Annex 1

Basic canal hydraulics

The aim of this annex is to refresh some basic knowledge on flow conditions and canal capacity. These are determined by hydraulic laws that are of use not only for design but also for diagnosis.

THE HYDRAULIC STEADY STATE

Steady-state open flow hydraulics is a branch of fluid mechanics. Steady-state hydraulics covers flows with a constant discharge in time. Specific laws have been established linking geometry, hydraulic properties and discharge for different types of structures and canals. These laws are translated into rules that are widely applied in irrigation design and operation (e.g. Chow, 1959).

Knowledge of steady-state hydraulics in open canals is fundamental in the design stage of a transport and delivery network. As far as the management and operation of irrigation systems are concerned, steady-state hydraulics is important for measuring, monitoring and managing discharges at various places along the system (measurement, control and operation infrastructure from headworks down to farm inlets). In open canals, discharges are rarely measured directly but are computed locally using a generic law such as Equation 1 and one or more measured proxy variables, e.g. water depth or gate opening:

$$Q = F(\text{geometry, hydraulic variables}) \tag{1}$$

Two types of flow (Box A1.1) should be distinguished while measuring or computing discharges:

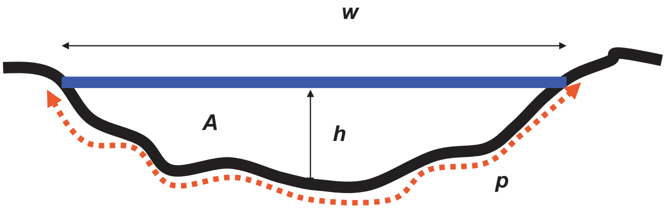
- uniform (normal) flow;
- influenced flow.

Uniform flow occurs when all variables of flow are constant, i.e. discharge (Q), depth (h), width (w_o) and mean velocity (V). Non-uniform or influenced flow can also be in a steady state (Q = constant), but the other variables of flow (geometry of the canal, and velocity) may change gradually from section to section. Both types of flow can frequently be found in irrigation systems.

Geometrical characteristics of a canal section

Two main variables of open canal hydraulics are the wetted perimeter, p, and the hydraulic radius, R. These variables are necessary in the calculation of uniform canal flows. Figures A1.1 and A1.2 introduce the geometric characteristics of irregular (random) and trapezoidal canal sections.

FIGURE A1.1
Geometric variables of a canal section



A	Flow area	(m^3)
p	Wetted perimeter	(m)
$R = A/p$	Hydraulic radius	(m)

Bed slope of the canal

In canal hydraulics, there are three determining variables: depth of flow, BOX A1.1

Definitions

Steady flow: A flow in which quantity of water passing a given point per unit of time remains constant.

Unsteady flow: As opposed to steady flow, it is a flow in which the elements of flow are subject to change in the course of time.

Uniform (or normal) flow: The flow in an open channel is said to be uniform when parameters, such as the cross-sectional area, the velocity and the hydraulic slope, remain constant from section to section. The water level in this case is parallel to the bottom line of the canal.

Influenced (or non-uniform) flow: The flow in an open channel is said to be influenced (non-uniform) whenever the depth and other features of flow, such as the cross-sectional area, the velocity and the hydraulic slope, vary from section to section. In an otherwise uniform canal, non-uniformity occurs under the influence of structures along the canal.

	Uniform cross-section of flow from point to point	Cross-section of flow varies from point to point
Flow is constant over time	Steady uniform flow	Steady influenced flow
Flow is variable over time	Unsteady uniform flow	Unsteady non-uniform flow

Wetted perimeter: The length of the wetted contact between a stream of flowing water and its containing conduit or channel, measured in a plane at right angles to the direction of flow.

Hydraulic radius: The cross-sectional area of the flowing water divided by the wetted perimeter.

Roughness coefficient: A factor that represents the effect of roughness of the pipe or the channel material upon the energy losses of water (K or n in hydraulic formulae).

Subcritical flow: A velocity of flow lower than critical; characterized by deep slow flows. Most open-canal flow is subcritical.

Critical flow: That velocity of flow at which the energy of flow is at a minimum; transition point.

Supercritical flow (shooting flow): A velocity of flow in excess of critical. Flows are superficial and very rapid. An important characteristic is that waves cannot travel upstream of flows that are above critical flow.

Open-channel flow: Flow in a channel with a free surface in contact with the atmosphere. This includes flow in pipes and closed conduits flowing partly full.

Free flow: A condition of flow through or over a structure where such flow is not affected by submergence or the existence of tail-water. The flow is governed only by upstream conditions.

Submerged flow (drowned flow): A condition of flow through or over a structure where such flow is affected by submergence or the existence of tail-water. The flow is governed by upstream and downstream conditions.

Overshot structure: A structure where the water passes from the parent channel to either the downstream canal or the offtaking channel by discharging over the crest of a wall, or over the top edge of a gate.

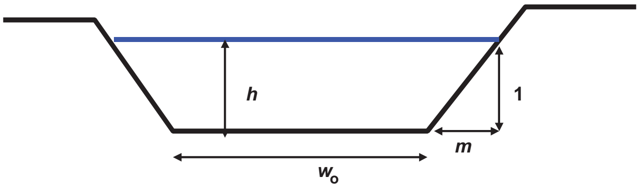
Undershot (orifice) structure: A structure where the water passes from the parent channel to the downstream canal or the offtaking channel below the gate opening formed between the sill of the gate opening and the lower edge of the gate or through an orifice formed by a pipe or a submerged hole in the structure.

Offtake (diversion) structure: A structure built at the head of an offtaking branch or distributary channel to control and admit regulated supplies into it from the parent canal.

Cross-regulator (check structure): A structure designed to control the water surface level and flow in a canal, maintaining a specified water depth or head on outlets or diversion structures, particularly when the flow is small.

width of flow, and the slope of the canal. Fixing two will give the third. The longitudinal bed slope is generally expressed as a fraction or a percentage (e.g. 0.001 or 0.1 percent for a slope of 1 m per 1 000 m). Under uniform flow conditions (Figure A1.3), the energy gradient of the water is parallel to the bed slope (and the mean water level). Stated differently, a constant velocity and water depth are obtained when the force moving water forward (weight as related to the bed slope) is in balance with friction forces.

FIGURE A1.2
Geometric parameters of a trapezoidal canal

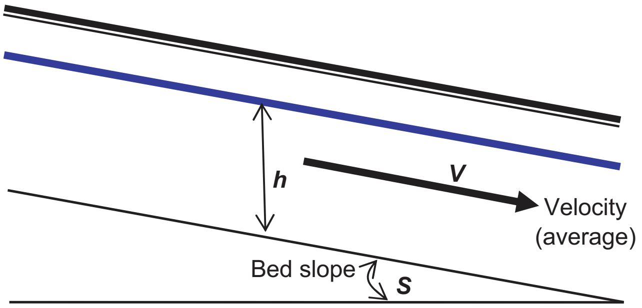


$$A = h\,(w_o + m.h)$$
$$p = w_o + 2.h\,(1 + m2)^{0.5}$$
$$R = [h\,(w_o + m.h)]/[w_o + 2.h\,(1 + m2)^{0.5}$$

If $m = 0$ and $h << w_o \rightarrow R = h$

The range of choice for longitudinal slopes of canals is limited. The slope should facilitate sufficient discharge and a minimum water level at control points, while not exceeding a maximum flow velocity. It should also allow a minimum velocity in order to avoid sediment deposit.

FIGURE A1.3
Flow surface parallel to bed slope with uniform flow in an open channel



Flow velocity

Velocity in uniform flows (Figure A1.4) is generally calculated using the empirical Manning–Strickler equation:

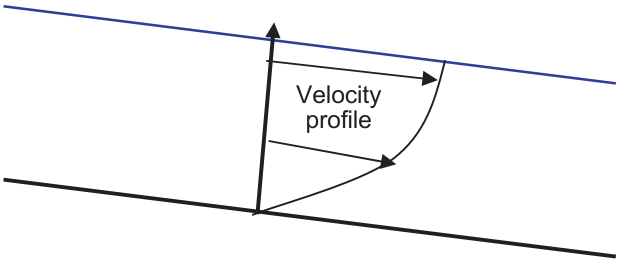
$$V = KR^{2/3}S^{1/2} \tag{2}$$

where:

- V = velocity (m/s);
- K = roughness coefficient ($m^{1/3}/s$);
- R = hydraulic radius (m);
- S = bottom bed slope (m/m).

Flow velocity in the canal has to be maintained within a small range. In order to prevent scouring in earth canals and maintain subcritical flow, maximum velocity values should not be exceeded. Flow in irrigation canals is nearly always subcritical (deep and slow flow). At diversion, division and especially measurement structures, supercritical flow may occur and even be necessary.

FIGURE A1.4
Velocity profile in a uniform flow section



Minimum velocities should also be maintained in order to prevent sedimentation when the flow has a high sediment load and to limit the occurrence of water-borne diseases favoured by standing or slowly moving waterbodies. Recommended velocities are given in Table A1.1.

In Table A1.1, *V* refers to mean velocity, as the velocity is not spread uniformly over the whole cross-section of the canal owing to friction.

TABLE A1.1
Usual threshold velocity in irrigation canals

		Threshold velocity (m/s)
V_{maxi} (m/s)	Earth canals in sandy soils	0.3–0.8
	Earth canals in stable soils	1.0
	Concrete canals	2.0
V_{mini} (m/s)		0.5

TABLE A1.2
Values of discharge coefficient K (n) drawn from the literature

Canal alignment	State	
	Perfect	Degraded
Smooth cement walls	100 (0.010)	75 (0.013)
Concrete lined canals	83 (0.012)	55 (0.018)
Earth canals (regular) [1]	60 (0.017)	40 (0.025)
Canals with stony beds	40 (0.025)	25 (0.040)

[1] Earth canals show strong variation in roughness during the season owing to weed growth, etc.

Roughness

The Manning–Strickler equation shows that velocity depends not only on hydraulic radius and slope, but also on the surface roughness of the canal. As mentioned above, equilibrium is established between energy dissipated by friction along walls and bottom, and the potential head loss along a sloping canal.

Roughness can be expressed by the Manning coefficient (n) (n increases with roughness) or by the discharge coefficient of Manning–Strickler ($K = 1/n$). Roughness is not a long-term permanent property of a canal section. It generally tends to increase over time (Table A1.2). However, a decrease in roughness can be observed immediately after maintenance of the walls of an earth canal. Thus, the phenomenon is related to smoother walls and/or the deposition of fine alluviums on the bed bottom.

Steady flow regimes

The transport capacity ultimately and most importantly refers to the discharges of canal flows. The discharge is equal to the product of the flow cross-section (A) and velocity (V).

$$Q = V * A \tag{3}$$

For uniform flow, the standard Manning–Strickler equation applies:

$$Q = KAR^{2/3}S^{1/2} \tag{4}$$

where:
- ➢ Q = discharge (m^3/s);
- ➢ K = roughness coefficient ($m^{1/3}/s$);
- ➢ A = canal cross-section (m^2);
- ➢ R = hydraulic radius (m);
- ➢ S = bottom bed slope (m/m).

Where the canal is rectangular and large, the hydraulic radius R is equal to water height h and the equation can be simplified. Transport capacity can be calculated with:

$$Q = Kw\ h^{5/3}S^{1/2} \tag{5}$$

where:
- ➢ w = bed width (m);
- ➢ h = water depth (m).

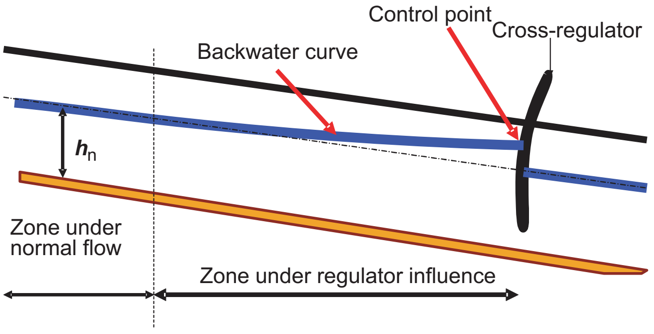
Influenced flow

The flow is influenced where water depth is controlled by a singular point along the canal. The equations for uniform flow no longer apply as the water profile deviates from a normal flow profile to progressively reach the control point (Figure A1.5).

THE UNSTEADY-FLOW APPROACH

By nature, steady-state flow is rarely found in irrigation canals. Fluctuations occur continually as a result of management interventions or of unexpected fluctuations in inflows or outflows. Therefore, knowing the steady-flow properties of a canal system is not sufficient for efficient management.

FIGURE A1.5
Flow regime under influenced flow



Unsteady flow introduces the dynamics of flow variation with time. The discharge varies as a function of time. Therefore, the generic Equation 1 is rewritten as:

$$Q(x,t) = F(\text{geometry, hydraulic variables, time}) \tag{6}$$

The Saint Venant differential equations have been developed to describe these conditions. Several methods of integrating unsteady flow have been proposed and used in the past, with various levels of simplification depending on the prevailing computational capacity. In the field of flow regulation for example, simplified approaches have been developed using transfer functions (Laplace and Fourier functions) to simulate wave propagation. Fully hydrodynamic models, based on numerical resolution of the two Saint Venant equations, can be run on personal computers.

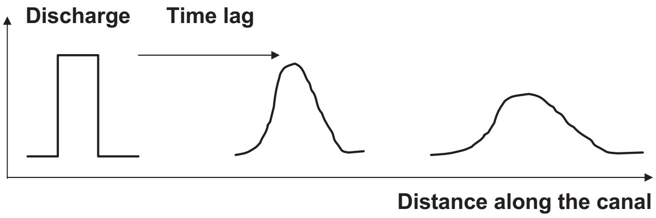
An unsteady flow approach is essential in order to describe fully the dynamics of the canal systems, for example to evaluate the time lag between issues and deliveries. For example, in order to anticipate operation of the headworks as a function of the expected demand, it is important to know the time taken for water to flow from the main reservoir to a user situated on the downstream network.

WAVE PROPAGATION

The characteristics of wave propagation along a canal are very important data for the management of a canal. In fact, the transit time of changes is relatively long on the canals. It is not rare that a change in supply to the canal takes more than 24 hours to become apparent downstream in the network. Thus, it is crucial for the manager to know how waves propagate in order to anticipate the changes in regulation to be implemented and so meet demand on time (Figure A1.6).

Knowing the transit time of the wave along a canal is also important for setting up a management strategy of the works and, in particular, for preventing that the type of rules established to operate the structures give rise to a large amplification of perturbations along the canal (oscillations).

FIGURE A1.6
Wave propagation along a canal



HYDRAULICS OF IRRIGATION STRUCTURES

Singular structures of irrigation systems can be classified into two main hydraulic categories: the orifice type (also called undershot); and the overshot type (Table A1.3). For both categories, two types of flows can be distinguished with different hydraulic laws and consequent operational

TABLE A1.3
Typology of irrigation structures

Hydraulic category	Examples	Type of flow	Modularity	Discharge determined by
Orifice type	Sluice gates, radial gates, baffle distributors	Free flow	Semi-modular	h_{US}
		Submerged	Non-modular	h_{US} & h_{DS}
Overshot type	Broad-crested weirs, duck-bill weirs, flumes	Free flow	Semi-modular	h_{US}
		Submerged	Non-modular	h_{US} & h_{DS}

FIGURE A1.7
Flow types at singular structures

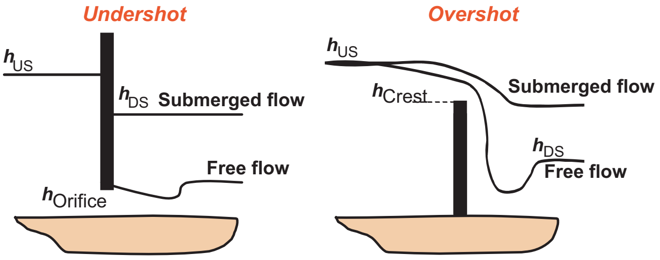
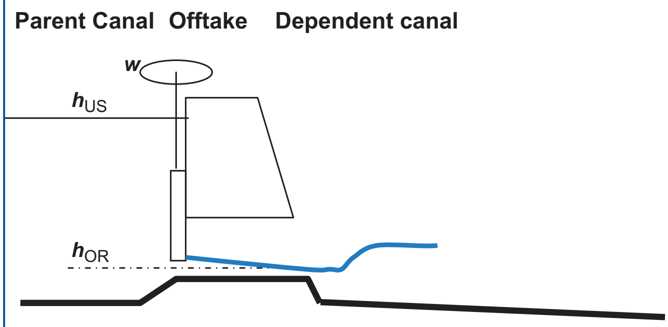


FIGURE A1.8
Orifice-type offtake with downstream free-flow conditions



demands.

The flow is said to be free if it passes through a critical (or supercritical) flow stage that dissociates the downstream and the upstream of the structure (Figure A1.7). Only the water head exerted by the supply level on the axis of the gate controls the discharge in the structure. These structures are called semi-modular. The flow is said to be submerged when the downstream part is submerged by a water line controlled by a downstream point (sill or other). Under this condition, the head downstream of the intake equally affects the discharge passing through the structure. These structures are called non-modular.

Except for pumps and perhaps Neyrpic distributors, there are no practical examples of modular structures. This means that for non-proportional systems, water-level control is a very important subsidiary target of canal operation.

Hydraulics of an orifice (undershot) with free-flow characteristics

Orifice-type structures can be found in any part of irrigation systems. They are often used as offtakes. For an orifice-type offtake with downstream free-flow conditions (Figure A1.8), only one equation is required to describe the flow:

$$q = a\,A\,(h_{US} - h_{OR})^{0.5} \tag{7}$$

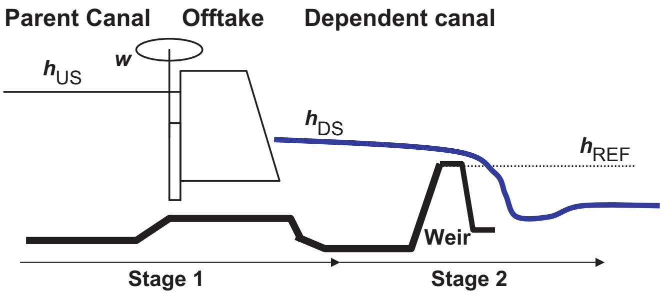
where:

- q = discharge through offtake (m^3/s);
- a = discharge coefficient equal to $c(2g)^{0.5}$;
- c = flow coefficient function of the shape of the orifice ($c \approx 0.5$);
- $A_{(w)}$ = flow cross-section of the structure, expressed as a function of the setting w (m^2);
- h_{US} = water level upstream of the structure (m);

- h_{OR} = level of the orifice axis (m).

Examples of undershot structures are sluice gates, orifices (pipe outlets) and Venturi. One of the main hydraulic characteristics is that discharge (q) is related to the head (h) (= h_{US} - h_{OR}) with exponent 0.5.

FIGURE A1.9
Undershot submerged by a measuring weir



Hydraulics of an orifice (submerged)

Structures are quite often submerged, i.e. the flow downstream of the structure is controlled by a control section or structure. The water level downstream of the gate is dependent on discharge and downstream setting and adjustment.

