43 - H44)	140 - 141 - 144 - 143

ANNEX C

The Impact of Watercourse Lining on Cropping Intensity

The following example demonstrates a simple application of the model, starting from the data already presented in the body of this report (fig. 2, 3, and 6). The analysis focuses on a single change to the data input—reduction in seepage losses from watercourses as a result of lining.

The originally assumed watercourse seepage loss is reduced from 27 percent (fig. 2) to 5 percent. The impact of this change, among other things, is to increase the computed value of consumptive use to 545 millimeters, compared with 531 millimeters in the original calculation (fig. 5). Clearly, if the original 531 millimeters is consistent with computed crop needs, there would be an opportunity to increase the cropped area after lining the watercourses. The potential impact can readily be assessed by experimenting with different values of irrigation intensity.[8] Increasing this value from 55 percent to 56 percent reduces consumptive use to 536 millimeters, and a further increase of irrigation intensity to 57 percent reduces consumptive use to 527 millimeters (fig. C.1). We can therefore estimate that the increase in irrigation intensity permitted by the lining program is less than 4 percent . That is a small increase given the very substantial reduction in “losses” from watercourse seepage—from 27 percent to only 5 percent. The explanation, of course, lies in groundwater use, which captures most of the “losses” for reuse.

FIGURE C.1.
Water balance based on a watercourse seepage of 5 percent and irrigation intensity of 55 percent.

Season: Winter Table 2: Sources and allocation by area	Command	Irrigated	Unirrigated	Command	Irrigated	Unirrigated
	000 m³			mm		
SOURCES						
Diversion	30,000	25,066	4,934	300	440	115
Rainfall	10,000	5,700	4,300	100	100	100
Total	40,000	30,766	9,234	400	540	215
ALLOCATION						
Net drain outfall	*3,771*			*38*		
From surface	3,430			34		
From rain	760			8		
Drainage pumping	-419			-4		
Crop use	*30,066*	*30,066*		*301*	*527*	
From surface	12,968			130	228	
From rain	3,990			40	70	
From groundwater pumping	12,773	12,773		128	224	
From drainage pumping	335	335		3	6	
NBET	*7,615*	*4,333*	*3,282*	*76*	*76*	*76*
From surface	4,150	3,018	1,132	41	53	26
From rain	2,571	421	2,150	26	7	50
From groundwater pumping	872	872		9	15	
From drainage pumping	23	23		0	0	
To Groundwater	*-1,451*	*-5,856*	*4,404*	*-15*	*-103*	*102*
From surface	11,311	8,670	2,641	97	124	61
From rain	3,203	1,440	1,763	27	17	41
Groundwater pumping	-15,966		-139	-244		
Leaching fracion at field (%)	*19*	*17*				

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[8] This is achieved most conveniently using the goal seek function in Excel. This allows the user to specify that the cell containing cropping intensity should be set to a value that results in crop consumptive use again equaling 531 mm.

The most important change from reducing watercourse seepage to 5 percent is the saving in pumping—from 15,386,000 cubic meters pumped in the first case (fig. 6) to 13,158,000 cubic meters after lining (fig. C.2). Watercourse lining has a minimal impact on cropped area, but saves about 17 percent in power. This solution is, of course, strongly related to the exploitation of the aquifer. It would be quite different if there were no potential to exploit losses to groundwater. This exercise demonstrates the relative simplicity of identifying and quantifying such important relationships once a reasonable approximation of the water balance has been assembled.

FIGURE C.2.

Summary results based on a watercourse seepage of 5 percent and irrigation intensity of 55 percent.

Season: Winter	Crop Consumptive Use					
Table 3: Summary	Direct	Pumped	Total	Drain	NBET	Groundwater
Diversion (000 m^3)	12,968	10,228	23,196	3,087	4,847	-1,131
Rain (000 m^3)	3,850	2,929	6,779	691	2,857	-326
Total	16,818	13,158	29,975	3,778	7,704	-1,457
Diversion (%)	32	26	58	8	12	-3
Rain (%)	10	7	17	2	7	-1
Total	42	33	75	9	19	-4

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INTERNATIONAL IRRIGATION MANAGEMENT INSTITUTE
P O Box 2075, Colombo, Sri Lanka
Tel (94-1)867404 • Fax (94-1) 866854 • E-mail IIMI@cgnet.com
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