FutureWater

FAO's Water Scarcity Program

# REWAS: REal WAter Savings tool: Technical Document

REPORT 200


CLIENT FAO

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# Executive Summary

The REWAS (REal WAter Savings) tool is developed to undertake a quick impact assessment of detailed field scale experiments (either by models or pilot plots) on basin-scale potential water savings. REWAS is based on proven concepts of water accounting, water productivity and the appropriate water terminology, as promoted by FAO (FAO, 2013). This technical document provides the underlying concepts, users' guide and example applications of the real water savings tool REWAS.

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# 1 Relevance

Irrigated agriculture is the largest consumer of freshwater withdrawals in Asia, responsible for up to 90% of water consumption in many of Asia's food-producing regions. Unsurprisingly, water shortages are most prevalent in regions with large areas of irrigation, often to the extent that the irrigation sector itself is heavily affected by a lack of sufficient, reliable (seasonal) freshwater, with direct impacts on farmer productivity and farmer livelihoods, and incomes. Options to save water therefore tend to focus specifically on irrigation. Improved irrigation techniques (such as drip irrigation, sprinkler, pressurized systems) are promoted as legitimate means of "saving water" for other uses (such as domestic use and the environment). However, a growing body of evidence shows that in the vast majority of cases, apparent water "savings" at field scale translate into an *increase* in water consumption when assessed at larger scales. Yet despite this growing and irrefutable body of evidence, "water savings" technologies continue to be promoted, subsidized and implemented as a solution to water scarcity in agriculture without careful evaluation of wider impacts. A summary of those evidence can be found in a accompany FAO Report "Guidance: Crop Water Productivity Options to Achieve Real Water Savings".

There is therefore an urgent need to develop and use simple and pragmatic tools that can evaluate the impact of field scale crop-water interventions at larger scales. More specifically results from the widely-used field scale models such as Cropwat and AquaCrop should be assessed on their basin scale water savings. Although many basin scale hydrological models exist, there is a clear need for a more straightforward analysis tool that converts field-scale results into a first order basin scale impact on real water savings.

The REWAS (REal WAter Savings) tool is developed to undertake a quick impact assessment of detailed field scale experiments (either by models or pilot plots) on basin-scale potential water savings. REWAS is based on proven concepts of water accounting, water productivity and the appropriate water terminology, as promoted by FAO (FAO, 2013). This technical document provides the underlying concepts, users' guide and example applications of the real water savings tool REWAS.

In addition to this technical document a training manual is available which can be used to understand step by step the concepts of real water savings and the use of the REWAS tool. The training manual is a "do-it-yourself" guidance including clear examples, questions and answers. For a further discussion and summary on real water savings, using the "Follow the Water" concept an accompany report (Guidance: Crop Water Productivity Options to Achieve Real Water Savings).

# 2 Introduction to REWAS

## 2.1 A typical example of the use of REWAS

The main objective of REWAS is to assess quickly the impact of field scale crop-water interventions on basin scale water savings. The REWAS approach is to "Follow the Water". In other words, drainage, runoff and percolation to the groundwater are in many cases considered as "losses", ignoring the fact that this water is used by downstream users. So, claiming that a reduction in drainage, runoff and percolation at a field saves water is incorrect as downstream reuse should be considered.

To briefly introduce what can be done with REWAS a typical water savings case will be summarized here. A study from Nepal (Jha, 2016) reported that by reducing irrigation applications, 75% water savings were achieved. However, the study failed to use the "Follow the Water" principle as it was assumed that at all Return Flows were losses, while in reality 80% of those Return Flows are Recovered by downstream users. Figure 1 indicates that the study reported water savings referred only to the irrigation application (solid yellow box in the Figure), while the focus should have been on the Recoverable Return Flows and Non-Beneficial Consumptions

Using the REWAS tool (Figure 2) it is evident that the claimed water savings of 75% are not true from a basin perspective and the real water savings at basin scale are much smaller and are in the order of around 6%.

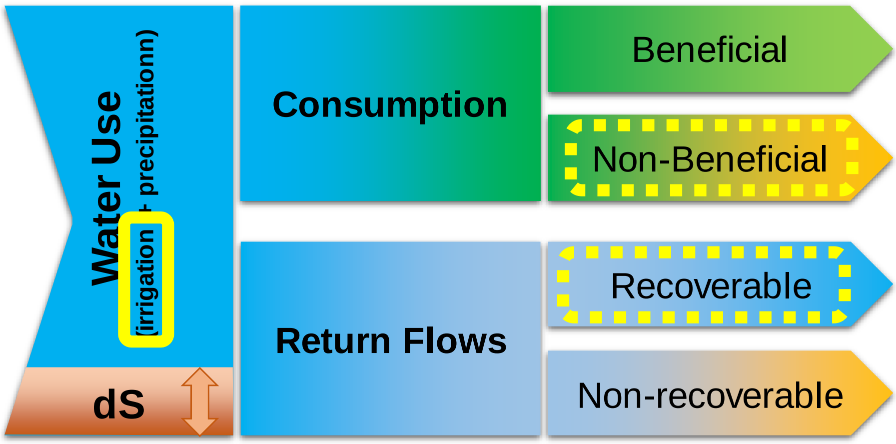


**Figure 1. The approach of "Follow the Water" as applied in the REWAS tool. The solid yellow box indicates on which water savings were reported: change in irrigation reduction. The dotted yellow boxes shows where real water savings can be achieved.**

| INPUT DATA | | | |
|---|---|---|---|
| | | Scenario | |
| | | Reference | Intervention A |
| **FIELD** | Units | | |
| Rainfall | (mm) | 910 | 910 |
| Irrigation | (mm) | 217 | 54 |
| Crop Transpiration | (mm) | 720 | 720 |
| Soil Evaporation | (mm) | 43 | 0 |
| Drainage | (mm) | 182 | 122 |
| Percolation | (mm) | 182 | 122 |
| | | | |
| **RECOVERABLE FLOW FRACTION** | | | |
| Recoverable drainage fraction RD | (%) | 80% | 80% |
| Recoverable percolation fraction RP | (%) | 80% | 80% |

| RESULTS | | | |
|---|---|---|---|
| | | Scenario | |
| | | Reference | Intervention A |
| **Percentage of Real Water Savings** | **(%)** | - | **6%** |