Structures that fall under this category are:

- offtakes equipped with measuring devices (weir or flume) downstream of the structure at the entrance of the dependent canal;
- offtakes serving a submerged canal that is controlled by a downstream structure;
- offtakes or regulators for which the submergence is dictated locally by normal flow conditions;
- regulators under the influence of the next downstream regulator.

Under submerged conditions (Figure A1.9), discharge calculations are more complicated than under free-flow conditions. This is because downstream water levels vary according to conditions in this canal. A variation in water depth within the parent canal (Δh_{US}) generates a variation in the discharge (Δq), which in turn generates a variation in the downstream water level (Δh_{DS}) controlled by the weir. As a consequence, the variation in head on the offtake is no longer equal to (Δh_{US}) but to (Δh_{US} - Δh_{DS}). Solving the problem requires considering two stages and two equations.

The governing equations of flow are:

Stage 1: $$q = a\,A\,(h_{US} - h_{DS})^{0.5} \tag{8}$$

Stage 2: $$q = a'\,b\,(h_{DS} - h_{REF})^{1.5} \tag{9}$$

where:

- q = discharge through the offtake (m³/s);
- $A_{(w)}$ = flow section through the structure expressed as a function of the setting w (m²)
- a = discharge coefficient equal to $c(2g)^{0.5}$;
- c = flow coefficient function of the shape of the orifice ($c \approx 0.5$);
- a', b = hydraulic parameters of the second stage law;
- h_{US} = water level upstream of the structure (m);
- h_{DS} = water level downstream of the structure (m);
- h_{REF} = reference level downstream taken as the crest level of the weir (m).

Hydraulics of an overshot structure

Overshot structures are used mainly for water control, water measurement and as safety structures. They are less frequently used as discharge regulation structures (Figure A1.10) because of their hydraulic characteristics and often more complicated operation requirements related to adjustments. Examples of overshot structures are: broad-crested weirs, stop logs, Cipoletti weirs, and Parshall flumes. The main hydraulic characteristic of all overshots is that discharge (q) is related to the head (h) (= h_{US} - h_{OR}) with exponent 1.5. The hydraulic equation is:

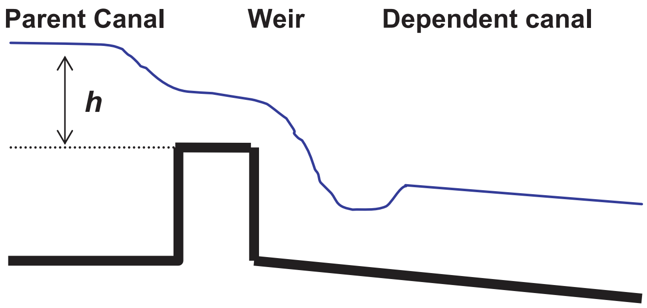
$$q = c\, b\, h^{1.5} \tag{10}$$

where:

- q = discharge through offtake (m³/s);
- c = weir coefficient for free flow (depending on size, shape and angle with cross-section; $c \approx$ 1.0–1.9);
- b = crest width (m);
- h = head above crest (m).

FIGURE A1.10

Overshot-type discharge regulator



WATER-LEVEL CONTROL

Given that the demand for water is not constant in time, discharges are usually fluctuating along an irrigation network. The consequence is that, without specific control, water depths along canals vary considerably and so do water-level conditions at diversion points. As discharges through offtakes are related to the water level in the parent canal, water-level control is important to ensuring a good water service.

Where there is no cross-regulator in the parent canal, the water depth can be calculated from the standard Manning–Strickler formula, provided the flow is uniform. For a large, rectangular canal, the solution is explicit and given by:

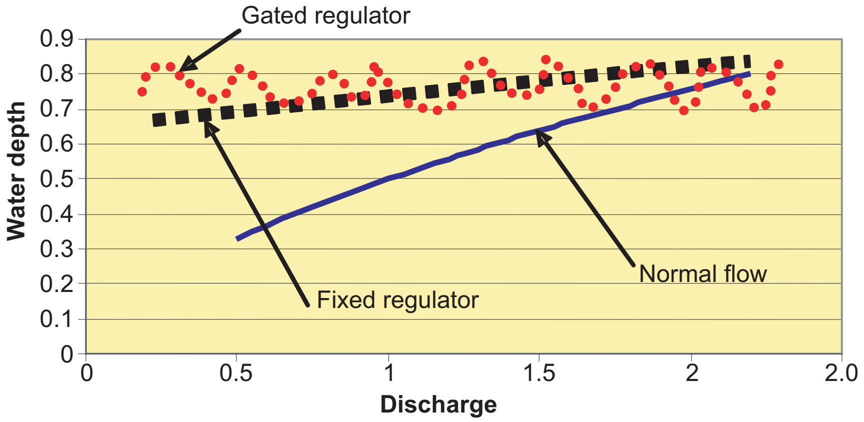
$$h = \left[\frac{Q}{Kw\, S^{1/2}}\right]^{3/5} \tag{11}$$

where:

- Q = discharge;
- K = roughness coefficient;
- w = bed width;

FIGURE A1.11

Variation in water depth with discharge under normal flow conditions, with fixed overflow regulator and with gated regulator



➢ S = bottom bed slope.

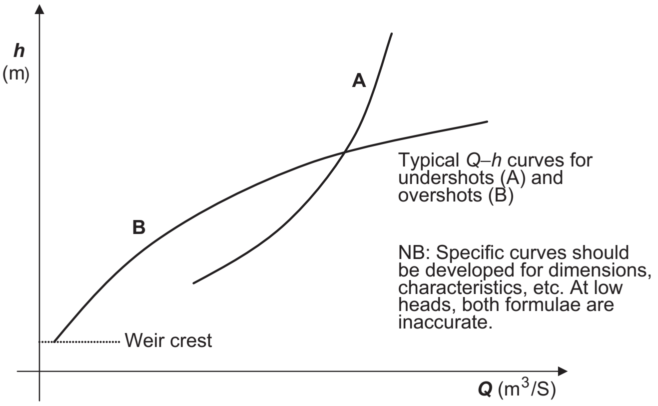
This implies that under normal-flow conditions, a variation in discharge of 50 percent will cause a variation in water depth of slightly more than 30 percent (Figure A1.11).

In order to ensure that offtakes (diversion structures) are properly supplied with enough and stabilized head, water heads must be regulated.

Discharge regulation structures can also serve as water-level control structures. These structures, also called check-structures or cross-regulators, are located just downstream of offtakes, their main function being to maintain a stable water level. The Q–h relations of water-level regulators are equal to those of discharge regulators. The same reason that makes overshots not suitable as discharge regulators – their insensitivity to variations in water heights – is a prime reason why they make excellent cross-regulators (Figure A1.12).

FIGURE A1.12

Q–h curves for hydraulic structures



Typical *Q–h* curves for undershots (A) and overshots (B)

NB: Specific curves should be developed for dimensions, characteristics, etc. At low heads, both formulae are inaccurate.

REFERENCES

Chow, V.T. 1959. *Open-channel hydraulics*. International Edition 1973. McGraw-Hill Book Company. 680 pp.

Annex 2

Sensitivity of irrigation infrastructure and performance

ASSESSMENT OF SENSITIVITY INDICATORS OF OPEN-CHANNEL STRUCTURES

Definition

For water diversion (offtake), the sensitivity indicator is the ratio of relative variation in withdrawal (discharge q) to the variation in water level in the parent canal (H):

$$S = \frac{\Delta q / q}{\Delta H} \tag{1}$$

For water-level control (regulator), the sensitivity indicator is the ratio of the variation in (H) to the relative variation in discharge Q in the main canal:

$$S = \frac{\Delta H}{\Delta Q / Q} \tag{2}$$

Estimating structure sensitivity

There are three ways to estimate the value of the sensitivity indictor of a structure:

- hydraulic formulation;
- direct measurement;
- data processing of recorded heights.

Computing sensitivity indicators with hydraulic formulations

Flow conditions can be free flow or submerged. Free flow means that the downstream side of the structure does not bring any influence on the flow conditions through the structure, whereas submerged ones do. Figure A2.1 illustrates an example for an undershot structure with these two possible conditions.

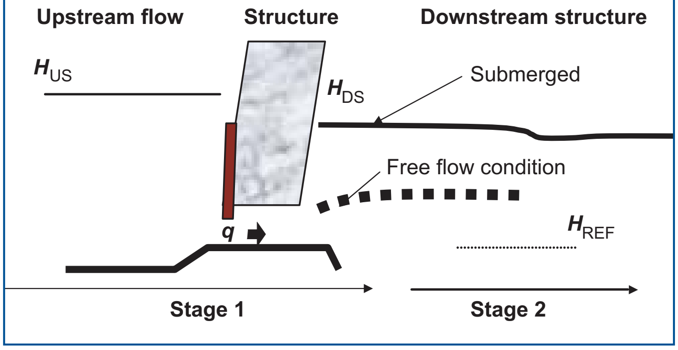
Submergence can result from various features:

- the presence of a measuring weir;
- the presence of a weir further downstream;
- a normal flow condition downstream;
- an influenced flow from a further downstream cross-structure.

In the general case of submergence, the input–output sequence is twofold: a variation in input H_{US} produces a variation in discharge q, which in turn produces a change in the water depth H_{DS} downstream of the structure. As a result, the resulting variation in q is dependent on both H_{US} and H_{DS}.

With the same initial head, the submergence of structures tends to reduce the variation in discharge, therefore reducing the sensitivity compared with a structure with free flow.

FIGURE A2.1
Flow through an irrigation structure with different downstream conditions



The exact computation requires two equations to be considered – one through the structure itself, and one for the flow regime immediately at the downstream side of the structure.

The general governing equations of flow through an open-channel structure are:

$$q = aA\left(H_{US} - H_{DS}\right)^{\alpha} \qquad \text{Stage 1} \qquad (3)$$

$$q = a'b\left(H_{DS} - H_{REF}\right)^{\beta} \qquad \text{Stage 2} \qquad (4)$$

where:

- A = flow section parameter through the structure (A = area through the orifice for an undershot flow, and A = the crest length for an overshot flow);
- a = discharge coefficient equal to $c(2g)^{0.5}$;
- c = flow coefficient function of the shape of the flow ($c \approx 0.5$ for an orifice);
- a' & b = hydraulic parameters of the second stage law;
- α, β = exponent equal to 1/2 for undershot flow, to 3/2 for overshot, and about to 1.6 for normal flow;
- H_{US} = water level upstream of the structure;
- H_{DS} = water level downstream of the structure;
- H_{REF} = a reference level depending on the downstream flow conditions;
- q = discharge through the structure.

H_{REF} is a constant reference level taken at: (i) the crest level of the weir where there is a measurement weir; or (ii) a reference level (bottom bed or a crest level) further down conditioning the flow at the structure (Table A2.1). It is assumed that $dH_{REF} = 0$.

Free-flow conditions

Under free-flow conditions at the offtake, Stage 2 (Equation 4) is irrelevant and the problem reduces to one equation, i.e. Equation 3. Then, H_{DS} is taken either as the crest level of the weir in the case of overshot, or as the orifice axis in the case of undershot.

Solution for the general case with submerged conditions

In a general case, rewriting Equations 3 and 4 produces:

$$\left(\frac{q}{aA}\right)^{1/\alpha} = H_{US} - H_{DS} \qquad (5)$$

and

$$\left(\frac{q}{a'b}\right)^{1/\beta} = H_{DS} - H_{REF} \qquad (6)$$

Adding Equations 5 and 6 yields:

$$\left(\frac{q}{aA}\right)^{1/\alpha} + \left(\frac{q}{a'b}\right)^{1/\beta} = H_{US} - H_{REF} \qquad (7)$$

TABLE A2.1

Conditions of flow and reference to be considered in calculations

Specific conditions	H_{REF}	2nd equation	α	β
Undershot free flow	Orifice axis	Not needed	0.5	no
Overshot free flow	Crest level of the weir	Not needed	1.5	no
Undershot submerged by a downstream measurement weir	*H* crest of the measurement weir	Needed	0.5	1.5
Undershot submerged normal uniform flow	*H* bed bottom of the downstream canal section	Needed	0.5	1.66

Then, taking the logarithm derivative with respect to the variable H_{US} gives:

$$\frac{1}{\alpha}\left(\frac{q}{aA}\right)^{1/\alpha-1}\left(\frac{\partial q}{\partial H_{US}}\right)+\frac{1}{\beta}\left(\frac{q}{a'b}\right)^{1/\beta-1}\left(\frac{\partial q}{\partial H_{US}}\right)=\frac{\partial(H_{US}-H_{REF})}{\partial H_{US}} \tag{8}$$

From this can be derived, given that $dH_{REF} = 0$:

$$dH_{US}=\left|\frac{q^{\frac{1}{\alpha}-1}}{\alpha[aA]^{1/\alpha}}+\frac{1}{\beta}\frac{q^{\frac{1}{\beta}-1}}{[a'b]^{1/\beta}}\right|dq \tag{9}$$

which can be rewritten as:

$$dH_{US}=\left[\frac{q^{\frac{1}{\alpha}}}{\alpha[aA]^{1/\alpha}}+\frac{1}{\beta}\frac{q^{\frac{1}{\beta}}}{[a'b]^{1/\beta}}\right]\frac{dq}{q} \tag{10}$$

Replacing Equations 3 and 4 leads to:

$$dH_{US}=\left[\frac{1}{\alpha}(H_{US}-H_{DS})+\frac{1}{\beta}(H_{DS}-H_{REF})\right]\frac{dq}{q} \tag{11}$$

which can be rewritten as:

$$dH_{US}=\frac{H_E}{\alpha}\frac{dq}{q} \tag{12}$$

by introducing the term of head-loss equivalent (H_E):

$$H_E=(H_{US}-H_{DS})\left[1+\frac{\alpha}{\beta}\frac{(H_{DS}-H_{REF})}{(H_{US}-H_{DS})}\right] \tag{13}$$

The head-loss equivalent, H_E, of a particular structure is equal to the head loss through the structure corrected by a factor expressing the influence of the submergence (Table A2.2).

A robust first approximation of sensitivity indicators, considering H_E = head, is:

Approx. $H_E = Head = (H_{US} - H_{DS})$ (14)

$$S_{Offtake}=\frac{\alpha}{H_{US}-H_{DS}} \tag{15}$$

$$S_{Regulator}=\frac{H_{US}-H_{DS}}{\alpha} \tag{16}$$

Offtake sensitivity

Depending on the type of offtake and the head exercised on it, sensitivity varies between low and very high values. With low-sensitive offtakes, the distribution of water is not affected by perturbations that are passing downward.

In a system aiming at delivering specific service to users (discharge), it is generally desirable that the offtakes be low-sensitive. For a system that is based on proportional distribution, a low sensitivity is not desirable, and the sensitivity of the offtake should be adjusted with that of the cross-regulator in order to have a flexible indicator of 1 at partition points.

TABLE A2.2

Expression of sensitivity indicators

S diversion (offtake)	$S=\frac{dq}{q\,dH_{US}}=\frac{\alpha}{H_E}$
For *S* control level (regulator)	$S=\frac{dH_{US}}{(dq/q)}=\frac{H_E}{\alpha}$
H_E	$H_E=(H_{US}-H_{DS})\left[1+\frac{\alpha}{\beta}\frac{(H_{DS}-H_{REF})}{(H_{US}-H_{DS})}\right]$

TABLE A2.3
Ranking of sensitivity for an offtake

Offtake	Sensitivity indicator	Example
Highly sensitive	Greater than 2	Overshot type offtake
		Undershot type with very low head (0.25 m or less)
Medium-sensitive	Between 1 and 2	Undershot type with head between 0.25 and 0.5 m
Low-sensitive	Below 1	An undershot gated structure fed with head > 0.5 m
		Specific modulated structure (baffle see below)

In some case along a gated system, it might be useful to have some highly sensitive offtakes for the purpose of diverting the surplus or compensating the deficit.

Offtake sensitivity might vary, as summarized in Table A2.3.

An example of low-sensitive offtakes

Neyrpic distributors (baffles) are designed to control discharge when available head is low and variable. The control is obtained by changing flow regimes. At low head, the regime is overshot free flow on the sill. For greater head, baffles create undershot orifice-type flow regimes with contracted veins.

In the example of the baffle distributor shown in Figure A2.2, the discharge is controlled within 10 percent for water level fluctuating between 13.5 and 28 cm above the sill level. Thus, the sensitivity is equal to S_{Baffle} = 0.1/(0.28 - 0.1345) = 0.68, which is quite low.

A classic undershot offtake placed in the same situation would have experienced sensitivity as follows: S = 0.5/(average head) = 0.5/0.2 = 2.5.

Factors affecting offtake sensitivity: head/water level in the main canal

The sensitivity of a structures depends, as a first approximation, on the head exerted on it. This may vary as a function of the operation regime of the canal (average height in the parent canal) and of some interventions on the structures.

For example, in Sri Lanka, a canal that was originally of very low sensitivity has started to have chaotic operation as a result of the combined effects that have increased the sensitivity from 0.5 to 3. The first of these effects is related to the systematic construction of the gauging weir downstream the offtakes, and this has resulted in raising the water level by about 40 cm, and moved the average sensitivity to approximately 2.