**Figure 2. Screenshot from the REWAS tool analysing real water savings for the Nepal case.**

## 2.2 Concept of REWAS

REWAS is a user-friendly tool designed to assess real water savings for field interventions in irrigation systems, following the water, looking beyond the traditional water savings believes. Real water savings are determined for field intervention scenarios by obtaining the relative change in water consumption and the relative change in return flows. Current water consumption and return flows in a selected irrigation system are used as the reference scenario for obtaining the relative change in water flows. In addition to water consumption and return flows, storage change and water productivity are obtained for each field intervention and the reference. An example of REWAS results is shown in Figure 3.

In REWAS, a field intervention is assumed to be uniform over the entire area of the irrigation system without spatial differences in crop development, crop transpiration, soil characteristics or field management. Many other tools are able to assess spatial variability (e.g. SPHY, Wflow, VIC, among others), but the unique feature of REWAS is that the tool follows the water and provides the user a clear reasoning on how much water is really saved with different field interventions in an irrigation system. Examples of field interventions are: i) changing the irrigation application, ii) changing to another irrigation technology, iii) changing to mulching practices, iv) changing the plant density, among other practices and combinations. Any of these interventions will lead to a change in water consumption, return flows, storage change and water productivity. More examples of field interventions and corresponding changes in flows and productivity can be found in the document “Guidance: Crop Water Productivity Options to Achieve Real Water Savings”.

| RESULTS | | | | |
|---|---|---|---|---|
| | | Scenario | | |
| | | Reference | Intervention A | Intervention B |
| **RESULTS FIELD** | | | | |
| Consumption, beneficial BC | (mm) | 403 | 242 | 242 |
| Consumption, non-beneficial NBC | (mm) | 163 | 130 | 130 |
| Return flows | (mm) | 555 | 21 | 21 |
| Storage change CS | (mm) | 0.0 | 0.0 | 0.0 |
| Water Productivity WP | (kg/m³) | 0.93 | 1.03 | 1.03 |
| Apparent Water Savings FWS | (mm) | - | 567 | 567 |
| **Percentage of Apparent Water Savings %FWS** | **(%)** | **-** | **51%** | **51%** |
| | | | | |
| **RESULTS SYSTEM** | | | | |
| Consumption, beneficial BC | (MCM) | 40.3 | 24.2 | 36.3 |
| Consumption, non-beneficial NBC | (MCM) | 16.3 | 13.0 | 19.5 |
| Return flows, recoverable RF | (MCM) | 47.6 | 1.8 | 2.7 |
| Return flows, non-recoverable NRF | (MCM) | 7.9 | 0.3 | 0.5 |
| Storage change CS | (MCM) | 0.0 | 0.0 | 0.0 |
| Water Productivity WP | (kg/m³) | 0.93 | 1.03 | 1.03 |
| Real Water Savings RWS | (MCM) | - | 10.9 | 4.2 |
| **Percentage of Real Water Savings %RWS** | **(%)** | **-** | **10%** | **4%** |

**Figure 3. Example of REWAS results: Apparent water savings at field scale and real water savings at irrigation system scale. The flows at field scale are in water depth (mm/season) and at system scale in water volume (MCM/season) for a given irrigated area. Water productivity is in kg/m³.**

In REWAS, for each field intervention the impact in water consumption, return flows, storage change and water productivity is determined at field scale and at irrigation system scale. An irrigation system consists of irrigated fields. REWAS follows the water flows and determines the apparent water savings at field scale and the real water savings at system scale. At irrigation field scale REWAS assumes the farmer's believe that drainage and percolation are water losses not capable to be recovered. At irrigation system scale part of the drainage and part of the percolation are recoverable flows downstream. REWAS allows the user to choose a recoverable flow fraction of drainage and a recoverable flow fraction of percolation. Hence recoverable flows and non-recoverable flows from drainage and percolation are obtained which is key to determine the real water savings.

REWAS is developed in Microsoft Excel to enhance usability, reach, transparency, transferability of data input and output. Input data is obtained from studies, field trails, measurements, ground observations or remote sensing. REWAS results are based on proven concepts of water accounting, and the appropriate water terminology, as promoted by FAO globally (FAO, 2013).

Details about the required input data in REWAS and the REWAS interface and underlying equations are presented is presented in section 3. The underlying theory and concepts of REWAS are explained in more detail in section 4. Finally, in section 5 some applications of REWAS in various Asian countries is presented.

# 3 REWAS Input and Output

## 3.1 REWAS interface

The interface of REWAS was developed in Microsoft Excel for easy usability, reach, transparency, transferability of data input and output. In Figure 4, the input data interface in REWAS is shown. The user can manually insert data values in the assigned cells for the scenarios: reference, intervention A and intervention B. Also, the user can unhide columns for intervention C, intervention D and intervention E. The impact of different field interventions can be assessed. For example, a different irrigation application/technology, a different agronomic practice, or a different irrigated area. For each field intervention the irrigation, crop transpiration, soil evaporation, drainage and percolation may vary. These changes can be obtained from field trials or remote sensing. Instead of using data from field trials/remote sensing the user can import AquaCrop results by clicking on the yellow/green arrow for each scenario. Steps on how to import AquaCrop results are described in section 3.4. Also, the area of the irrigation system and the recoverable flow fraction for drainage and percolation can be manually field in. More information about the recoverable flow fraction can be found in section 4.

If needed, click to import AquaCrop Results — Ref — A — B

| INPUT DATA | | | | |
|---|---|---|---|---|
| | | Scenario | | |
| | | Reference | Intervention A | Intervention B |
| **FIELD** | Units | | | |
| Rainfall | (mm) | | | |
| Irrigation | (mm) | | | |
| Crop Transpiration | (mm) | | | |
| Soil Evaporation | (mm) | | | |
| Drainage | (mm) | | | |
| Percolation | (mm) | | | |
| Yield | (kg/ha) | | | |
| | | | | |
| **SYSTEM** | | | | |
| Area | (ha) | | | |
| | | | | |
| **RECOVERABLE FLOW FRACTION** | | | | |
| Recoverable drainage fraction RD | (%) | | | |
| Recoverable percolation fraction RP | (%) | | | |

**Figure 4. REWAS input data: Field data, irrigation area and recoverable flow fractions. If required, data can be imported from FAO AquaCrop.**

## 3.2 Required input data

REWAS input data is rainfall, irrigation, crop transpiration, soil evaporation, drainage and percolation in water depth per cropping season (mm/season) in an irrigated field (Table 1). The harvested crop yield (kg/ha) for the selected cropping season can also be provided to obtain the water productivity (details about water productivity are presented in section 4). The input data can be obtained from field trails, remote sensing, crop growth models or any other source of information available. If necessary, REWAS has the option to import data from FAO AquaCrop simulations. More details about importing data from FAO AquaCrop are presented in section 3.4. BOX 1 elaborates further on obtaining data in real world situations.

In REWAS, the user can choose a desired irrigated area (in hectares) to obtain the flow results in millions of cubic meters (MCM) and the crop production in millions of kilograms (Mkg). In addition, REWAS allows the user to choose a recoverable flow fraction of drainage and a recoverable flow fraction of percolation. Section 4.3 and BOX 2 elaborates further on recoverable flow fractions from return flows.

**Table 1. Input variables for REWAS**

| Input variables | Units | Normal range of values |
|---|---|---|
| Rainfall | mm/season | 0-1000 |
| Irrigation | mm/season | 0-1000 |
| Crop transpiration | mm/season | 0-1000 |
| Soil evaporation | mm/season | 0-1000 |
| Drainage | mm/season | 0-1000 |
| Percolation | mm/season | 0-1000 |
| Yield | kg/ha | 0-10000 |

### BOX 1. Obtaining data in real world situations

The main reason for using AquaCrop is to be able to input estimate values for actual crop transpiration and soil evaporation for real field conditions. This still relies on a fair number of assumptions. Actual crop transpiration and soil evaporation should be obtained with the easiest method available. If remote sensing data is available, it would be a good alternative.

Generally, drainage (sub-surface and/or surface flows) and percolation (flow to aquifer) is only derived at field experiment stations and is difficult to assess on farm. Real values will always require some sort of measurement set up (e.g. soil moisture device to assess fluxes below the root zone) which is cumbersome. In theory, measuring surface drainage is easier (e.g. using calibrated Parshall flumes), but often hard to do in practice. AquaCrop can provide a guidance on how drainage and percolation flows change for different soil conditions and field interventions.

**BOX 2. Recoverable flow fractions from return flows**

Recoverable flow fractions from return flows are key to estimate real water savings. Using the recoverable flow fraction from drainage allows the estimate of the water returning to a river for potential reuse. In addition, using the recoverable flow fraction from percolation allows the estimate of water returning to an aquifer for potential reuse. Values of recoverable flow fractions can vary between 20% and 90% depending on the basin. Accurate values of recoverable flow fractions are difficult to get. However, knowledge about non-recoverable flows in specific basins can provide an estimate of the recoverable flow fraction. Non-recoverable return flows are flows to the sea, flows to saline aquifers or flows to other economically unviable sinks. BOX 4 elaborates further on non-recoverable return flows in Asia.

## 3.3 Obtaining results in REWAS

The output results of the REWAS tool are separated at field (FIELD) and system (SYSTEM) level (Figure 5). The units of the output variables are in mm at field level and MCM at system level according to the area of the irrigation system (defined in the input variables). The output results are shown with the terminology of the water accounting framework. See section 4.1 and section 4.2 for more information about water accounting. Also, the water productivity results are provided. The water savings are determined between reference and different field interventions (Intervention A and Intervention B). The real water savings are determined at system scale.

| RESULTS | | | | |
|---|---|---|---|---|
| | | Scenario | | |
| | | Reference | Intervention A | Intervention B |
| **RESULTS FIELD** | | | | |
| Consumption, beneficial BC | (mm) | | | |
| Consumption, non-beneficial NBC | (mm) | | | |
| Return flows | (mm) | | | |
| Storage change CS | (mm) | | | |
| Water Productivity WP | (kg/m³) | | | |
| Apparent Water Savings FWS | (mm) | | | |
| **Percentage of Apparent Water Savings %FWS** | **(%)** | | | |
| | | | | |
| **RESULTS SYSTEM** | | | | |
| Consumption, beneficial BC | (MCM) | | | |
| Consumption, non-beneficial NBC | (MCM) | | | |
| Return flows, recoverable RF | (MCM) | | | |
| Return flows, non-recoverable NRF | (MCM) | | | |
| Storage change CS | (MCM) | | | |
| Water Productivity WP | (kg/m³) | | | |
| Real Water Savings RWS | (MCM) | | | |
| **Percentage of Real Water Savings %RWS** | **(%)** | | | |