FIGURE A2.2
Operation curve of a Neyrpic distributor and an estimate of its sensitivity

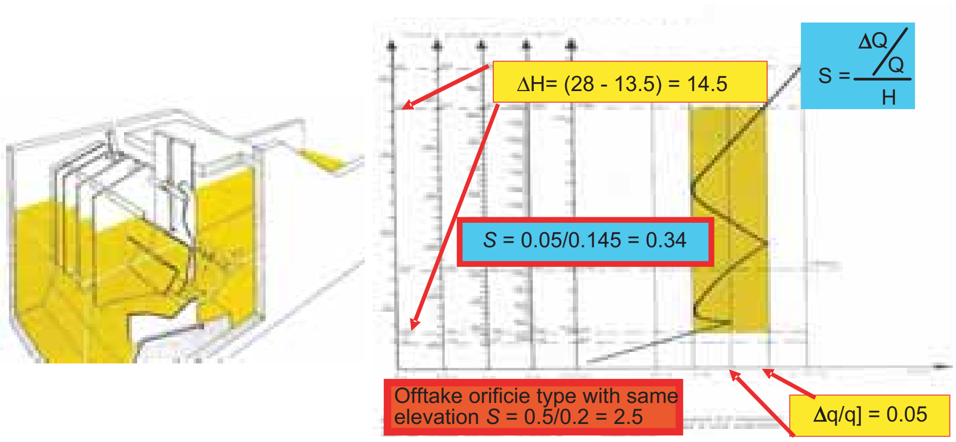
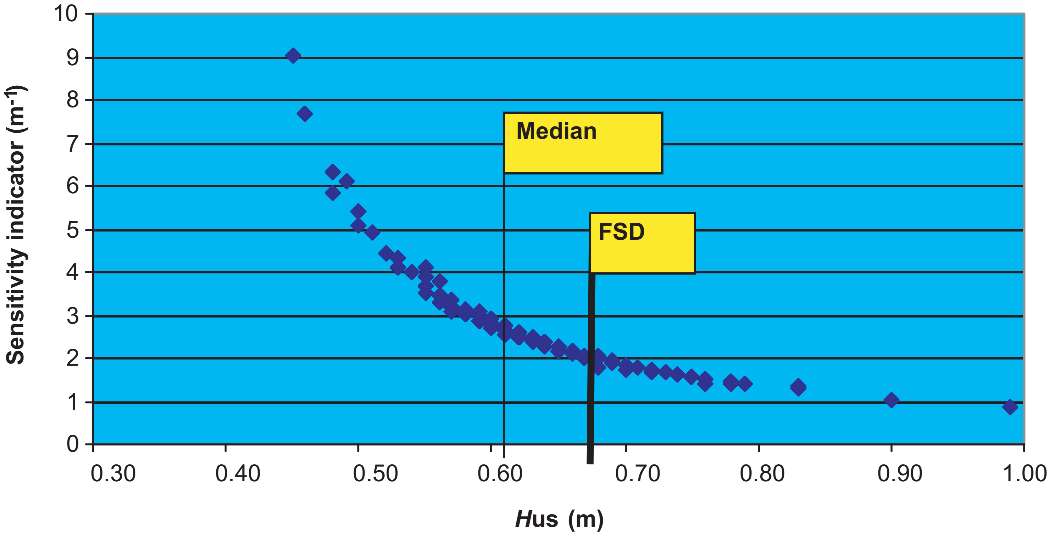


FIGURE A2.3

Evolution of sensitivity vs the average level of the water observed in a canal (Sri Lanka), difference between the nominal value (FSD) and the observed median value



The second effect is a subregime operation of the parent canal (median height of the water level in the main canal 10 cm lower with respect to the nominal value full supply depth [FSD]), and this further reduces the average head available at the offtakes. Thus, the average sensitivity has moved to 3.

The effect of the water line in the canal on the sensitivity indicator is illustrated in Figure A2.3.

A similar case of increased sensitivity caused by the construction of a measurement weir has been found in the Sunsari Morang Irrigation System.

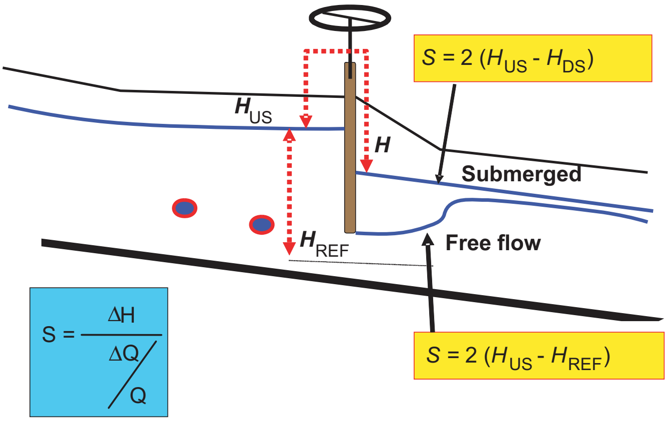
Regulator sensitivity

Cross-regulators are irrigation structures controlling the water depth along a canal, by adjusting local head losses (Figure A2.4). The degree of control and the magnitude of variation in water depth between zero and full discharge vary with the type of structure. For example, a fixed weir has no control on water depth, but the magnitude of the resulting variation with respect to discharge change is very low. Inversely, gated regulators have a high control level, but where managed improperly the magnitude of variation in water depth can be high.

For cross-regulators, the distinction between delivery and conveyance makes no sense. However, both the upward effect as well as the downward effect have to be considered.

FIGURE A2.4

Orifice-type regulator



Downward cross-regulator sensitivity

The equations governing the flow of a regulator are those presented earlier (Table A2.1):

$$S = \frac{H_E}{\alpha} \tag{17}$$

In the case of a free orifice, H_E is equal to the difference between the upstream level H_{US} and the axis of the opening below the gate ($H_{REF} = H_{OR}$). In general, the regulators are submerged downstream, and the difference in head to be considered is the value of H_E in its complete formulation (Equation 13).

For an orifice-type structure, $\alpha = 0.5$ and thus:

$$S = 2.H_E \tag{18}$$

The orifice-type regulators are generally equipped with gated offtakes, and their control function is obtained by operating these gates.

For an overshot-type structure, $\alpha = 3/2$ and thus:

$$S = 2/3.h \tag{19}$$

with h the height of the flow on the crest.

The case of a weir-type level regulator (duck-bill)

A duckbill-weir-type regulator is a low-sensitive regulation structure. By design, its function is to transform an important variation in the flowing discharge into a close variation of the flow height, without any intervention on the work.

Assuming a free weir (with no influence downstream), the overshot-type flow equation is:

$$Q = c.\ L_c.\ [h]^{3/2} \tag{20}$$

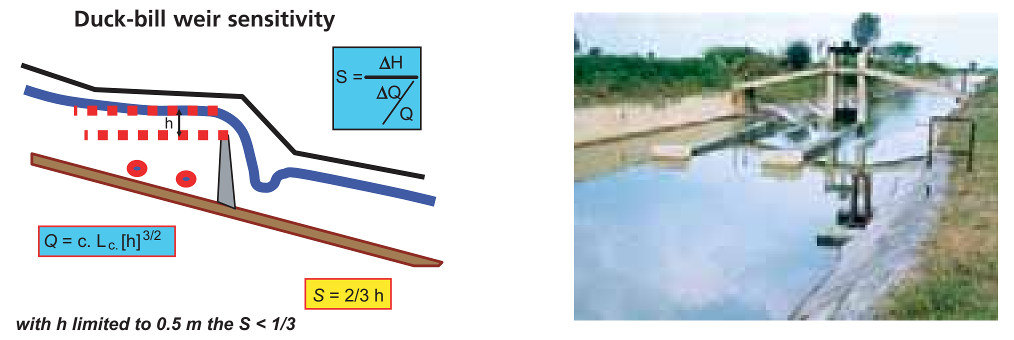
where:

- ➢ c = flow coefficient on the weir depending on the shape of the crest ($c \approx 1.5–1.7$);
- ➢ L_c = length of the crest;
- ➢ h = water head on the weir (measured at a given distance upstream of the weir);
- ➢ Q = discharge flowing on the weir.

From the logarithm derivative expression of Equation 20, it is possible to determine the sensitivity indicator, which is equal to:

$$S = 0.66\ h \tag{21}$$

With h limited to 0.5 m, then $S < 1/3$.



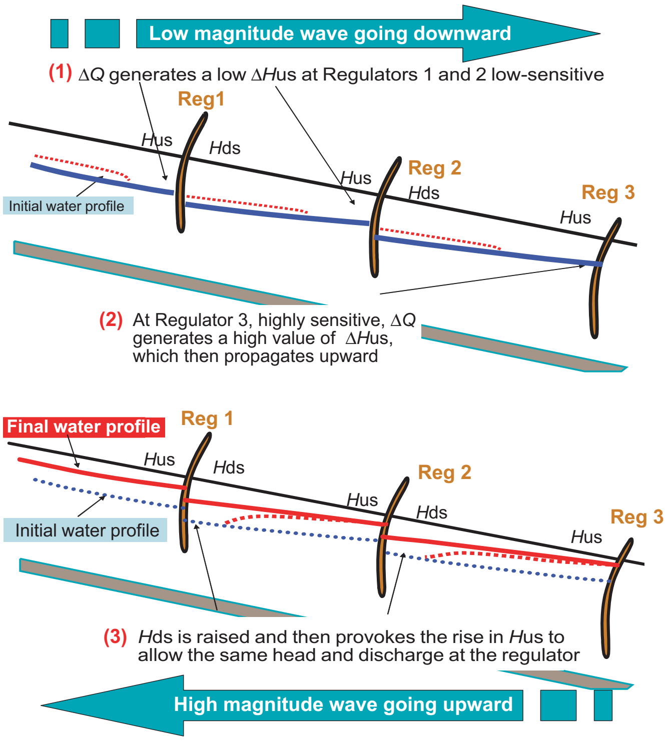
Cross-regulator interference

Regulators are often submerged downstream. A first approach that neglects submergence gives a preliminary indication on sensitivity based on the difference in head between upstream and downstream.

A difficulty in the vicinity of regulators can result from their mutual interference. The control point downstream of a regulator is sometimes the next regulator located downstream. Therefore, the flow condition downstream of a regulator may depend on the variations in regulations and the sensitivity of the next regulator.

FIGURE A2.5

Downstream influence of sensitive regulator on upstream regulators



Regulators that intrinsically are not sensitive may become so when influenced. This means that, taken independently, they react poorly in height upon a change in discharge. However, where situated in the backwater curve of a very sensitive downstream regulator, they might ultimately react by transforming the level variation downstream of them (ΔH_{DS}) into level variation upstream (ΔH_{US}).

In the example presented in Figure A2.5, the perturbation wave initially moves down the canal and crosses Regulators 1 and 2 (low-sensitive) without causing large variations in the height of the water level upstream. However, at Regulator 3 (very sensitive), a strong variation in the height of the water level upstream is generated, and this rises up along the canal so much as to provoke a similar variation in magnitude at Regulators 2 (first) and 1 (later).

The direct measurement of sensitivity

For an offtake, the direct measurement consists in generating a variation in the water level in the parent canal, and measuring the resulting variation in discharge at the offtake. Thus, the indicator is given by the direct formula of Equation 1.

For a level regulator, the measurement is the opposite: generate a discharge variation in the main canal and measure the resulting one on the head upstream of the regulator; the indicator is thus equal to that given by Equation 2.

Influence of downstream submergence of the structure on sensitivity

The exact expression of the hydraulic formulations of indicators involves the back-effect of submergence on sensitivity through the expression H_E (Equation 13). With a similar head (upstream–downstream difference), submergence tends to reduce the sensitivity of the structure compared with a free-flow structure.

For offtake structures, this effect can initially be neglected by calculating the simple indicator (Table A2.2) with the difference in head (H_{US} - H_{DS}). Only the structures with a high sensitivity indicator (> 1.5) have to be calculated more exactly, taking into account the submergence effect.

Data processing of the recorded heights

Processing of frequently recorded data of the heights H_{US} and H_{DS} of the discharges, enables their evolutions to be estimated. Provided there is no change in the regulation of the opening of the gate, it is also possible to infer the operation law of the work. In particular, it is then possible to determine empirically the hydraulic laws of Stage 2 (inlet of the downstream canal), which are difficult to define, and identify the values for H_{REF} and for β. The calculation of the indicator is then made, starting from the hydraulic formulations.

Accuracy in assessing behaviour of canal structures

For capacity assessment of static characteristic such as transit capacity, a high degree of accuracy is required. However, for behaviour, a low degree of accuracy is sufficient.

It is necessary to know whether the sensitivity of the part of the system, subsystem reach or single structure under consideration is: very low, low, medium high, or very high. Therefore, knowing these parameters to within plus or minus 25 percent is acceptable.

AGGREGATED CHARACTERISTICS AT REACH AND SUBSYSTEM LEVEL

The sensitivity study of the offtakes and regulators is important as such for understanding the behaviour of the structures. However, it is even more important to examine the offtake–regulator combination. In fact, a sensitive offtake may cause no problems where a performing regulator controls it. However, an inefficient level regulator that generates important head variations in the canal can affect a low-sensitivity offtake.

The combined sensitivity of regulators and offtakes

Under the influence of an entering variation in discharge (ΔQin), a reach will react by absorbing a fraction of the flow change through its offtakes and by propagating the remaining part after the flow stabilizes. The balance between absorption and propagation is an indicator of the reach behaviour that managers are interested in.

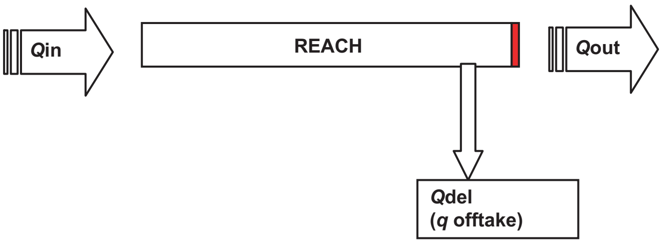
A simple case of an offtake–regulator couple

Figure A2.6 shows an example that considers a reach as the pool between two regulators and a perturbation entering (ΔQin). After a period of transition caused by the variation in water level within the reach, the entering perturbation will be equal to the fraction absorbed by the reach itself and diverted at the offtake (ΔQdel), and that transmitted downwards at the downstream regulator(ΔQout). The share between the two parts depends on:

- the regulator sensitivity reflected through the variation in water depth (ΔH_{US});
- the sensitivity of the offtakes within the reach;
- the ratio of discharge withdrawn within the reach compared with the main discharge.

The system can be analysed in a number of steps. First, a perturbation (ΔQin) entering the reach upstream results in a variation of water level within the reach (Δ*H*), which depends on both regulator and offtake sensitivities. For example, if (ΔQin) is

FIGURE A2.6
Sketch of a reach with downstream associated structures: regulator and offtake



positive, then the water level will rise, causing an increase in the diverted flow at the offtake (ΔQdel) as well as at the regulator (ΔQout). The situation stabilizes when the perturbations compensate each other, i.e.:

$$\Delta Qin = \Delta Qdel + \Delta Qout \tag{22}$$

At the regulator, the sensitivity equation is:

$$S_{\mathrm{reg}} = \frac{\Delta H}{\Delta Q_{\mathrm{out}} / Q_{\mathrm{out}}} \tag{23}$$

from which the value of ΔQout can be extracted.

$$\Delta Q_{\mathrm{out}} = \frac{Q_{\mathrm{out}} \Delta H}{S_{\mathrm{Reg}}} \tag{24}$$

Similarly, the offtake under the influence of the regulator will experience a variation in head corresponding to Δ*H*, which will then be converted into a variation in discharge (ΔQdel), which depends on the offtake sensitivity:

$$S_{Offtake} = \frac{\Delta Q_{\mathrm{del}} / Q_{\mathrm{del}}}{\Delta H} \tag{25}$$

from which the value of ΔQdel can be extracted.

Replacing the calculated values of ΔQdel and ΔQout in the balance equation (Equation 22), allows the implicit value of Δ*H* to be resolved:

$$\Delta H = \left[\frac{\Delta Q\mathrm{in}}{S_{\mathrm{Offtake}} Q_{\mathrm{del}} + \dfrac{Q_{\mathrm{out}}}{S_{Regulator}}} \right] \tag{26}$$

This value is then used in Equations 23 and 25 to compute the variation in discharge that is absorbed ΔQdel and that which is propagated ΔQout.

Defining the reach sensitivity for delivery, S_{RD}, as the ratio of perturbation absorbed, ΔQdel, vs that entering, ΔQin:

$$S_{\mathrm{RD}} = \frac{\Delta Q_{\mathrm{del}}}{\Delta Q_{\mathrm{in}}} \tag{27}$$

then replacing ΔQdel and ΔQin from their expression in Equations 25 and 26 leads to S_{RD} as:

$$S_{\mathrm{RD}} = \frac{Q_{\mathrm{del}}}{Q_{\mathrm{in}}} S_{Offtake} S_{Regulator} \left[\frac{1}{1 + \left(S_{Offtake} S_{Regulator} - 1 \right) \dfrac{Q_{\mathrm{del}}}{Q_{\mathrm{in}}}} \right] \tag{28}$$

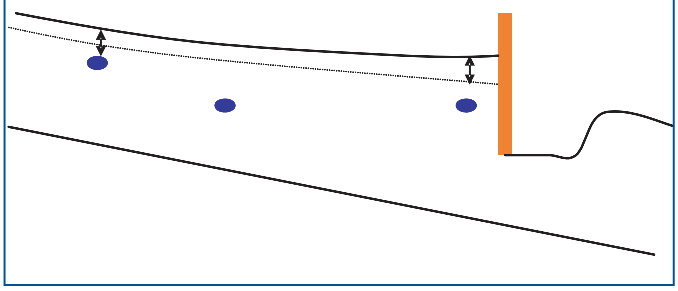
and for a diverted value *q (*or Qdel) that is small compared with Qin, an acceptable simplification of the above exact solution is:

$$S_{\mathrm{RD}} = \frac{Q_{\mathrm{del}}}{Q_{\mathrm{in}}} S_{Offtake} S_{Regulator} \tag{29}$$

The sensitivity for delivery in a reach depends on the product of the sensitivity indicators of the two structures and the weight of the withdrawal *q*/*Q* [Qdel/ Qin] within the reach.

This S_{RD} indicator can sometimes help in understanding the behaviour of canals under perturbation.

FIGURE A2.7
Aggregation of offtakes of the same reach



Aggregation for offtakes within a reach

The simple case described above is for an offtake controlled by a nearby regulator. In reality, it is often necessary to consider more than one offtake, and also the fact that some offtakes might not be close to the regulator (Figure A2.7) and, therefore, experience a reduced control and variation in water depth from the regulator.

In the general case, it thus assumed that the pool between two consecutive hydraulic control cross-structures serves "*n*" offtakes, which in the general case do not have the same values for sensitivity and discharge.

As with the case described above, ΔQin entering the reach will be partitioned into ΔQdel and ΔQout for which it is possible to use the same balance and flow-deviation equations (Equations 22 and 24).

It is then necessary to aggregate the diverted deviation at the offtakes. At each offtake of the reach, the diverted perturbation can be described as a function of the sensitivity and the deviation of water level, ΔH_i:

$$\Delta q_i = q_i \, S_{Offtake}(i) \Delta H_i \tag{30}$$

Then, the total deviation of discharge delivered ΔQ_{del} within the reach is computed by summing the offtake deviations:

$$\Delta Q_{del} = \sum_{i=1}^{n} q_i \, S_{Offtake}(i) \, \Delta H_i \tag{31}$$

If the offtakes are relatively close to the regulator, then the variation in water level experienced should be assumed constant and equal to the one at the regulator, ΔH. In this case, the equation simplifies to:

$$\Delta Q_{del} = \Delta H_{Reg} \sum_{i=1}^{n} q_i \, S_{Offtake}(i) \tag{32}$$

However, for more distant offtakes, the deviation in water depth will be only a fraction of that experienced at the regulator. In this case, it can be easily introduced a fixed parameter [0,1] for each offtake assuming that the change in water depth at the location of Offtake(i) [$\Delta H_{Offtake}(i)$] is linearly related to the change occurring at the downstream cross-regulator [ΔH_{Reg} , controlling the reach through a parameter m_i. This means:

$$\Delta H_{Offtake}(i) = m_i \, \Delta H_{Reg} \tag{33}$$

The coefficient m_i varies with ongoing discharge, but is relatively independent of usual water depth deviations. It can be considered as a site-specific parameter ($0 < m_i < 1$), and constant for each offtake within a limited range of discharge variation. Its value depends on the position of the point along the backwater curve and has to be determined by hydraulic computation or experimental measurements. Values of m_i range between 1 for offtakes close to a regulator and 0 for offtakes fed by a canal section under normal flow. For the latter, the offtake is still experiencing a water depth variation as a result of the change in the normal flow conditions.

The linear approximation, expressed in Equation 33, has been validated using computational outputs of hydraulic simulations in typical conditions of Sri Lanka. It is also supported by the outputs of a study by Strelkoff *et al.* (1998) on the steadiness of the backwater curves once put into non-dimensional form.

Sensitivity and performance

Sensitivity is an indicator of how structures react when they are left unattended – the higher the sensitivity, the faster and higher the reaction. This has consequences on performance. Sensitive delivery structures tend to deviate from their initial setting. Assuming that this initial setting is the perfect target for the discharge, it is then possible to estimate the consequences of deviation in terms of performance.

In general, the overall objective in controlling a canal is to maintain a constant head on the upstream side of the delivery structures (offtakes – outlets) in order to maintain the required discharge within permissible limits. The control of the head in a canal is enabled by cross-structures, also called cross-regulators, at strategic points along the canal. The extent and the magnitude of control exercised by a particular cross-structure depends both on its property in controlling local water depth (precision) and on the extension (influence) of the backwater curve effect within the controlled reach (upstream in most cases). Therefore, the efficacy of any particular control structure and, by extension, of an entire system, can be expressed through two concepts: precision and influence.

Precision is a parameter under the control of the manager. The precision exerted by the operator can be assessed through the fluctuation in water depth (ΔH_{R}) experienced at the regulator. Influence is a more permanent property and depends on the density of control structures and the hydraulic characteristics of the canal.

Other structures, offtakes and outlets along a canal aim to deliver the targeted discharge. Their role is to convert an input, the water depth in the parent canal, into an output, a discharge series, feeding the dependent canal. For a delivery structure, the sensitivity of delivery expresses the link between a variation in water depth (ΔH_{Off}) in the parent canal and the resulting deviation in discharge (Δq) in the dependent canal. A highly sensitive structure generates high changes in discharge for slight deviations in water depth and vice versa.

By manipulating the control structures along the canal, managers attempt to reach and maintain a water profile close to the target, to achieve a given level of performance. Thus, assessing the performance of operation can be formalized in a conceptual relationship:

$$\text{PERFORMANCE} = \textit{Function}\begin{bmatrix}\text{SENSITIVITY} & & \text{CONTROL} \\ \text{of delivery structures} & \textit{and} & \text{on water depth}\end{bmatrix}$$

The objective here is to establish and validate analytical relationships between internal performance indicators related to the quality of the water service (performance), the physical properties of delivery structures (sensitivity), and the level of control (control) exercised on the water depth along the parent canal.

Adequacy and efficiency under uniform precision

For local relationships, given an offtake with an initial discharge corresponding to the target, the consequences of a perturbation in water depth ($\Delta H_{\mathrm{Off(i)}}$) in the parent canal can be examined in terms of the discharge variation (dq_{i}) at the offtake. For the perturbed state, the performance indicator for adequacy is:

$$PA(\mathrm{i}) = \frac{q_{\mathrm{i}} + dq_{\mathrm{i}}}{q_{\mathrm{i}}} = 1 + \frac{dq_{\mathrm{i}}}{q_{\mathrm{i}}} \qquad \text{(if } dq_{\mathrm{i}} \text{ is negative, and 1.0 otherwise)} \qquad (34)$$

The performance indicator for efficiency is, in the same way, derived as:

$$PF(\mathrm{i}) = \frac{q_{\mathrm{i}}}{q_{\mathrm{i}} + dq_{\mathrm{i}}} \qquad \text{(if } dq_{\mathrm{i}} \text{ is positive and 1.0 otherwise)} \qquad (35)$$

which simplifies to:

$$PF_{(i)} = 1 - \frac{dq_i}{q_i} \tag{36}$$

The sensitivity for delivery for Offtake(i) is derived from Equation 1 as:

$$S_{(i)} = \frac{dq_i / q_i}{\Delta H} \tag{37}$$

which replaced in Equation 34 leads to the following local relationship:

$$P_{(i)} = 1 \pm \Delta H_{Off(i)} S_{(i)} \qquad (P_{(i)} \le 1.0) \tag{38}$$

In Equation 38, the minus sign applies for adequacy when ($\Delta H_{Off(i)}$) is positive and the plus sign applies for efficiency when ($\Delta H_{Off(i)}$) is negative. Equation 38 expresses explicitly the link between the adequacy or efficiency performance indicator, the sensitivity and the control exercised on the water depth at the local level.

For aggregated relationships, the objective is to derive a similar relationship to Equation 38 at an aggregated level to enable the performance of subsystems, or even whole systems to be compared considering a uniform precision (ΔH_R). A particular assumption has to be made regarding the way the deviations in water depth affect the system. It is proposed here to refer to a system where positive and negative deviations are fully balanced. Thus, this assumption is called the varied sign perturbation (+/- ΔH_R). Another possible option is to consider a constant sign perturbation (ΔH_R) at every regulator (either + or -).

The aggregation process, with varied sign perturbations, corresponds to the fully balanced system. Therefore, it is assumed that the number of offtakes (n) of the unit considered can be regrouped into two similar subsets of ($n/2$) offtakes. The similarity between the two subsets is based on the discharge delivery and the sensitivity of the offtakes. Reaches of one subset experience a positive perturbation ($+\Delta H_R$), while the others experience a negative one ($-\Delta H_R$), making a balance in the global discharge.

Performance indicators for adequacy and efficiency, as defined by Molden and Gates (1990), are aggregated here using a weighted process, the weight, k_i, being the relative offtake discharge

$$q_i \Big/ \sum_{j=1}^{n} q_j$$

Only instantaneous values are considered in this estimation and the performance for the whole system is the sum of the two subset indicators derived from Equation 38, as follows:

$$P = \sum_{i=1}^{n/2} k_i \left(1 - \Delta H_R \, S_{(i)}\right) + \sum_{i=n/2+1}^{n} k_i \tag{39}$$

For adequacy, the first term in Equation 39 corresponds to the set of underfed offtakes, and the second term corresponds to the set of overfed offtakes. For efficiency, the first term corresponds to overfed offtakes, and the second term to underfed offtakes. Knowing that the sum of the weights k_i over the whole set is equal to 1, by definition, and including Equation 33 in Equation 39, leads to:

$$P = 1 - \Delta H_R \sum_{i=1}^{n/2} k_i \, m_i \, S_{(i)} \tag{40}$$

Assuming a similarity in discharge and sensitivity of the two subsets of offtakes enables the rewriting of Equation 40 as:

$$P = 1 - \frac{1}{2}\Delta H_R \sum_{i=1}^{n} k_i m_i S_{(i)} \qquad (41)$$

Equation 41 has been established for a varied sign perturbation with a perfect initial state. It can also be shown, by a similar computation, that this relationship (Equation 41) holds true with any initial state $P_{(o)}$, under the restriction that no offtake switches from one condition to the other (overfed/underfed); in that case $P_{(o)}$ replaces 1 in Equation 41.

Equation 41 states the relationship between performance, the precision and influence of control, and the sensitivity of delivery structures along the canal. A system sensitivity indicator (S_s) can then be proposed for adequacy and efficiency as follows:

$$S_S = \sum_{i=1}^{n} k_i m_i S_{(i)} \qquad (42)$$

and the performance indicator (Equation 41) is written:

$$P = 1 - \frac{1}{2}\Delta H_R S_S \qquad (43)$$

For subnetworks, it is possible to define sensitivity indicators that enable better linking of the performance of the water service, the efficiency in the control of the water height and the sensitivity indicators, aggregated at the subnetwork level:

$$S_S = \sum_{i=1}^{n} k_i m_i S_{(i)} \qquad (44)$$

where:

- k_i = contribution of the offtake to the whole set (weight), equal to $1/n$ if the weight is identical for each offtake, or to $q_i/\Sigma q_i$ for weighting by discharge;
- m_i = indicator of the regulator control on the offtake, $m_i = 1$ when the offtake is very close to the regulator, and becomes zero when the offtake is far from it.

The performance expected from an irrigation system is the product of two terms: the capacity of control on water depth (tolerance on water depth H), and the system sensitivity. This allows managers to estimate the control to exercise [tol.(H)] given the performance required for the service and the physical properties of the system. Different global sensitivity indicators at system level have been developed (Renault, 1999) for adequacy, efficiency and equity performance.

The performance for adequacy and efficiency is related to the precision and influence of control. A system sensitivity indicator along the canal can be proposed as follows:

$$P = 1 - \frac{1}{2}\Delta H_R S_s \qquad (45)$$

in which S_s is a system sensitivity indicator, equal to:

$$S_S = \sum_{i=1}^{n} k_i m_i S_{(i)} \qquad (46)$$

Using the coefficient of variation approach, a system sensitivity indicator for equity (S_{se1}) can be proposed as the square root of the arithmetic mean of the product of the square of local sensitivity and the influence factor:

$$S_{Se1} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} m_i S_{(i)}^2} \qquad (47)$$

This global sensitivity indicator is related to the performance equity indicator by the following equation:

$$P_E = \Delta H \, S_{Se1} \qquad (48)$$

For the analysis based on the Theil index, a system sensitivity indicator for equity (S_{se2}) can also be proposed as:

$$S_{Se2} = \sum_{i=1}^{n} \frac{q_i}{Q_D} m_i^2 S_{(i)}^2 \tag{49}$$

This system indicator is related to the system performance equity indicator by the following relationship:

$$\mathrm{Thi} = \frac{1}{2} (\Delta H_R)^2 S_{Se2} \tag{50}$$

Table A2.4 summarizes the sensitivity indicators discussed in this annex.

TABLE A2.4
Summary of sensitivity indicators

Structure	Variable studied	Definition	Geometric formulation	Approximate formula by neglecting submergence
Offtake (orifice)	Offtake discharge *q* as a function of the variation in the supply water surface	$S = \frac{\Delta q / q}{\Delta H}$	$S = \frac{0.5}{H_E}$	$S = \frac{0.5}{\text{Head}}$ The "Head" variable is the difference in head exerted on the structure (H_{US} - H_{DS})
Regulator (orifice)	Water level height as a function of the flowing discharge *Q*	$S = \frac{\Delta H}{\Delta Q / Q}$	$S = 2.H_E$	$S = 2\text{Head}$ The "Head" variable is the difference in head exerted on the structure (H_{US} - H_{DS})
Sill regulator	Water surface height as a function of the flowing discharge *Q*	$S = \frac{\Delta H}{\Delta Q / Q}$	$S = 0.66 h$ *h* = water head on the crest	
Canal section	Height of the water level as a function of the flowing discharge *Q*	$S = \frac{\Delta H}{\Delta Q / Q}$	*S* is variable between 0.5 and 0.8 *D* according to the geometry of the canal (*D* = flowing height)	$S = \frac{3}{5} D$ for a very large rectangular canal
Divider	Relative value of the discharge *q* of the branch with respect to the inflowing discharge *Q*	$P = \frac{\Delta q / q}{\Delta Q / Q}$	$P = S_{Offtake} . S_{Regulator}$	

REFERENCES

Molden, D.J. & Gates, T.K. 1990. Performance measures for evaluation of irrigation-water-delivery systems. *J. Irrig. Drain. Eng*., 116(6): 804–823.

Renault, D. 1999. Offtake sensitivity, operation effectiveness and performance of irrigation systems. *J. Irrig. Drain. Eng*., 125(3).

Strelkoff, T.S., Deltour, J.L., Burt, C.M., Clemmens, A.J. & Baume, J.P. 1998. Influence of canal geometry and dynamics of controllability. *J. Irrig. Drain. Eng*., January.

Annex 3

The Rapid Appraisal Process

BACKGROUND

The Rapid Appraisal Process (RAP) enables qualified personnel to determine key indicators of irrigation projects both systematically and quickly. The RAP can generally be completed within two weeks of fieldwork and office work – assuming that some readily available data on the project have been organized by project authorities in advance of the RAP.

Key performance indicators from the RAP help to organize perceptions and facts, thereby facilitating informed decisions regarding:

- the potential for water conservation within a project;
- specific weaknesses in project operation, management, resources and hardware;
- specific modernization actions that can be taken to improve project performance.

A parallel activity to the RAP is called benchmarking. As defined in preliminary documents by the International Programme for Technology and Research in Irrigation and Drainage (IPTRID), benchmarking is a systematic process for securing continual improvement through comparison with relevant and achievable internal or external norms and standards. The overall aim of benchmarking is to improve the performance of an organization as measured against its mission and objectives. Benchmarking implies comparison – either internally with previous performance and desired future targets, or externally against similar organizations, or organizations performing similar functions. Benchmarking is in use in both the public sector and the private sector.

Benchmarking incorporates various indicators, many of which are developed from the RAP. Both the RAP and the IPTRID benchmarking activity are still evolving. Therefore, the indicators in this annex will not always be identical to those in IPTRID documents. This annex also reflects current efforts by the World Bank to combine the processes.

The RAP for irrigation projects was introduced in a joint FAO/IPTRID/World Bank publication titled *Modern water control and management practices in irrigation – impact on performance* (FAO, 1999). The report provides an explanation of the RAP and also gives RAP results from 16 international irrigation projects.

The RAP makes use of a computer spreadsheet (Excel) with 12 internal worksheets. The investigators input the data collected into these worksheets.

THE RAPID APPRAISAL PROCESS

The RAP for irrigation projects is a 1–2-week process of collection and analysis of data both in the office and in the field. The process examines external inputs such as water supplies, and outputs such as water destinations (evapotranspiration, surface runoff, etc.). It provides a systematic examination of the hardware and processes used to convey and distribute water internally to all levels within the project (from the source

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to the fields). External indicators and internal indicators are developed in order to provide: (i) a baseline of information for comparison against future performance after modernization; (ii) benchmarking for comparison against other irrigation projects; and (iii) a basis for making specific recommendations for modernization and improvement of water delivery service.

The RAP has only recently been used for diagnosis of international irrigation projects. However, variations of the RAP presented here have been used since 1989 by the Irrigation Training and Research Center (ITRC) at California Polytechnic State University on dozens of irrigation modernization projects throughout the west of the United States of America.

Traditional diagnostic procedures and research tend to examine portions of a project, whether they are the development of water user associations (WUAs) or the fluctuation of flow rates in a single canal lateral. Such research projects typically require the collection of substantial field data over extended periods.

The time and budgetary requirements of such standard research procedures are significant. Kloezen and Garcés-Restrepo (1998) state that: “three engineers worked full-time for more than a year to collect primary data and make measurements to apply process indicators at the level of selected canals and fields” for just one project. Furthermore, they state that: “In addition, the work in Salvatierra was supported by an M.Sc. student...In addition, much time was spent on visiting the selected field and taking several flow measurements per field, per irrigation... Five more months were spent on entering, cleaning, and processing data.” Although time-consuming research can provide valuable information about irrigation, decisions for modernization improvements must be made more quickly and must be comprehensive.

An essential ingredient for successful application of the RAP is adequate training of the evaluators. Experience has shown that successful RAP programmes require: (i) evaluators with prior training in irrigation; (ii) specific training in the RAP techniques; and (iii) follow-up support and critique when the evaluators begin their fieldwork.

An RAP will be unsuccessful if its accompanying computer spreadsheet files are merely mailed to local irrigation projects to be filled out. Evaluators must understand the logic behind all the questions, and they must learn how to go beyond the obvious when obtaining data. Ideally, if two qualified persons complete a RAP on a single irrigation project, the indicators that are computed by both persons will be very similar.

Typical baseline data for external indicators (such as water balances and irrigation efficiency) are either readily available or they are not. Individual irrigation projects have differences in the ease of access to typical baseline data on the command area (CA), weather, water supply, etc. In some projects, the data can be gathered in a day; in others, it may take weeks. Usually, the delays in data organization are related to finding the time to pull the data out of files and organizing them. If the data do not already exist, spending an additional three months on the site will not create them.

A quick and focused examination of irrigation projects can give a reasonably accurate and pragmatic description of the status of the project and of the processes and hardware that influence that status. This allows for the identification of the major actions that can be taken quickly in order to improve water delivery service – especially if the RAP is conducted in cooperation with the local irrigation authorities.

The question of what is “reasonably accurate” in data collection and computations can always be debated. Confidence intervals should be assigned to most water balance data – reflecting the reality that there are always uncertainties in data and computation techniques. In irrigation matters, studies are typically concerned about 5–10-percent accuracy ranges, not 0.5–1-percent accuracy ranges (Clemmens and Burt, 1997). The problems encountered in irrigation projects are typically so gross and obvious to the properly trained eye that it is unnecessary to strive for extreme accuracy when attempting to diagnose an irrigation project. Furthermore, projects typically have such unique sets of characteristics that the results from a very detailed study of just a few items on one project may have limited transferability to other projects. In addition, even with very sophisticated and detailed research, it is difficult to achieve better than about 5–10-percent accuracy on some key values, such as crop evapotranspiration of irrigation water.

For the RAP, it is necessary to begin with a prior request for information that can be assembled by the irrigation project authorities – information such as cropped areas, flow rates into the project, weather data, budgets, and staffing. Upon arriving at the project, the evaluators organize these data and interview project managers regarding missing information and their perceptions of how the project functions. The evaluators then travel down and through the canal network, talking to operators and farmers, and observing and recording the methods and hardware that are used for water control. Through this systematic diagnosis of the project, many aspects of engineering and operation become very apparent.

Experience has shown that an RAP is not suitable for the collection of some economic data. Data such as the overall cost of a project, per capita income, and the size of typical farm management units were not readily available in most of the projects described in FAO (1999).

In summary, where executed properly with qualified personnel, the RAP can provide swift and valuable insight into many aspects of irrigation project design and operations. Furthermore, its structure provides a systematic project review that enables an evaluator to provide pragmatic recommendations for improvement.

Some of the data collected during an RAP are also useful in quantifying various benchmark indicators established by the IPTRID. Most of the IPTRID benchmark indicators fall into the category of "external indicators", whereas RAP indicators include both "external" and "internal" indicators. As discussed below, internal indicators are necessary for understanding the processes used within an irrigation project and the level of water delivery service throughout a project. They also help an evaluator to formulate an action plan that will eventually result in an improvement in external indicators. External indicators and traditional benchmarking indicators provide little guidance as to what must be done in order to accomplish improvement. Rather, they only indicate that things should be improved.

EXTERNAL INDICATORS FOR WATER SOURCES AND WATER DESTINATIONS

External indicators

External indicators for irrigation projects are ratios or percentages that generally have forms such as:

$$\frac{\text{Water Required}}{\text{Total Water Available}}$$

or:

$$\frac{\text{Crop Yield}}{\text{Irrigation Water Delivered to the Fields}}$$

The IPTRID benchmarking indicators fall into the category of external indicators, and the RAP also generates a long list of external indicators.

The common attribute of external indicators is that they examine inputs and outputs for a project. External indicators are expressions of various forms of efficiency, whether the efficiency is related to budgets, water or crop yields. Moreover, they only require knowledge of inputs and outputs to the project. By themselves, external indicators do not provide any insight into what must be done in order to improve performance or efficiency. The identification of what actions must be taken to improve these external indicators comes from an examination of internal indicators, which examine the processes and hardware used within the project.