**Figure 5. REWAS output results at field level (units in mm) and system level (units in MCM), to evaluate real water savings for different intervention scenarios.**

In Figure 6, the interface of intermediate results in REWAS is shown. Inflow and outflows at field and system scale are determined. At system scale the intermediate results for drainage and percolation volumes for recoverable flow fractions are obtained. The calculations developed in this table are described in section 4.

| INTERMEDIATE RESULTS | | | | |
|---|---|---|---|---|
| | | Scenario | | |
| | | Reference | Intervention A | Intervention B |
| **FIELD** | | | | |
| InflowTotal | (mm) | | | |
| OutflowTotal | (mm) | | | |
| | | | | |
| **SYSTEM** | | | | |
| Rainfall | (MCM) | | | |
| Irrigation | (MCM) | | | |
| Crop Transpiration | (MCM) | | | |
| Soil Evaporation | (MCM) | | | |
| Drainage | (MCM) | | | |
| Percolation | (MCM) | | | |
| Production | (Mkg) | | | |
| | | | | |
| DrainageTotal | (MCM) | | | |
| DrainageRecoverable | (MCM) | | | |
| DrainageNonRecoverable | (MCM) | | | |
| PercolationTotal | (MCM) | | | |
| PercolationRecoverable | (MCM) | | | |
| PercolationNonRecoverable | (MCM) | | | |
| | | | | |
| Inflow Total | (MCM) | | | |
| Outflow Total | (MCM) | | | |

**Figure 6. Intermediate results in REWAS. Inflow and outflows at field and system scale. At system scale the intermediate results for drainage and percolation volumes for recoverable flow fractions are obtained.**

The user can select which scenario to show in the water balance plot (inflows and outflows) at field scale and system scale (Figure 7). The size of the arrows changes according to the selected scenario.

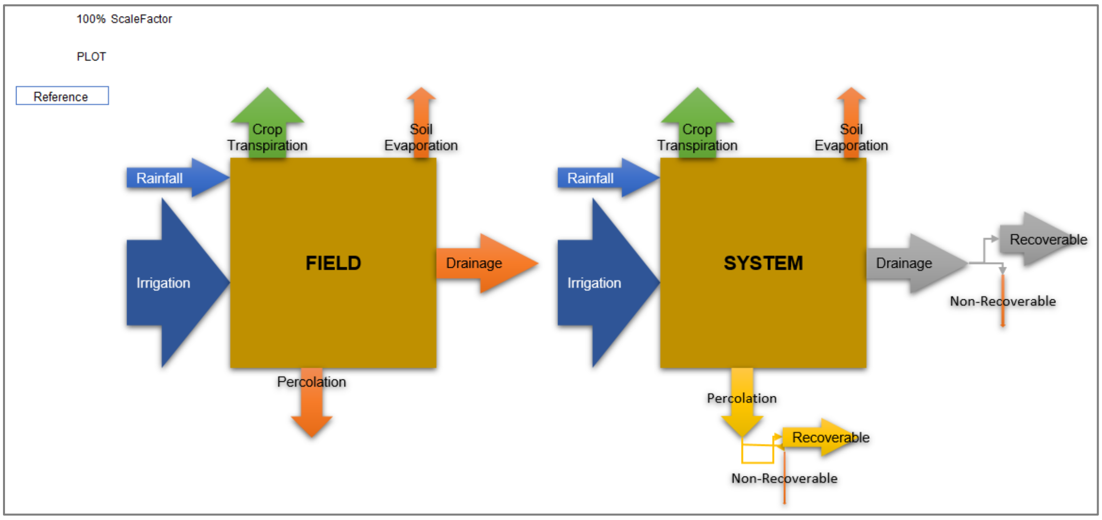


**Figure 7. Example of water balance plot (inflows and outflows) at field scale and system scale for reference scenario. At system scale recoverable flows and non-recoverable flows for drainage and percolation are obtained.**

## 3.4 Importing data from AquaCrop results

REWAS input data can be obtained from various sources such as field experiments on pilot plots, published data, model outputs, remote sensing amongst others. Since AquaCrop is considered as the standard to undertake crop water intervention analysis, REWAS has an option to import AquaCrop results directly.

AquaCrop results are prepared in advance in the “AC” folder, so the user can select these results as input data in REWAS. First open the REWAS excel file called: REWAS_v6.xlsm. Click on sheet name “Main”. Look for “If needed, click to import AquaCrop Results” and click on the desired scenario: Ref, A or B (Figure 8). For this example, first click on the reference scenario Ref (yellow arrow). The user can browse to the directory where one of the AquaCrop Output files (*.out) is located. Browse to the “AC” folder containing different folders for different countries (e.g. Iran, Vietnam, Nepal). As an example, select the “Nepal” folder (Figure 9). In this folder the user can find different field interventions (e.g. change in irrigation application, change in plant density, change in soil fertility, etc) for rice in Namobuddha, Nepal. For field intervention “Irrigation” import a desired reference scenario into REWAS (see Figure 10, Figure 11 and Figure 12). The file is imported by clicking on it and then click open. Repeat the procedure for desired field interventions. Click and open the file ProjectPROseason.OUT (Figure 11). This will automatically import the required data into the corresponding column in REWAS (Figure 12). If no file is selected a message will appear: “No file was selected”. Press “Ok” to ignore it. And try again.

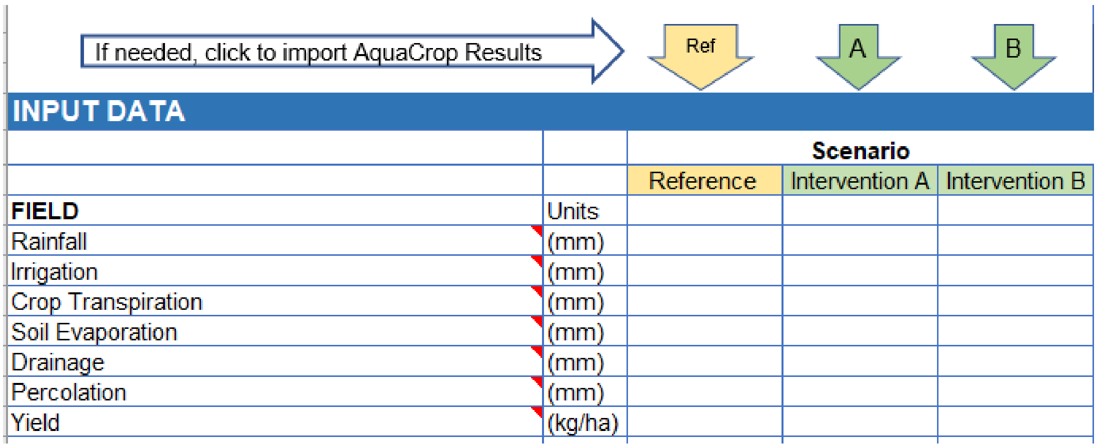


**Figure 8. REWAS input data: Field data from AquaCrop model and clicking on one scenario to browse for data. In this example first click on Ref, and later click on A and B for desired field interventions.**