However, external indicators do establish key values – such as whether or not it might be possible to conserve water (without defining how that might be accomplished). As such, low values of external indicators often provide the justification for modernization of projects – with the anticipation that modernization or intervention will improve the values of those external indicators.

The RAP external indicators focus on items of a typical water balance. As such, values such as crop evapotranspiration, effective precipitation, and water supplies must be obtained. The primary purpose of Worksheets 1–3 in the spreadsheet that accompanies the RAP package is to estimate water-related external indicators.

Confidence intervals

A certain amount of error or uncertainty is inherent in all measurement or estimation processes. Therefore, the true or correct values for the water volumes needed to calculate terms such as "irrigation efficiency" are unknown. Estimates must be made of the component volumes, based on measurements or calculations.

In reports that provide estimates of terms such as crop yield and water balance ratios, such as "irrigation efficiency" and "relative water supply", the uncertainties associated with these estimates should be acknowledged and quantified. Otherwise, planners may not know whether the true value of a stated 70-percent efficiency lies between 65 percent and 75 percent, or between 50 percent and 90 percent.

One method of expressing the uncertainty in a single-valued estimate is to specify the confidence interval (CI) for that estimate. Where it is believed that a reasonable evaluation of data indicates that the correct value lies within 5 units of 70, then it should be stated that the quantity equals 70±5. More specifically, the essence of a CI should be illustrated as follows when discussing an estimated quantity: "The investigators are 95-percent confident that their estimate of the irrigated area in the project is within ±7 percent of 500 000 ha (between 465 000 ha and 535 000 ha)."

Statistically, a CI is related to the coefficient of variation (CV), where: CV = (mean)/(standard deviation). The "CV" has no units. In addition, CI = ±2 × CV where the CI is expressed as a fraction (%/100) of the estimated value. Stated differently, if the CI is declared to be 0.10, this means that the ±2 standard deviations cover a range of ±10 percent of the stated value.

Assuming a normal distribution of data, then in about 68 percent of cases the true value is found within plus or minus one standard deviation of the estimated value. Similarly, in about 95 percent of cases (from which comes the "95-percent confident" statement), the true value is found within plus or minus two standard deviations of the estimated value.

A logical question could be: "How confident are you of the CI that has been selected?" The answer for an RAP is: "The CI is not precise, but it nevertheless gives a good idea of the evaluator's sense for the accuracy of various values." It is better to provide a relative indication of the uncertainty in a value than it is to ignore the uncertainty and have people treat estimates as if they are absolute values.

In the RAP, the evaluator is asked to provide CI estimates for various data quantities. These CI estimates are manually entered into blank cells of Worksheet 4 (External Indicators). The computer spreadsheet then calculates automatically CI estimates for indicators that use these data.

There are two common conventions for computing the CI of a computed value (result). If two independently estimated quantities are added, the CIs are related by:

$$CI_r = \frac{\sqrt{m_1^2 CI_1^2 + m_2^2 CI_2^2}}{m_1 + m_2}$$

where:

- CI_r = CI of the result;
- CI_1 = CI of the first quantity added to form the result;
- CI_2 = CI of the second quantity added to form the result;
- m_1 = estimated value of the first quantity;
- m_2 = estimated value of the second quantity.

If two independently estimated quantities are multiplied together, the CIs are related by:

$$CI_r = \sqrt{CI_1^2 + CI_2^2 + \frac{CI_1^2 CI_2^2}{4}}$$

A rigorous estimate of CIs would require assigning CI values to each of the original data in the first three "input" worksheets of the computer spreadsheet used for the RAP. However, for a typical RAP, it is not worth striving for more precision than can obtained by inserting CI estimates in the "Indicator Summary" worksheet. For the convenience of the evaluator, the "Indicator Summary" worksheet automatically computes the CI_r for some pertinent quantities, utilizing various CI values provided by the evaluator.

INTERNAL PROCESSES AND INTERNAL INDICATORS

The broad goals of modernization are to achieve:

- improved irrigation efficiency (an external indicator);
- better crop yields (another external indicator, which is not used here);
- less canal damage from uncontrolled water levels;
- more efficient labour;
- improved social harmony;
- an improved environment as accomplished by fewer diversions or better-quality return flows.

In general, these goals can only be achieved by paying attention to internal details. The specific details addressed by the RAP are: (i) improving water control throughout the project; and (ii) improving the water delivery service to the users.

Therefore, Worksheets 5–11 have the following purposes:

- identify the key factors related to water control throughout a project;
- define the level of water delivery service provided to the users;
- examine specific hardware and management techniques and processes used in the control and distribution of water.

Many of these items are described in the form of "internal indicators", with assigned values of 0–4 (0 indicating least desirable, and 4 denoting the most desirable).

A summary of the internal indicators is found in Worksheet 12. Most of the internal indicators have subcomponents, called "subindicators". At the end of the spreadsheet, each of the subindicators is assigned a "weighting factor".

As an example of the use of internal indicators, Primary Indicator I-1 is used to characterize the actual water delivery service to individual ownership units (Table A3.1). Primary Indicator I-1 has four subindicators:

- I-1A. Measurement of volumes to the field;
- I-1B. Flexibility to the field;
- I-1C. Reliability to the field;
- I-1D. Apparent equity.

Each of the subindicators (e.g. I-1A) has a maximum potential value of 4.0 (best), and a minimum possible value of 0.0 (worst).

The value for each Primary Indicator (e.g. I-1) is computed automatically in the "Internal Indicators" worksheet by:

TABLE A3.1
Primary Indicator I-1 information

No.	Primary Indicator	Subindicator	Ranking criteria	Wt.
I-1	Actual water delivery service to individual ownership units (e.g. field or farm)			
I-1A		Measurement of volumes to the individual units (0–4)	4 – Excellent measurement and control devices, properly operated and recorded. 3 – Reasonable measurement and control devices, average operation. 2 – Useful but poor measurement of volumes and flow rates. 1 – Reasonable measurement of flow rates, but not of volumes. 0 – No measurement of volumes or flows.	1
I-1B		Flexibility to the individual units (0–4)	4 – Unlimited frequency, rate and duration, but arranged by users within a few days. 3 – Fixed frequency, rate or duration, but arranged. 2 – Dictated rotation, but it approximately matches the crop needs. 1 – Rotation deliveries, but on a somewhat uncertain schedule. 0 – No established rules.	2
I-1C		Reliability to the individual units (0–4)	4 – Water always arrives with the frequency, rate and duration promised. Volume is known. 3 – Very reliable in rate and duration, but occasionally there are a few days of delay. Volume is known. 2 – Water arrives about when it is needed and in the correct amounts. Volume is unknown. 1 – Volume is unknown, and deliveries are fairly unreliable, but less than 50% of the time. 0 – Unreliable frequency, rate, duration, more than 50% of the time, and volume delivered is unknown.	4
I-1D		Apparent equity to individual units (0–4)	4 – All fields throughout the project and within tertiary units receive the same type of water delivery service. 3 – Areas of the project receive the same amounts of water, but within an area the service is somewhat inequitable. 2 – Areas of the project receive somewhat different amounts (unintentionally), but within an area it is equitable. 1 – There are medium inequities both between areas and within areas. 0 – There are differences of more than 50% throughout the project on a fairly widespread basis.	4

1. Applying a relative weighting factor to each subindicator value. The weighting factors are only relative to each other within the indicator group; one group may have a maximum value of 4, whereas another group may have a maximum value of 2. The only factor of importance is the relative weighting factors of the subindicators within a group.
2. Summing the weighted subindicator values.
3. Adjusting the final value based on a possible scale of 0–4 (4 indicating the most positive conditions).

THE SPREADSHEETS FOR THE RAP

Table A3.2 describes the worksheets for the RAP.

GENERAL GUIDELINES FOR WORKSHEET USAGE

Names and types

The worksheet names within any Excel file are identified at the bottom of the screen. These must not be changed.

The Excel file has two general types of worksheets:

➢ Input worksheets. These worksheets request data:

TABLES A3.2

Summary of the worksheets to be compiled as part of an RAP

Worksheets in spreadsheet	Worksheet description
1. Input – year 1	For an average water year, requires input (mostly monthly) of: - crop names - irrigation water salinity - crop threshold ECe values - field crop coefficients, by month - areas of crops - water supply - precipitation - recirculation and groundwater pumping - special agronomic requirements.
4. External indicators (ignore these, except to input needed "CI" values)	Automatic computations of monthly and annual values of various water supply indicators. These are temporary values- except the user must input "CI" values. The final, important values can be found in the Worksheet 14 "World Bank BMTI Indicators".
5. Project office questions	Most of the data for this sheet are obtained from the project office. They include: - general project conditions - water supply location - ownership of land and water - currency - budgets - project operation, as described by office staff - stated water delivery service at various levels in the system.
6. Project employees	Requests information on employee training, motivation, dismissal, & work descriptions.
7. WUA	Data for WUAs that were not obtained in the "Project Office Questions" are obtained here. This requires asking questions in the project office as well as having interviews with WUAs. Questions relate to: - size of WUAs - strength of organization - functions - budgets - water charges.
8. Main canal	Data for the main canal, including: - control of flows - general canal characteristics - cross-regulators - general conditions - operation rules - turnouts - communications - regulating reservoirs - the level of service provided to the next lower level.
9. Second-level canals	Same as main canal.
10. Third-level canals	Same as second-level canals.
11. Final deliveries	Information regarding the level of water delivery service to individual ownership units, and at the last point of operation by paid employees.
12. Internal Indicators	This worksheet summarizes the internal indicators that were calculated in the previous worksheets, plus asks for input regarding a few extra indicators. Weighted category indicators are computed for groups of subindicators.
13. Benchmark Indicators	This worksheet holds intermediate calculated values. Ignore this page.
14. World Bank BMIT Indicators	This, plus Worksheet 12, provides the final summary for the exercise.

  - In the first worksheet, the data are manipulated and/or used in computations on the far right-hand side of the data sheets, out of view of the input pages. (Some computations can be seen by scrolling the pages to the right.)
  - In the Worksheets 5–11, a few internal computations appear vertically in line with input data.
- ➢Summary worksheets. These are Worksheets 4, 12, 13 and 14. The two important ones are 12 and 14. Worksheets 4 and 12 require a limited number of input values, but their primary function is to summarize various data, computed values, and indicators.

Cell colouring and input conventions

The colour convention for the first Input – Year “x” worksheet is:

- ➢Blank cell – indicates a place for data input.
- ➢Shaded cell – contains a default or calculated value or an explanation, or indicates that no data entry is required. In general, any values within the shaded cells should not be changed unless one understands all of the programming.
- ➢Red letters – indicate computed values.
- ➢Blue values – indicate values that were transferred from elsewhere in the file. They may be computed or input elsewhere.

The colour convention for Worksheet 4. – External Indicators is:

- ➢Blank cell – in the “Est. CI” column only – requires the manual input of a value.
- ➢Shaded cell – indicates values that are linked to previous worksheets or are calculated within this worksheet.
- ➢Red letters – indicate values computed within this worksheet.
- ➢Blue values – indicate values that were transferred from elsewhere in the file.

Conventions for Worksheets 5–13 are:

- ➢Blank cells with a light-lined border require input.
- ➢Blank cells with a dark-lined border indicate that the value is needed, but that it requires information that may only be available at a later time.
- ➢Any cell that is filled with a pattern or which is shaded should not receive input.
- ➢Shaded cells contain formulas and will show the results of automatic computations.
- ➢Cells with patterns are merely dividers between sections, or indicate that no data are needed.

The first input worksheet requires data for a single year, but it is important to provide data for multiple years (i.e. run the program several times with new data), because an examination of only a single year can be misleading for many projects that have wide fluctuations in climate and water supply.

WORKSHEET DESCRIPTIONS

Worksheet 1. Input – Year 1

The worksheet contains ten tables that require data, as well as various individual cells for specific information. Information requests are described below.

Before Table 1

Total project area: This is the gross project area (hectares), including fields that are supported by a project water delivery infrastructure (“command”) and fields that are not supported by the infrastructure.

Total field area in the CA: This is the number of hectares that are supported by a project water delivery infrastructure. There may be some zones of this CA that never receive water because of infrastructure damage, shortage of water, etc.

Estimated conveyance efficiency for external water:

$$\text{Conveyance Efficiency} = \frac{\text{Volume of external irrigation water delivered}}{\text{Volume of external irrigation water at the source(s)}} \times 100$$

where, in this case, the "point of delivery" is where farmers take control of the water – that is, where the WUA and project authorities hand the water over. Sometimes, a turnout (offtake) represents the final point of delivery by an irrigation authority, yet that turnout supplies 100 fields. Conveyance losses include seepage, spillage, water lost in filling and emptying canals, evaporation from canals, and evapotranspiration from weeds along the canals. The conveyance efficiency includes losses that occur between the point of original diversion and the entrance to the CA, which in some cases may be many kilometres apart.

Estimated conveyance efficiency for internal project recirculation: This is the conveyance efficiency for water that originates within the project, by project authorities. That is, it includes water that the agency pumps from wells or drain ditches or other internal sources. It does not include any water that is imported into the project boundaries.

Estimated seepage rate for paddy rice: There will only be an answer here if paddy rice is grown in a project. This is the percentage of water applied to fields that goes below the rootzone of the rice. Seepage rates are often expressed in millimetres per day, in which case they must be converted to a percentage of the field-applied irrigation water. Many studies combine "seepage" together with "evapotranspiration" for rice, to arrive at a combined "consumptive use". This convention is not used in the RAP because such a combination makes it very difficult to separate evapotranspiration (which cannot be recirculated or reduced) from seepage water (which can be recirculated via wells or drains). Furthermore, such a convention ignores the fact that deep percolation is unavoidable on all crops, not only on paddy rice. Therefore, the convention would apply to all crops, not just paddy rice.

Estimated surface losses from paddy rice to drains: There will only be an answer here if paddy rice is grown in a project. This is the percentage of irrigation water applied to fields, or groups of fields, that leaves the fields and enters surface drains. This does not include water that flows from one paddy into another paddy unless it ultimately flows into a surface drain.

Estimated field irrigation efficiency for other crops: This is an estimate for non-rice crops. The elements of inefficiency for paddy rice (deep percolation and surface runoff losses) have already been dealt with. The term "irrigation efficiency" has a rigorous definition (Burt *et al.*, 1997). However, the nature of an RAP is such that the values required for the rigorous application of the definition will not be available. Therefore, for the purposes of the RAP:

$$\text{Field Irrigation Efficiency} = \frac{\text{Irrigation Water Used for ET and Special Practices}}{\text{Irrigation Water Applied to the Field}} \times 100$$

where:

- The only water considered in the numerator and denominator is "irrigation" water. Water from precipitation is not included as this indicator is a measure of how efficiently irrigation water is used.
- "Special practices" include water for leaching of salts, land preparation, and climate control. However, for each of these categories, there is an upper limit on the amount that is accepted as beneficial use (and that can be included in the numerator). The RAP computations include an estimate of actual leaching requirement needs. The water assigned for land preparation for rice should not include excess deep percolation (caused by holding water too long on a field) or water that flows off the surface of a field.

- For crops such as rice, which are often farmed as a unit that includes several fields that pass water from one field to another, "field" efficiency can be based on the larger management unit of several smaller field parcels.

In general, this value is a rough estimate. The spreadsheet computes a correct value of "field irrigation efficiency" in Worksheet 4. External Indicators (Indicator No. 31), which should be compared against this assumed value. This value is only used for one purpose in the spreadsheet: to estimate the recharge to the groundwater from field deep percolation. If, upon completion of the RAP, this estimate is different from the computed estimate, the RAP user should adjust this assumed value (and/or the rice deep percolation and surface runoff values) until Indicator 2 approximately equals Indicator 31.

Flow rate capacity of the main canal (or canals) at diversion point (or points): This value should reflect the sum of the actual (as opposed to "design") maximum flow rate capacities from each diversion point. Sometimes, the actual capacities are higher than the original design capacities, and in other cases they have been reduced owing to siltation or other factors.

Actual peak flow rate into the main canal (or canals) at the diversion point (or points): The purpose of this question is to define the maximum flow rate of irrigation water that enters the project boundaries. It should not include any internal pumping or recirculation of water.

Average salinity (ECe) of the irrigation water: Where possible, this "average" should be the annual weighted average, based on the salt load (ppm × flow rate × time). It should be computed as a combination of the well water and surface water.

Table 1 – Field coefficients and crop threshold ECe

Water Year Month

The table provides 12 cells at the top of the Field Coefficient section into which the names of all 12 months are to be placed. Although the table could have had a default month of "January" in the first cell, many projects have "water years" that begin at other months, such as April in Southeast Asia, or October or November in Mexico. Place the appropriate month in the highlighted empty cell in order to begin the water year accounting.

Irrigated Crop Name

This column allows the user to input the names of the irrigated crops in the CA. A total of 17 crops are allowed, although the first three are already assigned to "Paddy Rice", leaving 14 other names blank for the user. A CA may have more than 17 crops. However, many of these crops have small areas of cultivation, and for practical purposes they can be lumped together as a single crop category. Where a crop is double-cropped, then that crop name should be entered twice. The table already has default names for three paddy rice crops, because so many projects have three or more rice crops per year. It is not possible to override the paddy rice crops; it is not possible to substitute other names for these 3 entries because certain computations assume rice in these cells. Crop names only need to be entered once – in Table 1. They are automatically carried into all other tables that require crop names. This ensures consistency between tables.

Salinity

There are two values for salinity:

- Average irrigation water salinity (ECw), dS/m. The average salinity of the irrigation water that comes into the project. The units of dS/m are equivalent to mmho/cm.
- Threshold ECe, dS/m. This is the salinity of a saturated soil-paste extract at which

TABLE A3.3
Salt tolerance of various crops to soil salinity, after germination

Crop	Threshold ECe (ECe at initial yield decline) dS/m	Crop	Threshold ECe (ECe at initial yield decline) dS/m
Alfalfa	2.0	Onion	1.2
Almond	1.5	Orange	1.7
Apricot	1.6	Orchard grass	1.5
Avocado	1.3	Peach	1.7
Barley (grain)	8.0	Peanut	3.2
Bean	1.0	Pepper	1.5
Beet, garden	4.0	Plum	1.5
Bermuda grass	6.9	Potato	1.7
Broad bean	1.6	Rice, paddy	3.0
Broccoli	2.8	Ryegrass, perennial	5.6
Cabbage	1.8	Sesbania	2.3
Carrot	1.0	Soybean	5.0
Clover	1.5	Spinach	2.0
Corn (forage and grain)	1.8	Strawberry	1.0
Corn, sweet	1.7	Sudan grass	2.8
Cowpea	1.3	Sugar beet	7.0
Cucumber	2.5	Sugar cane	1.7
Date	4.0	Sweet potato	1.5
Fescue, tall	3.9	Tomato	2.5
Flax	1.7	Wheat	6.0
Grape	1.5	Wheat grass, crested	3.5
Grapefruit	1.8	Wheat grass, tall	7.5
Lettuce	1.3		

Source: After Maas and Hoffman (1977).

a crop yield will begin to decline. Example values are found in Table A3.3.