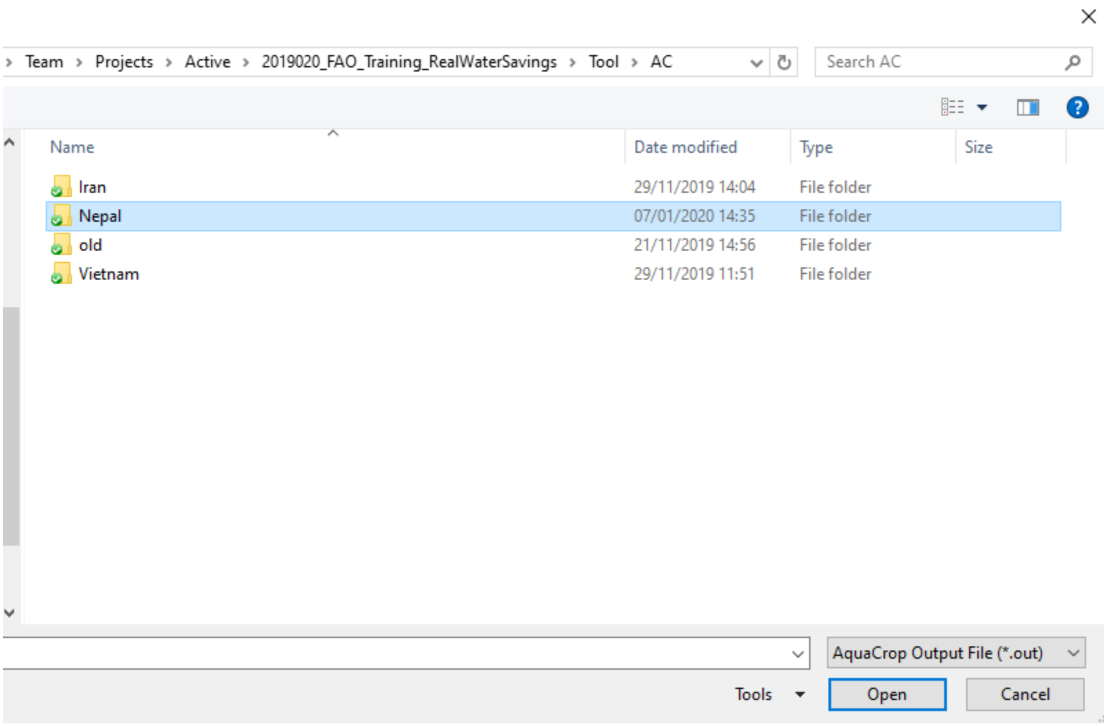


**Figure 9. REWAS input data: Clicking on the desired country data (e.g. Nepal, Vietnam and Iran).**

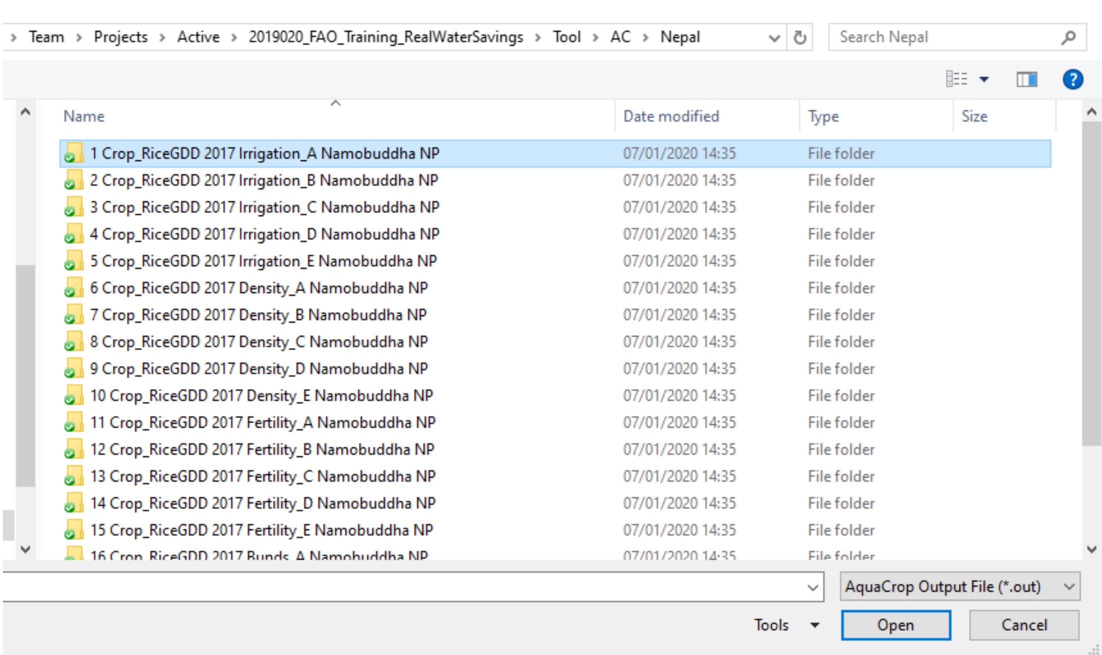


**Figure 10. Scenarios for Nepal. For example, scenario "1 Crop_RiceGDD 2017 Irrigation_A Namobuddha NP" (In this example the reference scenario).**

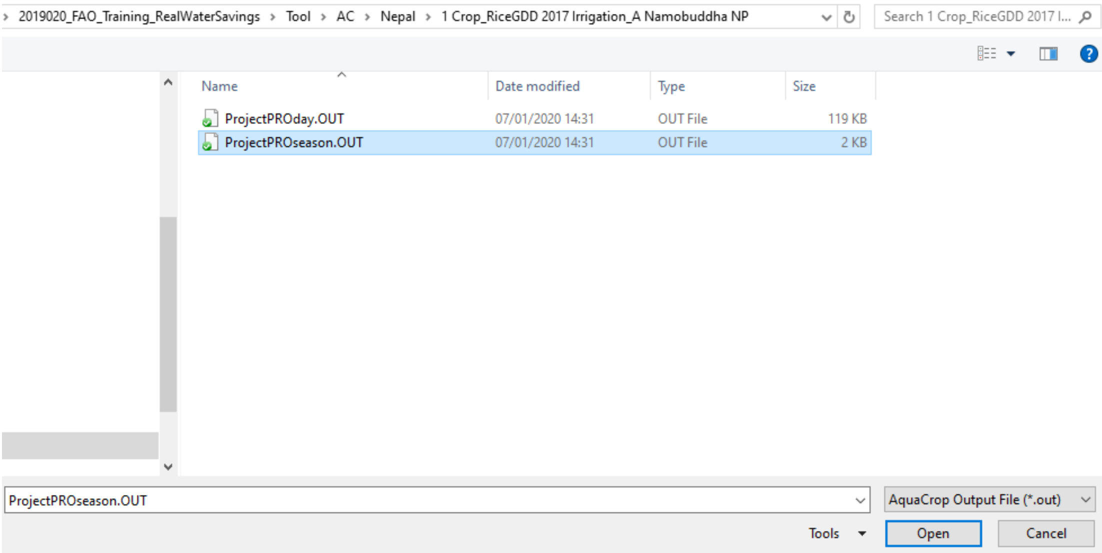


**Figure 11. ProjectPROseason.OUT for scenario "1 Crop_RiceGDD 2017 Irrigation_A Namobuddha NP" (In this example the reference scenario).**

If needed, click to import AquaCrop Results → Ref | A | B

| INPUT DATA | | | | |
|---|---|---|---|---|
| | | Scenario | | |
| | | Reference | Intervention A | Intervention B |
| **FIELD** | Units | | | |
| Rainfall | (mm) | 707 | | |
| Irrigation | (mm) | 270 | | |
| Crop Transpiration | (mm) | 216 | | |
| Soil Evaporation | (mm) | 176 | | |
| Drainage | (mm) | 353 | | |
| Percolation | (mm) | 248 | | |
| Yield | (kg/ha) | 3.12 | | |

**Figure 12. Imported AquaCrop result for reference scenario "1 Crop_RiceGDD 2017 Irrigation_A Namobuddha NP" for irrigated rice in Nepal. In AquaCrop the crop yield is given in t/ha. Hence, the user must change the crop yield to kg/ha by multiplying by a factor of 1000. In this case 3.12 t/ha must be changed to 3120 kg/ha.**

In AquaCrop the crop yield is given in t/ha units. Hence, the user must change the crop yield to kg/ha by multiplying by a factor of 1000. In this case 3.12 t/ha must be changed to 3120 kg/ha to obtain the correct REWAS results.

# 4 Theory and concepts underlaying the REWAS tool

## 4.1 Water accounting

For water accounting it is important to distinguish between "using" water (for example to generate hydro-power or to wash clothes) and "consuming" water (for example in an irrigation system by evapotranspiration (ET) through crops). In the former case, the vast majority of the water used returns directly to the same hydrological system from which it was abstracted, perhaps at a different location, perhaps polluted in some way, but *physically* the water remains available for reuse. When water is consumed through evaporation and transpiration, however, it is no longer available (unless in closed systems, as in hydroponic greenhouses where ET may be condensed and re-used).

The second clarification relates to the engineering perspective, which is entirely valid and appropriate for planning, designing and operating irrigation facilities. This perspective tends to treat water that flows beyond the boundary of the scheme as losses. An environmental analyst, on the other hand, might be very interested in these "losses" as a source of recharge to aquifers or flows into wetlands, i.e. the engineer's "loss" is the environmentalist's "source".