The leaching requirement (LR) for each crop is computed within the spreadsheet as:

$$LR = \frac{ECiw}{(5 \times ECe) - ECiw}$$

where: ECiw = EC of the irrigation water (dS/m); and ECe = threshold saturated paste extract of the crop (dS/m). For example, if ECiw = 1.0 dS/m and the crop is grain corn (Table A3.3), then LR =

$$\frac{1}{(5 \times 1.8) - 1} = .125$$

The extra water required for each crop, to remove salinity that arrives with the irrigation water, is then computed as:

Extra water for salinity control = $(\text{ET of irrigation water}) \times \frac{LR}{1 - LR}$

For example, if for a specific crop, ET of irrigation water = 100 000 MCM and LR = 0.125, then volume of water needed for salinity control = 14 286 MCM. However, deep percolation of rainwater will accomplish the same task (it washes accumulated salts out of the rootzone). Therefore, this RAP approximates the irrigation water requirement as: Volume of irrigation water needed for salinity control = Volume of water needed for salinity control - Rainfall deep percolation.

Field coefficients

Most irrigation specialists are familiar with the term “crop coefficient”. Crop coefficients have been widely used in estimates of crop evapotranspiration (ET) since the mid-1970s. The general formula used is: ETcrop = *Kc* × ETo, where: *Kc* = the crop coefficient; and ETo = grass reference ET. Guidelines for estimating ET and ETo are given in FAO (1998).

“Reference” values other than ETo are sometimes used, but they are being replaced rapidly with weather stations that provide the hourly data needed to compute ETo. This spreadsheet uses ETo as defined in FAO (1998) because:

- ETo is the standard “reference”.
- Most excellent ET research on a variety of crops uses ETo as the reference crop.
- ETo estimates tend to be more accurate than other reference methods, such as evaporation pans.

Where the only local data are from evaporation pans, it is advisable to consult with FAO (1998) in order to determine the proper conversion from monthly Epan to monthly ETo values. In Table A3.4, ETo = *Kp* × Epan.

This spreadsheet uses the term “field coefficient” because often a “crop coefficient” is only used during the crop-growing season, and often the common usage of “crop coefficients” ignores the impacts of soil moisture contents.

In reality, the “field coefficient, *Kc*” is the same as the “crop coefficient, *Kc*” if the crop coefficient is properly adjusted – using FAO (1998) guidelines – to include factors such as:

- stress (reduced transpiration) caused by a dry rootzone;
- soil surface evaporation due to rainfall or irrigation.

TABLE A3.4
Pan coefficients (*Kp*) for Class A pan for different pan siting and environment and different levels of mean relative humidity (RH) and wind speed

Class A pan description →	Case A: Pan placed in short green cropped area				Case B: Pan placed in dry fallow area			
RH mean (%) →		low (< 40)	medium (40–70)	high (> 70)		low (< 40)	medium (40–70)	high (> 70)
Wind speed (m/s)	Windward side distance of green crop (m)				Windward side distance of dry fallow (m)			
Light (< 2)	1	.55	.65	.75	1	.7	.8	.85
	10	.65	.75	.85	10	.6	.7	.8
	100	.7	.8	.85	100	.55	.65	.75
	1 000	.75	.85	.85	1 000	.5	.6	.7
Moderate (2–5)	1	.5	.6	.65	1	.65	.75	.8
	10	.6	.7	.75	10	.55	.65	.7
	100	.65	.75	.8	100	.5	.6	.65
	1 000	.7	.8	.8	1 000	.45	.55	.6
Strong (5–8)	1	.45	.5	.6	1	.6	.65	.7
	10	.55	.6	.65	10	.5	.55	.65
	100	.6	.65	.7	100	.45	.5	.6
	1 000	.65	.7	.75	1 000	.4	.45	.55
Very strong (> 8)	1	.4	.45	.5	1	.5	.6	.65
	10	.45	.55	.6	10	.45	.5	.55
	100	.5	.6	.65	100	.4	.45	.5
	1 000	.55	.6	.65	1 000	.34	.4	.45

Source: FAO, 1998.

The proper selection of field coefficients depends on a good understanding of Table 8 in the input spreadsheets (Precipitation, effective precipitation, and deep percolation of precipitation). The computation procedure that the spreadsheet uses includes:

- effective precipitation and irrigation water are assumed to be the only external sources of water for field ET;
- the field ET is computed on a monthly basis as: ET = $Kc \times$ ETo.

Effective precipitation includes all precipitation that is lost through either evaporation (from the soil or plant) or transpiration, as computed by the formula above. Therefore, in order to account for soil evaporation for those months when the crop is not in the ground, it is necessary to do two things simultaneously:

- The effective precipitation must be computed to account for that evaporation.
- A field coefficient (*Kc*) of greater than 0.0 must be applied to those months.

The following procedure is recommended for the RAP:

- For crops with no irrigation water used for pre-plant irrigation. If for a month the crop has not yet been planted, or a crop is not in the field, assume that for that month:
  - crop coefficient = 0.0;
  - effective rainfall that is reported for that month will only include water that is stored in the rootzone for ET after the seeds are planted.
- For crops that use irrigation water for pre-plant irrigation (e.g. rice field preparation, cotton pre-irrigation). Follow the above procedure until the irrigation water is first applied. Then do the following for each month until the crop is planted or transplanted:
  - crop coefficient > 0 to account for soil evaporation of both irrigation water and effective rainfall;
  - effective rainfall that is reported for that month will include water that is stored for ET after planting, plus the rainfall contribution to the soil evaporation prior to planting.

For example, it is possible to consider a case in which:

- A pre-plant irrigation is applied to a field on the first day of the month.
- The crop will not be planted for another month.
- The soil remains bare and free from weeds for this month.
- The soil remains "dark" for three days after standing water disappears from the soil surface.

Table A3.5 indicates how to compute an average monthly *Kc* that takes the soil evaporation properly into account. Rules to follow include:

TABLE A3.5
Example computation of an average monthly *Kc* value for a month following a pre-plant irrigation, but prior to planting

Day	Kc	Explanation
1	1.05	Irrigation – wet soil surface.
2	1.05	2nd day of irrigation - wet soil surface.
3	1.05	1st day after irrigation. No standing water. Soil surface still dark.
4	1.05	2nd day after irrigation. Soil surface still dark.
5	1.05	3rd day after irrigation. Soil surface still dark.
6	0.70	4th day after irrigation.
7	0.50	5th day after irrigation.
8	0.30	6th day after irrigation.
9	0.15	7th day after irrigation.
10	0.15	8th day after irrigation.
11	1.05	Rain – wet soil surface.
12	1.05	2nd day of rain – wet soil surface.
13	1.05	1st day after rain. Soil surface still dark.
14	1.05	2nd day after rain. Soil surface still dark.
15	1.05	3rd day after rain. Soil surface still dark.
16	0.70	4th day after rain.
17	0.50	5th day after rain.
18	0.30	6th day after rain.
19	0.15	7th day after rain.
20	0.15	8th day after rain.
21	1.05	Rain – wet soil surface.
22	1.05	2nd day of rain – wet soil surface.
23	1.05	1st day after rain. Soil surface still dark.
24	1.05	2nd day after rain. Soil surface still dark.
25	1.05	3rd day after rain. Soil surface still dark.
26	0.70	4th day after rain.
27	0.50	5th day after rain.
28	0.30	6th day after rain.
29	0.15	7th day after rain.
30	0.15	8th day after rain.
Average *Kc* =	0.71	for this month of 30 days.

- The minimum value of *Kc* is typically 0.15.
- Where a soil surface is dark in appearance from moisture, even if there is no standing crop, a crop coefficient of 1.05 is appropriate.
- Most unstressed field crops (cotton, rice and corn) have a crop coefficient of about 1.1 once they have achieved 100-percent canopy cover.

Table 2 – Monthly ETo values

ETo values (in millimetres) by month should be entered. See the above discussion regarding crop coefficients. Ideally, ETo should be computed on an hourly basis using the Penman–Monteith method (FAO, 1998).

Table 3 – Surface water entering the command area boundaries (MCM)

All values for this table should be in units of million cubic metres (MCM), and should only include water that can be used for irrigation. In other words, flows from a river flowing through a CA that has no diversion structures or pumps would not be included. The table allows for three general categories of surface inflows:

- Irrigation water entering from outside the CA. The MCM should be the total MCM at the original diversion point (or points). Therefore, technically speaking it is not the MCM entering the CA. This category of "irrigation water" is the "officially diverted" irrigation water supply.
- Other inflows from External Source #2. This source can be defined by the RAP user, and can be a consolidation of several physical sources – but all placed in one category. However, these inflows must be accessed by users within the CA as an irrigation supply – either through diversion or through pumping from rivers.
- Other inflows from External Source #3. This has the same qualification as External Source #2.

The key concepts for Table 3 are:

- Table 3 only includes surface volumes that enter from outside the CA boundaries.
- The surface volumes are only included if they are volumes of water used for irrigation. For the purposes of the RAP, External Sources #2 and #3 are considered irrigation water if they consist of water that individual farmers or groups of farmers divert or pump. Many projects have such supplemental supplies that do not enter the CA through designed and maintained canals, yet these supplies are important parts of the overall irrigation supply in the CA.

The important value here is the volume of water that enters the CA, not the volume of water that is pumped from drains (as that may also include recirculation of spills and field runoff).

Table 4 – Internal surface water sources (MCM)

Table 4 values do not represent original supplies of water (as the surface sources were already accounted for in Table 3). Rather, this is the volume of water that is recirculated or pumped from surface sources within the project. This may be water that originated from the irrigation canal and was spilled, deep percolated, or ran off from fields. The origin of the water is not the important thing in Table 4. Rather, the important feature for Table 4 is which entity diverts or pumps this non-canal water.

Table 5 – Hectares of each crop in the command area, by month

Table 5 provides information on how much area is used for each crop during each month.

The *Kc* values for each crop are found in the row immediately above the row into which it is necessary to input the hectares of that crop. If a *Kc* value greater than

0.0 exists for a month for that crop, it is necessary to input the number of hectares associated with that crop, for that month.

Table 6 – Groundwater data

These questions only need to be answered where groundwater is used by farmers or by the project authorities.

Groundwater accounting in irrigation projects frequently ignores external sources of groundwater, and the fact that much of the groundwater may simply be recirculated surface water. The RAP eliminates the double-counting of recirculated water, which is what happens where groundwater is treated as an independent supply.

Table 6 recognizes that an aquifer may extend well beyond the confines of the CA.

The questions are divided into two categories: pumping from the aquifer within the CA; and pumping from the aquifer but outside the CA. Both areas must be considered if the aquifer is to be examined properly. The external indicators and benchmarking indicators do not utilize the external pumping information. However, the pumping from outside the CA is frequently completely dependent upon seepage and deep percolation from within the CA. In such a case, a "water conservation" programme within the CA to minimize seepage may actually eliminate the water source for groundwater pumpers outside the CA. There may also be considerations such as contamination of the groundwater as it passes through old marine sediments – increasing the salinity of groundwater as compared with surface water.

The "net" groundwater pumping within the CA can only be greater than or equal to zero (given the way the spreadsheet is designed). For the computations:

- estimates of deep percolation from fields are made;
- estimates of seepage from canals are made.

When combined, these two represent the recharge of the aquifer from external irrigation water.

Estimates are then made of the groundwater pumping that occurs within the CA – either by project authorities or by individual farmers. This groundwater pumping volume is then discounted for estimated losses. The result is an estimate of the groundwater that actually contributes to evapotranspiration.

The volume of groundwater that is used for ET is compared with the recharge from surface water supplies. If the recharge is greater than the ET of groundwater, then the "net" groundwater pumping = 0.0. If the ET of groundwater is greater than the recharge, the difference is the "net" groundwater pumping. In most projects, the "net" groundwater pumping will equal zero because typically the aquifer is recharged with the imported surface irrigation water.

Although groundwater pumping is an important aspect of recirculation of irrigation water, it is not a "new" supply of water any more than recirculation of surface water would be. Recirculation of any type will increase the irrigation efficiency of the project. However, it will not have any impact on the irrigation efficiency of the field units unless the recirculation occurs on the fields themselves.

Table 7 – Precipitation, effective precipitation, and deep percolation of precipitation

The monthly gross precipitation (in millimetres) is required at the top of the table. These values are generally easy to obtain.

The other values may be a bit of a mystery to most users although the concepts of effective precipitation and deep percolation are common concepts. The problem the users will have is in identifying proper values. Simple assumptions about deep percolation and the percentage of rainfall that is effective do not work for spreadsheets such as these, which are designed to be applied over a wide range of geography, each having vast differences in climates and crops.

Effective precipitation is defined as precipitation that is destined for ET (evaporation or transpiration) either this month or in the future.

Effective precipitation and deep percolation can be input in this table for any or all months, regardless of whether a crop is in the field that month. The deep percolation of rainfall is used for only one computation purpose: as a computed reduction of the amount of irrigation leaching water that is necessary to wash salts from the rootzone.

In general, values for "effective precipitation" and "deep percolation" are not available as monthly values, and they are almost never available for individual crops. Nevertheless, it is important to make an estimate of these values.

As an aid to the spreadsheet user, the calculated ETfield values (in millimetres) are carried forward from previous tables (these tables are found on the far right-hand side of the pages of this worksheet, and include computations using ETo and *Kc* values). Once the spreadsheet user inputs an estimate of the percentage of effective precipitation, a corresponding depth of effective precipitation will appear in the next row.

In general, if there is a light rainfall during a month yet the ETfield is high, there will be very little deep percolation of rainfall. Conversely, if there is a large amount of rainfall and very little ETfield, then more deep percolation can be expected. Deep percolation also depends on the soil type (sandy soils have more deep percolation than do clay soils). The deep percolation cannot exceed the quantity: Precipitation - Effective precipitation.

Table 8 – Special agronomic requirements (mm)

Only a few crops will have values in this table. The most notable crop is paddy rice.

In the following example for a rice crop, the assumption is that the rice field needs to be flooded prior to planting:

- flooding – 1 March;
- planting – 15 March.

The field stays covered with a small depth of water the entire time, or at least the soil is very wet the entire time. Therefore, the "field coefficient, *Kc*" equals 1.05. It is further assumed that there is a monthly ETo of 120 mm during March.

Furthermore, it is assumed that the field coefficient, *Kc*, has been computed following the example at the beginning of this annex. The difference between this example and the earlier one is that this example is very simple – the soil is always wet, so the *Kc* is always equal to 1.05.

If the crop coefficient for March were entered as 1.05, then ET for the whole month of March would be computed separately. Therefore, Table 9 would not include any ET amount that occurred between 1 March and 15 March.

However, if the crop coefficient for March were entered as 1.05/2 = 0.53, this would indicate that the spreadsheet user only wanted to count the ET starting on 15 March as "crop ET", and the ET between 1 March and 15 March would be included in Table 8. It is recommended that the first approach be used (using a *Kc* of 1.05 for the month).

Assuming that the first approach is used (*Kc* = 1.05 for March), then the value in Table 8 must only include two things:

- the deep percolation amount of irrigation water;
- the amount of irrigation water that runs off the field, or group of fields, into surface drains.

If there had been rainfall during March, some of the runoff and deep percolation would have been rainwater. Table 8 only includes irrigation water amounts, so any rainfall amounts must be subtracted from total seepage and runoff.

Table 9 – Crop yields and values

Three types of input are needed:

- the local exchange rate (US$/local currency);
- typical average yields of each crop, in tonnes per hectare;
- the farmgate selling price of each crop, in local currency per tonne.

Worksheet 4. External indicators

This worksheet is a temporary holding place for some values and computations.

For the user, the primary usage of this worksheet is to enter confidence interval values.

INTERNAL INDICATOR SECTION

Worksheets 5–12 require a good field visit to the project by qualified evaluators. They focus on how the project actually works – what the instructions are, how water is physically moved throughout the canal/pipeline system, what perceptions and reality are, and other items such as staffing, budgets and communication. A quick look (rapid appraisal) of these items will immediately identify weaknesses and strengths in the project. Action items are virtually always readily apparent after the systematic RAP has been conducted.

Worksheets 5–12 contain a large number of pages. However, only about 25 percent of the lines require an answer (the other lines are explanations or blanks), and computations are only necessary for a few items such as budget questions. Furthermore, the questions for the main canal are identical to those for the second-level canals and the third-level canals. Once an evaluator understands the questions for the main canal, the remainder of the pages are easily answered after a field visit.

Worksheet 5. Project office questions

Most of the questions in this worksheet should be filled out by the irrigation project employees prior to the visit, as this includes many simple data values such as salaries, number of employees, and stated project policies.

However, the evaluator must answer some of the questions during the visit.

This worksheet includes questions that address the possibility of chaos existing in a project. “Chaos” exists when the reality in a project does not match what project authorities believe occurs. Therefore, the evaluator must ask the project authorities what levels of water delivery service the main canal delivers, what various operators do, and how water reaches individual farmers. These “stated” conditions are later compared against what the evaluator actually observes in the field.

In general, it is easiest to modernize irrigation projects that have a minimum of chaos. If the project authorities are either not aware of actual field conditions, or if they refuse to recognize certain problems, it is then very difficult to make changes.

This worksheet also introduces the concept of assigning a rating of 0–4 to project characteristics, with 0 being the worst rating and 4 being the best. In the majority of cases, the evaluator reads a series of descriptions, and assigns a rating to each of that “internal indicators” that are later summarized in Worksheet 12 (Internal indicators).

Some indicator values (such as “O&M adequacy”) are calculated automatically based on previous answers. The rating scale for those values can be found by highlighting the calculated value and reading the formula in the cell.

This worksheet has some drainage and salinity information questions at the very end. These are used in various benchmarking indicators.

Where there is an “umbrella” WUA (elected by smaller WUAs) that manages the project, then that “umbrella” WUA is considered part of the “project office”.

Worksheet 6. Project employees

Most of these questions require a qualitative assessment of conditions in the project, with the evaluator giving a rating of 0–4 for each question. Topics include:

- adequacy of employee training;
- availability of written performance rules;
- power of employees to make independent decisions;
- the ability of the project to dismiss employees with cause;
- rewards to employees for good work.

Worksheet 7. WUA

In the worksheets, the abbreviation WUA stands for water user association. Some irrigation projects have a large WUA that operates the whole project canal system, but the final water distribution is done by many smaller WUAs. In such a situation, the WUA questions pertain only to the smaller WUAs.

Many of the questions are identical to those in Worksheet 5 (Project office questions).

The answers must reflect average conditions throughout the whole irrigation project, rather than any single WUA. Therefore, several WUAs must be visited in order to answer the questions properly.

Worksheet 8. Main canal

This worksheet begins with six questions about general conditions throughout the project. The answers will have a large CI (defined earlier in the section covering external indicators). However, because there are large differences between various projects, the answers are meaningful.

The remainder of the questions are identical to those for the second-level and third-level canals. While most of the questions are self-explanatory, a few points warrant special explanation.

The wave travel time is the is the lag time between making a change in flow rate at one point in a canal and having the change stabilize at another point downstream.

Concerning the functionality of various structures and instructions, evaluators must always consider the operations from the point of view of the operator, and ask themselves: “If I were to walk up to this structure, how would I know what to do and would it be easy to do?” For example, where the objective is to maintain a constant water level with a structure:

- What does “constant” mean – within 1 cm or within 5 cm?
- How many times a day would the structure need to be moved, and even with that movement would it be possible to achieve the desired result?
- Is the structure dangerous or difficult to operate?

If an operator is told to deliver a flow rate into a canal, yet there is no flow rate measurement device (or the device is inaccurate, improperly maintained, improperly located, or requires significant time to stabilize), then it will be almost impossible to accurately achieve the desired result.

Therefore, the evaluator should not simply listen to explanations. The evaluators must put themselves into the operator’s shoes. It is not sufficient to know that the operator moves something and then looks at something; the evaluators must understand whether those “somethings” do indeed give the proper answer.

The format of Worksheet 8 is:

- General observations are recorded.
- Ratings are given to various aspects of operation, maintenance and process. Some of these ratings depend on the general observations that are recorded in the same worksheet. Other ratings stand on their own.

It may appear that some of the general observations are not necessary because they are addressed later in the form of ratings. However, they have been included in order to force the evaluators to make a more systematic examination of various features – which are summarized in later ratings.

The questions about actual service are key. RAP evaluators must recognize that the RAP has been designed under the assumption that all employees of an irrigation project have their jobs for one reason only – to provide service to customers.

By analysing a project by "levels" (office, main canal, second-level canal, third-level canal, distributaries, and field), a huge project can be understood in simple terms. The operators of the main canal have one objective only – everything they do should be done to provide good water delivery service to their customers, the second level canals (and perhaps a few direct turnouts from the main canal). This "service concept" must be understood and accepted by everyone, from the chief engineer to the lowest operator. Once it is accepted, then system management becomes very simple. Personnel on each level are only responsible for the performance of that level.

Main-canal operators do not need to understand the details of that day's flow-rate requirements on all the individual fields. In order to subscribe to the service concept, operators generally need to know that their ultimate customer is the farmer. However, the details of day-to-day flow rates do not need to be known at all levels. Rather, the main-canal operators have one task to accomplish – to deliver flow rates at specific turnouts (offtakes) with a high degree of service. Service is described in the RAP with three indices:

- ➢ flexibility, composed of:
  - frequency,
  - flow rate,
  - duration;
- ➢ reliability;
- ➢ equity.

For very simple field irrigation techniques, reliability and equity are crucial. Without good reliability and equity, there are generally social problems, such as vandalism and non-payment of water fees. Thus, reliability and equity are cornerstones of projects that have good social order.

In order to have efficient field irrigation practices, some minimum level of flexibility is required. Even with the most basic irrigation methods, such as paddy rice, the flow rates are completely different at the beginning of the season (for land preparation) compared with when the rice crop is established. Moreover, not everyone plants at the same time, meaning that the irrigation project must have some flexibility built into it.

In order to obtain a high project efficiency, the canal system must have sufficient flexibility built into it to be able to change flows frequently in response to continually changing demands and weather. However, most irrigation projects are not very flexible. Furthermore, most irrigation projects have low project efficiencies.

Finally, evaluators need to consider that a major purpose of the RAP is to identify what can be done in order to improve project performance. Modern field irrigation methods, e.g. sprinkler and drip, require a much higher degree of flexibility and reliability than do traditional surface irrigation methods. The evaluators must always be asking themselves during the RAP: "I do not only want to recommend how to rehabilitate the project – I want to recommend steps that will move the project closer to a higher efficiency and better water management as the future will certainly demand. Will these structures and operating instructions and personnel be capable of meeting the new requirements, and if not, what adjustments must be made?"

Therefore, the examination of the main canal must be thorough. The evaluators need to start at the source, and work their way to the downstream end of the canal. This is not to say that every single structure must be analysed. However, evaluators must examine the key structures along the complete length of the canal.

Common challenges that evaluators have to overcome are:

- The project authorities want to spend a disproportionate amount of time at the dam, discussing dam maintenance, the watershed, and politics. Actually, the only items of interest at the dam are: (i) the storage; and (ii) how discharges are computed and actually made and measured.
- Evaluators will be told: "the canal is all the same". The explicit or implied conclusion is that the evaluators only need to examine portions of the canals near the headworks. It may be true that the canal is indeed identical along its complete length. However, in general, there are significant differences in maintenance, slope, structures, etc. along its length. Only by physically travelling along the canal will the evaluators learn about those differences.
- The operation will be explained by project authorities that are accompanying the evaluators. This is a difficult challenge. The office visit (Worksheet 5) is designed to obtain the perspective of the office staff and bosses. A purpose of the field visit is to talk to the actual structure operators and review their notes – without having their bosses interrupt and give the "official" answer. In many cases, it is necessary to separate the bosses from the operators, so that the operators are not cautious with the answers they give. Therefore, the "rules of the game" must be understood before the field visit is made.

Another challenge arises in the selection of which canals to visit. Sometimes, a project will have two or more main canals, and dozens of "second-level" canals. However, in general, operator instructions, hardware, and maintenance levels will be similar on all of the canals at a specific level. Visiting more canals is helpful, but it is not necessary to visit all of the canals in a project.

Different main canals each have a few specific engineering/hydraulic challenges. One canal may have a bottleneck (restriction) at a river crossing, and another canal may have a peculiar control problem – even though everything else seems the same. If the RAP evaluators can provide good recommendations for such specific hydraulic problems (that are not covered specifically in the RAP forms), the credibility of the evaluators will be enhanced, and RAP recommendations will have a better chance of being accepted. Therefore, the evaluators should take ample pictures and notes during the visit.

Basic advice for evaluators as they tour the canals (main, second, third, etc.) is summarized in Box A3.1.

BOX A3.1
Advice for evaluators

Understand everything. Understand how the operators think things should work. Question everything. If you do not understand explanations, continue to question the explanations until you understand the perspective of the operators. But go beyond that. Every structure has a function. Do not be satisfied with attempting to visualize how that function can be accomplished more easily or better; question the very reason why the structure has been assigned that function. Perhaps in a modernization plan, a structure that is currently operated under flow-rate control should instead be operated under upstream water-level control. In other words, question the very nature of the strategies of operation – not just individual structures. The RAP is not an examination of individual structures – it is a comprehensive examination of a whole process…in which structures have functions. One must understand the pieces (operators, rules and structures) in order to understand the process, but the RAP also questions the assumptions behind the specific processes themselves. The RAP requires evaluators who can look beyond the individual pieces; it requires evaluators who can visualize how the pieces can be manipulated and re-arranged as parts of a complete process that provides good service and high efficiency.

Worksheet 9. Second-level canals

See the discussion for Worksheet 8. Second-level canals are those that receive water from the main canals. In general, the second-level canals are operated differently from the main canals.

Worksheet 10. Third-level canals

See the discussion for Worksheet 8. In many medium-sized projects, the "third level" does not exist; therefore, this worksheet would not be filled out in such cases.

Worksheet 11. Final deliveries

There are two possible points that are considered in this worksheet. One is the Individual Ownership Units – the smallest unit that is owned by a single individual (where private ownership is allowed) or that is managed by a farmer. The Individual Ownership Unit may be larger than a single field where one farmer receives water and then distributes the water over several fields from a single turnout (very common in the United States of America). The key feature of the Individual Ownership Unit is that, at this point, there is no cooperation needed between individual farmers.

The second point is the Point of Management Change. In projects with a high density of turnouts, the Point of Management Change may be the same as the point of Individual Ownership Units. In other words, the irrigation project authority (or the WUA) employee delivers water all the way to the field level. The Point of Management Change is the "hand-off" point between paid employees and volunteers or farmers.

In some projects, the irrigation authorities place great emphasis on the number of farmers within a project. It is necessary to go beyond this statistic when examining the present operation, because the project authorities may relinquish control of the water to groups of 200 farmers – who are expected to somehow provide equitable and reliable water distribution among themselves. Therefore, there are two important indicators for this discussion:

- The number of fields (Individual Ownership Units) downstream of the Point of Management Change. The greater is the number, the poorer is the reliability, equity and flexibility of water delivery service. Furthermore, any number greater than 1 or 2 indicates that drip and sprinkler irrigation are almost impossible to support.
- The number of turnouts that are operated per employee. This is much more meaningful than the "number of farmers per employee", because employees may never provide water directly to individual farmers.

Worksheet 12. Internal indicators

This worksheet contains three types of values:

- Summaries of the various internal subindicators that were rated in the previous worksheets, and then computed weighted values for each primary indicator. The shaded columns on the right-hand side provide information about the values, the weighting factors, and the worksheet location for detailed rating criteria of the subindicators. All of these values are given a rating of 0–4, with 4 being highest and most desirable.
- Subindicators and primary indicators, the values of which are input directly into this worksheet (as opposed to being transferred from previous worksheets). These are indicators I-32, I-33 and I-34. These values all have a rating of 0–4.
- A few indicators (I-35+) that do not conform to the rating scale of 0–4. Rather, these are direct ratios of values or individual values that have special significance.

Worksheet 13. IPTRID indicators

This worksheet is an intermediate worksheet that should not be used. Instead, refer to Worksheet 14, as described below.

Worksheet 14. World Bank BMTI indicators

This worksheet contains the “Benchmarking Technical Indicators”, or BMTI values, as of October 2002 for the water year described. The definitions of the various BMTI values are given in Tables A3.6–A3.9.

HOW TO INTERPRET RAP RESULTS

The RAP, by itself, is only a diagnostic tool. It allows a qualified evaluator to examine an irrigation project systematically in order to determine the external indicators and the internal indicators.

The external indicators give an indication of whether it is possible to conserve water and enhance the environment through improved water management. The internal indicators give a detailed perspective of how the system is actually operated, and of the water delivery service that is provided at all levels.

The interpretation of the results requires one or more irrigation specialists who have a clear understanding of the options for modernization. Without a thorough knowledge of these options, the recommendations can be ineffective and even counterproductive.

The basic rules are:

- ➢In almost all projects, modernization requires both hardware and management changes.
- ➢In general, it is quite possible to provide high levels of water delivery service to turnouts without good water control if the system is very inefficient and there is a very abundant supply of water. However, if the system must also be efficient, the only way to provide good water delivery service is to have excellent control of the water.
- ➢In almost all projects, water delivery service needs to be improved in order to meet the basic objectives of lower labour costs, reduced spill, improved crop yields, and less environmental damage. The RAP process allows the evaluator to target the appropriate level (or levels) on which to begin modernization.
- ➢In general, there are many very simple changes that can be made in operational procedures, and numerous others that require only a moderate investment in capital for hardware changes.
- ➢All changes must be accompanied by quality control and excellent training.
- ➢There must be a clear understanding the difference between CA irrigation efficiency and field irrigation efficiency. In projects without internal recirculation, the CA irrigation efficiency is generally lower than the field irrigation efficiency. However, in projects with internal recirculation of water, the CA irrigation efficiency may be greater than the field irrigation efficiency.

The CA irrigation efficiency benchmarking indicator combines many of the previous indicators into a single indicator value:

$$\frac{\text{Crop ET - Effective precipitation + Leaching irrig. water needed}}{\text{Surface irrigation water into the project + Net groundwater pumping}} \times 100$$

This expression of irrigation efficiency does not conform to the precise requirements defined by Burt *et al.* (1997), but it is close enough to give a reasonable estimate of the CA irrigation efficiency.

A CA irrigation efficiency of 100 percent is impossible. In general, efficiencies greater than 60 percent require internal recirculation of losses – either as surface water recirculation or from groundwater pumping, or both.

In short, improvement in command area irrigation efficiency can be achieved in two ways: (i) reduce first-time losses; and (ii) recirculate first-time losses.

First-time losses occur in two areas:

- ➢Conveyance losses. These include:

TABLE A3.6

Definitions of Benchmarking Technical Indicators: water balance indicators

Indicator	Definition	Data specifications
Total annual volume of irrigation water available at the user level (MCM) (also called "irrigation water delivered").	Total volume of irrigation water (surface water plus groundwater) directly available to users, MCM – using stated conveyance efficiencies for surface and groundwater supplies. It includes water delivered by project authorities as well as water pumped by the users themselves. Water users in this context describe the recipients of irrigation service; these may include single irrigators or groups or irrigators organized into water user groups. This value is used to estimate field irrigation efficiency; it is not used to estimate project irrigation efficiency.	Calculated from the stated value of system water delivery efficiency (from the dam or diversion point to the final project employee delivery point). Includes farmer pumping, because this is a "delivery" in the sense that it is irrigation water that is available to the farm/field.
Total annual volume of irrigation supply into the three-dimensional boundaries of the command area (MCM).	This is the irrigation water that is imported into the project boundaries, to include river diversions, reservoir discharges, and net groundwater extraction from the aquifer. This value is used to estimate project irrigation efficiency; it is not used in the computation of field irrigation efficiency.	Determination of this value requires a detailed water balance where there is groundwater pumping, because the net extraction must be estimated.
Total annual volume of irrigation water managed by authorities (MCM).	This is the irrigation water that is imported into the project boundaries by the authorities, plus any internal groundwater pumped by the authorities. The value is not used to compute any efficiencies, as some of the internal pumping may be recirculation of original source water. However, this is the volume of water that the project authorities administer, so it is used for the computations related to costs.	
Total annual volume of water supply (MCM).	Total annual volume of surface water diverted and net groundwater abstraction, plus total rainfall, excluding any recirculating internal drainage within the scheme.	This is the irrigation water that is imported into the project boundaries, to include river diversions, reservoir discharges, and net groundwater extraction from the aquifer. Plus, this includes total rainfall.
Total annual volume of irrigation water delivered to users by project authorities.	Total volume of water delivered to water users by the authorities over the year that was directly supplied by project authorities (including WUA) diversions or pumps. Water users in this context describe the recipients of irrigation service, these may include single irrigators or groups or irrigators organized into water user groups. This does not include farmer pumps or farmer drainage diversions.	This can be measured directly, or is more commonly estimated based on an assumed conveyance efficiency.
Total annual volume of groundwater pumped within/to the command area (MCM).	Total annual volume of groundwater that is pumped by authorities or farmers that is dedicated to irrigated fields within the command area. This groundwater can originate outside of the command area.	An answer must be provided even if the user does not precisely know the volume of groundwater pumped. The uncertainty can be handled by assigning a large confidence interval, if necessary.
Total annual volume of field ET in irrigated fields (MCM).	Total annual volume of crop ET. This includes evaporation from the soil as well as transpiration from the crop. Depending on how the user entered the data, this may include off-season soil evaporation.	This is computed based on crop coefficients and ETo values.
Total annual volume of ET – effective precipitation (MCM).	The volume of evapotranspiration that must be supplied by irrigation water. Regardless of how one enters data for ET (above), if one follows the guidelines in this manual, one obtains the same final answer of (ET – effective ppt.) – which is the net irrigation requirement.	The user gives an estimate of the effective rainfall, by month, and by crop. Effective rain contributes to the ET.
Peak net irrigation water ET requirement (CMS).	The net peak daily irrigation requirement (ET – effective rainfall) for the command area, based on actual cropping patterns for this year (CMS).	Calculated as the peak monthly (ET – effective rainfall) value, divided by the number of days in that month.
Total command area of the system (ha).	The physical hectares of fields in the project that that are provided with irrigation infrastructure and/or wells.	

TABLE A3.6

Definitions of Benchmarking Technical Indicators: water balance indicators (Continued)

Indicator	Definition	Data specifications
Irrigated area, including multiple cropping (ha).	The hectares of cropped land that received irrigation. If a 1-ha field has two irrigated crops per year, the reported irrigated area would be 2.0 ha.	
Annual irrigation supply per unit command area (m^3/ha)	(Total annual volume of irrigation supply into the command area) / (Total command area of the system)	Total annual volume of irrigation supply into the command area: see earlier definition. Total command area of the system: see earlier definition.
Annual irrigation supply per unit irrigated area (m^3/ha)	(Total annual volume of irrigation supply) / (Total annual irrigated crop area)	Total annual volume of irrigation supply: see earlier definition. Total annual irrigated crop area: see earlier definition. Includes multiple cropping.
Conveyance efficiency of project-delivered water (%). (Weighted value using stated values)	(Volume of irrigation water delivered by authorities) / (Total annual volume of project authority irrigation supply)	Volume of external irrigation water delivered by authorities: total volume of irrigation water supply that is delivered to water users by the project authorities over the year. Water users in this context describe the recipients of irrigation service; these may include single irrigators or groups or irrigators organized into water user groups. Total annual volume of project authority irrigation supply: see earlier definition.
Estimated conveyance efficiency for project groundwater (%).	(Annual volume of project groundwater delivered to users × 100) / (Annual volume of groundwater pumped by authorities)	Annual volume of project groundwater delivered to users: This refers to a weighted value of conveyance efficiency for groundwater that is pumped by authorities from wells both inside and outside of the command area, but which is delivered within the command area. Annual volume of groundwater pumped by authorities: self-explanatory.
Annual relative water supply (RWS).	(Total annual volume of water supply) / (Total annual volume of field ET in irrigated fields)	Total annual volume of water supply: see earlier definition. Total annual volume of field ET: see earlier definition.
Annual relative irrigation supply (RIS).	(Total annual volume of irrigation supply into the 3-D boundaries) / (Total annual volume of ET – effective precipitation)	Total annual volume of irrigation supply into the 3-D boundaries: see earlier definition. Total annual volume of ET – effective precipitation: see earlier definition.
Water delivery capacity.	(Canal capacity to deliver water at system head) / (Peak irrigation water ET requirement)	Canal capacity to deliver water at system head: actual gross discharge capacity of main canal (canals) at all diversion points (CMS). Peak irrigation water ET requirement: : see earlier definition (CMS).
Security of entitlement supply (%).	The frequency with which the irrigation organization is capable of supplying the established system water entitlements.	System water entitlement: the bulk volume (MCM) or bulk discharge of water (CMS) to which the scheme is entitled per year.
Average field irrigation efficiency (%).	((ET - Effective precipitation + LR water) × 100) / (Total public and private water delivered to fields)	All values are expressed in 12-month volumes.
Command area irrigation efficiency (%).	((ET + Leaching needs - Effective ppt.) × 100) / (Surface irrigation imports + Net groundwater)	All values are expressed in 12- month volumes.