The water accounting framework (Perry, 2007; Batchelor *et al.*, 2016) differentiates the various flows that are associated with any type of water use, and can be applied to any sector, at any scale, without modification. The water use is defined as any application of water to a selected purpose (irrigation, diversion through a power station, domestic washing, industrial processes, etc.). All *Water Use* goes to one or more of the following categories:

1. Consumptive use (conversion of water into water vapour), comprising:
    a. Beneficial Consumption ($BC$)
        - Crop transpiration
        - Evaporation from cooling towers
    b. Non-beneficial consumption ($NBC$)
        - Evaporation from free water surfaces and from wet soil
        - Transpiration by weeds
2. Non-consumptive use (also called return flows), comprising:
    a. Recoverable flows ($RF$)
        - Returning to a river for potential reuse
        - Returning to an aquifer for potential reuse
    b. Non-recoverable flows ($NRF$)
        - Flowing to the sea
        - Other economically unviable sink
3. Change in storage ($CS$)

The water accounting framework is based on the law of conservation of mass resulting in the following equation (Equation 1) for water use calculation:

$$Water\ use = BC + NBC + RF + NRF + CS \qquad (1)$$

## 4.2 Water accounting in REWAS

REWAS is based on the water accounting framework. In REWAS, the water accounting framework is simplified in order to evaluate the water use in irrigation systems. The consumptive use is limited to crop transpiration and soil evaporation, and the non-consumptive use is limited to (Non-) recoverable flows from drainage and percolation in irrigation systems (Figure 13). Additional analysis considering other water users (e.g. environment, urban area) is done with the WEAP tool. More information about the application of WEAP can be found in the training manual (FAO_Training_v10.docx).

| | | |
|---|---|---|
| Water use in irrigation systems (*WU*) | Consumptive use (*CU*) | Beneficial consumption (*BC*)<br>○ Crop transpiration |
| | | Non-beneficial consumption (*NBC*)<br>○ Soil evaporation |
| | Non-consumptive use or return flows (*NCU*) | Recoverable flows (*RF*)<br>○ From drainage<br>○ From percolation |
| | | Non-recoverable flows (*NRF*)<br>○ From drainage<br>○ From percolation |
| | Change in storage (*CS*) | |

**Figure 13. The REWAS tool in irrigation systems based on the water accounting framework.**

In REWAS, it is important to determine the different components of the water use to evaluate the real impact at irrigation systems. For example, if a farmer increases the crop area in irrigation system A through introduction of improved irrigation technology *and the volume of water delivered to his farm is unchanged*, some or all of the following changes occur:

- Beneficial consumption (crop transpiration) increases
- Non-beneficial consumption (evaporation from wet soil) decreases
- Percolation decreases
- Drainage flows decrease

The increase in beneficial consumption is usually the most important impact—indeed this is a primary reason for introducing improved irrigation technology. This typically means that the overall result is increased water consumption in irrigation system A and reduced return flows to aquifers, and the surface system. Describing these changes in flows is essential to promote clarity in the reporting and evaluation of the physical impact of improved irrigation technology. Hence, when proponents of drip irrigation argue that the technique can “double the irrigated area”, we should interpret this as “doubling the proportion of water delivered to the farm that is consumed”, and thus dramatically decreasing return flows.

## 4.3 Recoverable flows for real water savings

The extent to which return flows to percolation and drainage are valuable to other users is key to determine “real” water savings in irrigation systems. Recoverable flows vary depending on environmental, infrastructure and management aspects of irrigation systems. For example, if the irrigation system has relatively light soils and water is pumped from underlaying aquifers to irrigate the fields the recoverable water from percolation may be high.

In REWAS recoverable flow fractions are used for drainage and percolation. Typical recoverable flow fractions are between 20% and 90%. As explained above, these values vary depending on the type of irrigation system. We invite and encourage researchers and field practitioners to better estimate, recommend and classify recoverable flow fractions for different types of irrigation systems.

The intention of REWAS is to allow a scenario analysis using established recoverable flow fractions to obtain recoverable flows from drainage and percolation, and determine real water savings in irrigation systems. In REWAS, the recoverable flows from drainage and percolation are obtained as follows (Equation 2 and Equation 3):

$$DrainageRecoverable = DrainageTotal \cdot RD \quad (2)$$
$$PercolationRecoverable = PercolationTotal \cdot RP \quad (3)$$

Where $RD$ is the recoverable drainage fraction, $DrainageTotal$ is the drainage flow, and $DrainageRecoverable$ is the recoverable flow from drainage. $RP$ is the recoverable percolation fraction, $PercolationTotal$ is the percolation flow, and $PercolationRecoverable$ is the recoverable flow from percolation.

In REWAS, the total recoverable flow in irrigation systems ($RF_{Sys}$) is obtained using both recoverable flows from percolation and drainage (Equation 4):

$$RF_{Sys} = DrainageRecoverable + PercolationRecoverable \quad (4)$$

Corresponding non-recoverable flows from drainage ($DrainageNRF_{Sys}$) and non-recoverable flows from percolation ($PercolationNRF_{Sys}$) are obtained with Equation 5 and Equation 6. In Equation 7, the total non-recoverable flow ($NRF_{Sys}$) is obtained:

$$DrainageNRF_{Sys} = (DrainageTotal) \cdot (1 - RD) \quad (5)$$
$$PercolationNRF_{Sys} = (PercolationTotal) \cdot (1 - RP) \quad (6)$$
$$NRF_{Sys} = \left(DrainageNRF_{Sys} + PercolationNRF_{Sys}\right) \quad (7)$$

## 4.4 Water productivity

In its broadest sense, water productivity is the net return for a unit of water used (Molden et al., 2010). Improvement of water productivity aims at producing more food, income, better livelihoods and ecosystem services with the same or less water. Water productivity consists of two components: crop production and water consumption. The water productivity of a crop is defined as the ratio between the amount of crop produced and the amount of water consumed to obtain such production. In REWAS, the water productivity is calculated with the following equation (Equation 8):

$$WP = \frac{Pr}{(BC+NBC)} \quad (8)$$

Where $Pr$ is the crop production (Mkg) obtained with the crop yield and the area of the irrigation system; and the beneficial consumption, $BC$ is the crop transpiration ($Mm^3$), and the non-beneficial consumption, $NBC$ is the soil evaporation ($Mm^3$).