TABLE A3.7
Definitions of Benchmarking Technical Indicators: financial indicators

Indicator	Definition	Data specifications
Cost recovery ratio.	(Gross revenue collected) / (Total MOM cost)	Gross revenue collected: total revenues collected from payment of services by water users. Total MOM cost: total management, operation and maintenance cost of providing the irrigation and drainage service excluding capital expenditure and depreciation/renewals.
Maintenance cost to revenue ratio.	(Maintenance cost) / (Gross revenue collected)	Maintenance cost: total expenditure on system maintenance. Gross revenue collected: total revenues collected from payment of services by water users.
Total MOM cost per unit area (US$/ha).	(Total MOM cost) / (Total command area serviced by the system)	Total MOM cost: see earlier definition. Total command area serviced by the system: see earlier definition.
Total cost per staff person employed (US$/person).	(Total cost of personnel) / (Total number of personnel)	Total cost of personal: total cost of personnel employed in the provision of the irrigation and drainage service, either in the field or office (including secretarial and administrative staff). Includes WUA employees and project employees. Total number of personnel engaged in irrigation and drainage service: total number of personnel employed in the provision of the irrigation and drainage service, either in the field or office (includes secretaries, administrators). This includes WUA employees and project employees.
Revenue collection performance.	(Gross revenue collected) / (Gross revenue invoiced)	Gross revenue collected: total revenues collected from payment of services by water users. Gross revenue invoiced: total revenue due for collection from water users for provision of irrigation and drainage services.
Staff persons per unit irrigated area (Persons/ha).	(Total number of personnel engaged in irrigation and drainage service) / (Total irrigated area serviced by the system)	Total number of personnel engaged in irrigation and drainage service: total number of personnel employed in the in provision of the irrigation and drainage service, including secretarial and administrative staff – in WUAs plus project employment. Total irrigated area (ha): see earlier definition.
Number of turnouts per field operator.	(Total number of turnouts [offtakes]) / (Total number of personnel engaged in field irrigation and drainage service)	Total number of personnel engaged in irrigation and drainage service: total number of field personnel employed in the provision of the irrigation and drainage service, including supervisors. Total number of turnouts: the number of turnouts (offtakes) to fields, farms, or groups of farmers, plus offtakes to laterals and sublaterals, that are physically operated by the field personnel.
Average revenue per cubic metre of irrigation water delivered to water users by authorities (US$/m^3).	(Gross revenue collected) / (Total annual volume of project irrigation water delivered)	Gross revenue collected: total revenues collected from payment of services by water users. Total annual volume of irrigation water delivered: see earlier definition.
Total MOM cost per cubic metre of irrigation water delivered to water users by the project authorities (US$/m^3).	(Total MOM cost) / (Total annual volume of irrigation delivered by project authorities)	Total MOM cost: total management, operation and maintenance cost of providing the irrigation and drainage service excluding capital expenditure and depreciation/renewals. Total annual volume of irrigation water delivered by project authorities: see earlier definition.

TABLE A3.8
Definitions of Benchmarking Technical Indicators: agricultural productivity and economic indicators

Indicator	Definition	Data specifications
Total annual value of agricultural production (US$).	Total annual value of agricultural production received by producers.	
Output per unit command area (US$/ha).	(Total annual value of agricultural production) / (Total command area of the system)	Total annual value of agricultural production: total annual value of agricultural production received by producers. Total command area of the system: the command area is the nominal or design area provided with irrigation infrastructure that can be irrigated.
Output per unit irrigated area, including multiple cropping (US$/ha).	(Total annual value of agricultural production) / (Total annual irrigated crop area)	Total annual value of agricultural production: see earlier definition. Total command area of the system: see earlier definition.
Output per unit irrigation supply (US$/m^3).	(Total annual value of agricultural production) / (Total annual volume of irrigation supply into the 3-D boundaries of the command area)	Total annual value of agricultural production: see earlier definition. Total annual irrigated crop area: see earlier definition.
Output per unit water supply (US$/m^3).	(Total annual value of agricultural production) / (Total annual volume of water supply)	Total annual value of agricultural production: see earlier definition. Total annual volume of water supply: see earlier definition.
Output per unit of field ET (US$/m^3).	(Total annual value of agricultural production) / (Total annual volume of field ET)	Total annual value of agricultural production: see earlier definition. Total annual volume of field ET: see earlier definition.

TABLE A3.9
Definitions of Benchmarking Technical Indicators: environmental performance indicators

Indicator	Definition	Data specifications
Water quality: average salinity of the irrigation supply (dS/m).	Salinity (electrical conductivity) of the irrigation supply.	Weighted (by volume) value, using monthly data. Should include both surface water and groundwater supplies.
Water quality: average salinity of the drainage water (dS/m).	Salinity (electrical conductivity) of the drainage water that leaves the command area.	Weighted (by volume) value, using monthly data.
Water quality: average biochemical oxygen demand (BOD) of the irrigation supply (mg/litre).	Biological load of the irrigation supply expressed as BOD.	Weighted (by volume) value, using monthly data. Should include both surface water and groundwater supplies.
Water quality: average BOD of the drainage water (mg/litre).	Biological load of the drainage water expressed as BOD.	Weighted (by volume) value, using monthly data.
Water quality: average chemical oxygen demand (COD) of the irrigation water (mg/litre).	Chemical load of the irrigation supply expressed as COD.	Weighted (by volume) value, using monthly data. Should include both surface water and groundwater supplies.
Water quality: average COD of the drainage water (mg/litre).	Chemical load of the drainage water expressed as COD.	Weighted (by volume) value, using monthly data.
Average depth to shallow water table (m).	Average annual depth of the shallow water table calculated from water table observations over the irrigation area.	This is an average value for the area of high water table.
Change in shallow water table depth over time (m) (+ indicates up).	Change in shallow water table depth over the last five years.	This is an average value for the area of high water table.

- spillage from canals and pipelines;
- seepage from canals;
- phreatophtye water consumption.

➢Field losses. These include:
- conveyance losses in field channels;
- surface runoff from fields;

  - deep percolation in fields, caused by: standing water in rice fields, non-uniformity of irrigation water application, and excess duration of irrigation water application.

There is considerable merit in reducing first-time losses because these can have a direct effect on required canal capacity, fertilizer loss, pesticide losses, local waterlogging, etc. In most projects, seepage from canals is targeted, although often other components of first-time losses are more important and cause greater damage to the environment.

Options for the recirculation of first-time losses:

- ➢ Surface recirculation. Surface drains, creeks, and rivers pick up first-time losses that originated as:
  - seepage or deep percolation that returns to creeks from a high water table;
  - surface runoff from fields;
  - spillage from canals.
- ➢ Pumping from the groundwater. This recirculates first-time losses that originated as:
  - seepage;
  - field deep percolation.

In some cases, recirculation is the least expensive and quickest option for improving project irrigation efficiencies.

A common mistake in modernization is the elimination of first-time losses with the belief that this will improve project irrigation efficiencies. However, where such first-time losses are already recirculated within the project, there may not be any true water conservation.

However, other benefits can be obtained from the elimination of first-time losses:

- ➢ easier operation of the distribution system from lining;
- ➢ better crop yields through better first-time water management;
- ➢ less contamination of water by fertilizers and pesticides.

At the beginning of the RAP input sheets, the RAP user is asked to provide estimates of field irrigation efficiency for rice and other crops. These estimates should account for all conveyance losses, field deep percolation, and surface runoff downstream of the delivery point from the project authorities. However, Worksheet 14 (World Bank BMTI indicators) gives a better estimate of field irrigation efficiency – based on a water balance of the project. This value should be compared with the stated value in Worksheet 1 in order to see whether the stated value corresponds to the water balance values. In general, the water balance values are much closer to the truth.

How to use field irrigation efficiency values

Where the field irrigation efficiency is low, it should not necessarily be concluded that the farmers need better education on how to irrigate properly. In many projects, such training is worthless because project authorities dictate the schedule and amounts of water delivery, and the farmers have almost no choice in the matter.

Low field irrigation efficiencies are typically an indication of a water delivery system that is unreliable, inequitable and/or inflexible. Generally, the water delivery system must be improved before significant field efficiency improvements can take place.

However, there is one practice that can be implemented immediately without changing the water delivery system. This is land grading. Most of the world's irrigation projects use surface irrigation, and good land grading is important for good in-field distribution uniformity of water.

Where the project irrigation efficiency is greater than the field irrigation efficiency, then there is considerable recirculation within the project.

Project irrigation efficiency is the key indicator as to whether there is an opportunity to conserve water. Field irrigation efficiency gives no indication of this by itself, because a large share of the field losses is often re-circulated.

"Water conservation" in a hydrological basin (as opposed to a specific irrigation project) can only be achieved where one of the following occurs:

- Water flows to salt sinks (ocean, localized salty groundwater) are eliminated.
- Excess evapotranspiration (ET) is reduced (weed and phreatophtye and drain ET is reduced).

Even where good water management does not conserve water in the basin, it does has appreciable benefits, including:

- improving downstream water quality;
- improving the timing of water usage;
- reducing the flow-rate requirements into a project;
- reduction in pumping (sometimes);
- improving crop yields through better timing of applications and reduced fertilizer leaching.
- improving the quality and quantity of flows in rivers and streams immediately downstream of irrigation diversion points.

Summary of the interpretation process

In general, the process of interpretation is as follows:

- Field irrigation efficiencies are examined. Good field efficiencies depend on receiving good water delivery service at the field.
- Project irrigation efficiencies are examined. It is very common for irrigation project personnel to want higher flow rates into the project, although the inefficiencies may be quite high. An important alternative to increasing the water supply is to improve efficiencies.
- Conveyance efficiencies are noted, and compared against field irrigation efficiencies. Both of these are considered in light of any recirculation (groundwater or surface water) that may occur. The comparison helps to determine where efforts might be made.
- The attributes of water delivery service are examined for each level.
- The appropriateness of hardware and operator instruction is reviewed.
- The existence of recirculation systems is noted. In many projects, installing surface water recirculation systems in strategic areas is a simple way to improve performance and water delivery service.
- Where employees spend their time is an important indication of where changes can be made. For example, many projects have a large staff of hydrographers who continually take current meter readings at many locations in the main canals. In general, this inaccurate (owing to the inherent nature of unsteady flows and point-in-time measurements) work can be eliminated completely if a new strategy for water delivery is adopted.

With modernization, some actions can be taken in parallel with others, but some actions require a foundation. For example, automation with electronic programmable logic controllers (PLCs) first requires excellent access to sites, excellent communications, and a strong infrastructure for electronic troubleshooting and repairs. They also require a project that has an excellent maintenance record. In other words, PLC automation requires a substantial foundation that is often lacking in irrigation projects. PLC implementation without that foundation is almost guaranteed to fail.

Typically, the key steps for modernization are:

1. Eliminate the discrepancy between "actual" and "stated" service. Where project managers refuse to accept reality, it is best to spend time and money on other projects.

2. All levels of staff must understand and adopt the "service mentality". While this is not achieved overnight, modernization concepts are rooted in this mentality. Without it, attempts to modernize a project will typically have minimal benefit.
3. Examine instructions that are given to operators, and modify them as needed. A classic example in many Asian projects is where the objective of cross-regulators is to maintain an upstream water level, but the gate operators must move the cross-regulators in strict accordance with instructions (of specific gate movements) from the office – based on computer programs or spreadsheets. A simple check in the field will show that water levels are not maintained properly. The instructions for the operators must be changed, and they are very simple: "Maintain the upstream water level within a specified tolerance of a defined target".
4. The first three items are the easiest, but they may also be the most difficult with some senior staff. If the first three items cannot be achieved, it is best to either walk away from a project, or else dismiss the senior staff. Changes in the first three items may take some training, study tours, etc.
5. The next steps, more or less in order of sequence, are to improve the following areas:
   - ➢ Understanding of what actually happens in the system. Experts can evaluate a project quickly and because of their background, understand almost immediately the cause/effect relationships and the probable level of service. The operators and supervisors often do not see things the same way. It is very helpful to install simple dataloggers and water-level sensors at key locations in order to record spills, flow-rate fluctuations, and water-level fluctuations. This is almost always revealing for operators who can only visit a location once per day.
   - ➢ Communications at all levels. This starts with person-to-person communications (often by radio).
   - ➢ Mobility of staff. In general, a small yet mobile staff is much more efficient than a large, immobile staff. This is because a small mobile staff is not responsible for just one or two structures, but must understand how various structures and actions affect other areas. Mobility may be improved by better roads, motorcycles, trucks, etc.
   - ➢ Flow-rate control and measurement at key bifurcation points. "Measurement" and "control" are not the same. Both are needed. There are many combinations of structures and techniques that provide rapid and accurate control and measurement of flow rates. This is typically a weak area for many irrigation projects.
   - ➢ Existence of recirculation points or buffer reservoirs in the main canal system. "Loose" water control may be very adequate in the main system – provided there exists a place to re-regulate about 70 percent of the way down a canal.
   - – Improved water-level control throughout the project. The flow-rate control and measurement (above) pertain only to the heads of canals and pipelines. Downstream of the head, it is important to easily maintain fairly constant water levels so that turnout flow rates do not change with time, and so that the canal banks are not damaged. With the proper types of structures, this is easy to do without much human effort.
   - ➢ Re-organization of procedures for ordering and dispersing water. In most modern projects, one group is responsible for operating the main canal; another is responsible for the second level, and so on. Each group then has a very specific service objective. If a main canal is broken into "zones" with different offices controlling different "zones", there is almost always conflict between the zones. Re-organization of the operators is typically necessary. In addition, the whole

procedure for receiving real-time information from the field and responding promptly to requests must typically be revamped for most projects.

- Remote monitoring of strategic locations. Such locations are typically buffer reservoirs, drains, and tail-ends of canals.
- Remote manual control of flow rates at strategic locations. These are the heads of the main canal, and heads of major offtakes (turnouts) from the main canal.
- Provision for spill, and the recapture of that spill, from the ends of all small canals.

The above points do not mention canal lining and maintenance equipment. Maintenance equipment must be adequate, and canal lining can reduce maintenance and seepage. However, these topics have been discussed for many decades, and the large sums of money spent on canal lining have generally not brought about modernization. This is because modernization is not just a single action. The items under point 5 represent a departure from traditional thinking of “concrete civil engineers” and a focus on operations.

Another “missing” item is a discussion about downstream control and sophisticated canal control algorithms. This is because an irrigation project must walk very well before it runs, and these technologies might be considered as “high risk”. Sophisticated controls should be selected only after other options have been ruled out, and never before an adequate support infrastructure exists. There is no “magic pill” for modernization and improved irrigation performance, and simple options often provide excellent results.

It is good to listen to the operators and try to detect a few things that give them a lot of problems. It is sometimes possible to solve some of these problems quickly. By solving these problems for the operators, they will become advocates of further modernization efforts.

CONCLUSIONS

When conducted and analysed by a qualified irrigation engineer, the RAP provides indicators that explain the results and processes of an irrigation project. Many of these indicators can be used for benchmarking purposes, allowing for a comparison between projects and pre-/post-modernization performance. In a short period of only a few weeks, the RAP provides sufficient information to target key action items for modernization. Therefore, it serves as a valuable tool for countries to prioritize investments in different projects, and to prioritize specific actions within individual irrigation projects.

REFERENCES

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A. & Eisenhauer, D.E. 1997. Irrigation performance measures - efficiency and uniformity. *J. Irrig. Drain. Eng.*, 123(6): 423–442.

Clemmens, A.J. & Burt, C.M. 1997. Accuracy of irrigation efficiency estimates. *J. Irrig. Drain. Eng.*, 123(6).

FAO. 1998. *Crop evapotranspiration – guidelines for computing crop water requirements*, by R.G. Allen, L.S. Pereira, D. Raes & M. Smith. FAO Irrigation and Drainage Paper No. 56. Rome. 300 pp.

FAO. 1999. *Modern water control and management practices in irrigation: impact on performance*, by C.M. Burt & S.W. Styles. FAO Water Report No. 19. Rome. 224 pp.

Kloezen, W.H. & Garcés-Restrepo, C. 1998. *Assessing irrigation performance with comparative indicators: the case of Alto Rio Lerma Irrigation District, Mexico*. IWMI Research Report 22.

Maas, E.V. & Hoffman, G.J. 1977. Crop salt tolerance - current assessment. *Proc. Irrig. Drain. J.*, 103(IR2): 115–134.

Plusquellec, H., Burt, C.M. & Wolter, H.W. 1994. *Modern water control in irrigation - concepts, issues, and applications*. World Bank Technical Paper No. 246. Irrigation and Drainage Series. Washington, DC, World Bank. 104 pp.

Note

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FAO TECHNICAL PAPERS

FAO IRRIGATION AND DRAINAGE PAPERS

1	Irrigation practice and water management, 1972 (Ar* E* F* S*)
1 Rev.1	Irrigation practice and water management, 1984 (E)
2	Irrigation canal lining, 1971 (New edition, 1977, available in E, F and S in the FAO Land and Water Development Series, No. 1)
3	Design criteria for basin irrigation systems, 1971 (E*)
4	Village irrigation programmes – a new approach in water economy, 1971 (E* F*)
5	Automated irrigation, 1971 (E* F* S*)
6	Drainage of heavy soils, 1971 (E* F* S*)
7	Salinity seminar, Baghdad, 1971 (E* F*)
8	Water and the environment, 1971 (E* F* S*)
9	Drainage materials, 1972 (E* F* S*)
10	Integrated farm water management, 1971 (E* F* S*)
11	Planning methodology seminar, Bucharest, 1972 (E* F*)
12	Farm water management seminar, Manila, 1972 (E*)
13	Water use seminar, Damascus, 1972 (E* F*)
14	Trickle irrigation, 1973 (E* F* S*)
15	Drainage machinery, 1973 (E* F*)
16	Drainage of salty soils, 1973 (C* E* F* S*)
17	Man's influence on the hydrological cycle, 1973 (E* F* S*)
18	Groundwater seminar, Granada, 1973 (E* F S*)
19	Mathematical models in hydrology, 1973 (E*)
20/1	Water laws in Moslem countries – Vol. 1, 1973 (E* F*)
20/2	Water laws in Moslem countries – Vol. 2, 1978 (E F)
21	Groundwater models, 1973 (E*)
22	Water for agriculture – index, 1973 (E/F/S*)
23	Simulation methods in water development, 1974 (E* F* S*)
24	Crop water requirements, (rev.) 1977 (C* E F S)
25	Effective rainfall, 1974 (C* E* F* S*)
26/1	Small hydraulic structures – Vol. 1, 1975 (E* F* S*)
26/2	Small hydraulic structures – Vol. 2, 1975 (E* F* S*)
27	Agro-meteorological field stations, 1976 (E* F* S*)
28	Drainage testing, 1976 (E* F* S*)
29	Water quality for agriculture, 1976 (E* F* S*)
29 Rev.1	Water quality for agriculture, 1985 (C** E* F* S*)
30	Self-help wells, 1977 (E*)
31	Groundwater pollution, 1979 (C* E* S)
32	Deterministic models in hydrology, 1979 (E*)
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34	Corrosion and encrustation in water wells, 1980 (E*)
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FAO IRRIGATION AND DRAINAGE PAPER

Modernizing irrigation management – the MASSCOTE approach

Mapping System and Services for Canal Operation Techniques

This publication describes the MASSCOTE methodology, illustrated by several applications in Asia. MASSCOTE is a comprehensive methodology for analysing the modernization of canal operation. The aim is to enable experts to work together with users in determining improved processes for cost-effective service-oriented management. It is based on previous tools and approaches widely used in Asia by FAO in its modernization training programme (rapid appraisal procedures and benchmarking). From diagnosis through to the formulation of operational units and the planning of a service (based on the vision agreed upon with the users), MASSCOTE entails a systematic, ten-step, mapping exercise.

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