For common field crops (food grains, forage crops, fibres, sugar) the relationship between crop yield and water consumption is essentially linear (Fereres and Soriano, 2007; Howell, 1990; Steduto, Hsiao, et al., 2012) over a wide range of intermediate yield levels. This linear relationship is not strictly proportional—the relationship between yield and ET intersects the consumption axis at a positive value.

An agronomic practice that has shown some influence on the water productivity is Deficit Irrigation. The practice of Deficit Irrigation (DI) consists in applying less water than the crop water requirements on potential crop evapotranspiration (ETc). As a result, two situations may develop. In one case, stored soil water and/or rainfall supply the deficit and the crop does not experience ET deficits, thus there are no savings in total water consumption. This scenario is often desirable to make best use of stored soil water, but requires precise management and water accounting to ensure that ET deficits do not develop. The second situation occurs when the irrigation supply is deliberately kept low enough to create deficits and actual crop ET is less than ETc. In this second case, given the close association between production and transpiration, crop yields would generally be less than those obtained under full irrigation.

Some crops (trees and vines are the most common examples) react positively to ET deficits at specific growth stages, offering opportunities for using Deficit Irrigation (DI) to increase water productivity. For the major cereals, however, the opportunities are extremely limited. For maize, many experiments have shown that full irrigation is the best economic option, and if water is limited it should be concentrated in less area. For wheat, the evidence from supplemental irrigation research in the Middle East and other areas shows that, while you can achieve higher irrigation water productivity, there is almost always some yield penalty. An optimal level of deficit may be found if water is very expensive/scarce but it would be at around 80 to 90 percent of ETc. Among other field crops, cotton and grain sorghum are good candidates for DI.

For most field and vegetable crops, DI has limited prospects and needs to be assessed through an optimization exercise based on local data. Even then, from the practical standpoint, managing small reductions in ET is very difficult, risky, and also tends to lead to salinization of the soil. In the case of woody perennials (fruit trees and vines), DI is a viable option to save water and to optimize the use of limited water resources (Steduto, Hsiao, et al., 2012). Another agronomic practices that has been shown to influence water productivity is Supplemental Irrigation (SI). Even though SI has several meanings in different environments, it is generally considered a form of deficit irrigation in which small water amounts are applied to supplement rainfall. Although the term has been used in the past in humid areas, the SI concept has been primarily developed in the arid areas of the Middle East for improving winter cereal production. It is often promoted in conjunction with rainwater harvesting (Oweis and Hachum, 2006). Many experiments have shown that relatively small amounts of water applied to winter cereals around flowering have dramatic effects on yield and on water productivity (kg/m³). The explanation is that the maintenance of adequate water status during that time has a positive effect on maintaining the crop harvest index under the drought conditions of those water-limited environments. However, despite the positive results at the experimental level, SI has not been widely adopted by farmers so far. The reasons for the limited adoption of SI have to do with the difficulties in the implementation of the technique. Main limitations are: a) uncertainties in the return of the investments required for the collection and application of the irrigation water; b) variations in the timing of water deficits relative to the limited irrigation supply available; and c) once a supply of water is made available, there is a tendency to concentrate it to maximize production per unit irrigated area (often of high-value crops such as vegetables) rather than spread it over a larger area as SI of cereals. For the reasons above, the application of the SI concept in practice has a scope that has turned out to be smaller than the experimental results have suggested. There are, however, a few cases in fruit tree production such as the olive where it has been practiced with success. BOX 3 elaborates further on Supplemental Irrigation (SI) and water productivity.

In sum, for a given crop and a given climate, increases in production are associated with increases in water consumption by the crop, and for most field crops, water productivity (kg/m³) is highest when water consumption and yield per hectare are maximum, because some degree of (non-beneficial) evaporation from wet soil or foliage is unavoidable but comprises a smaller proportion of total consumption when transpiration is at its maximum potential level—not least because healthy plant development quickly shades the soil and minimises soil evaporation.

**BOX 3. Supplemental irrigation and water productivity**

The key attraction of supplemental irrigation is the marginal water productivity improvement. However, comparisons of water productivity outputs are complicated with most crops. Water productivity components are crop yield and evapotranspiration which is sourced from rainfall and irrigation. With simple metrics we cannot separate the water productivity components due to rainfall and irrigation, and even in experimental conditions it is hard to determine the marginal water productivity improvement of added irrigation. Adoption of supplemental irrigation in Asia has been low, but it is common practice in European farming.

# 5 Examples of Applications of REWAS

The following are examples of REWAS applications in irrigation systems in Asia. Irrigation systems in Iran and Vietnam were selected to evaluate real water savings and water productivity.

## 5.1 Irrigation system in the Mashhad basin, Iran

The Mashhad basin is located in the northeast of Iran. The total irrigated area in the Mashhad basin is approximately 160,000 hectares (Figure 14), from which 20% is pressurized irrigation (e.g. drip irrigation) and 80% is surface irrigation. Wheat and barley are the dominant crops with 46% and 26% of the total irrigated area (ISC, 2015). Most of the irrigated water is pumped from aquifers serving irrigation systems from 50 hectares to 5000 hectares in size.

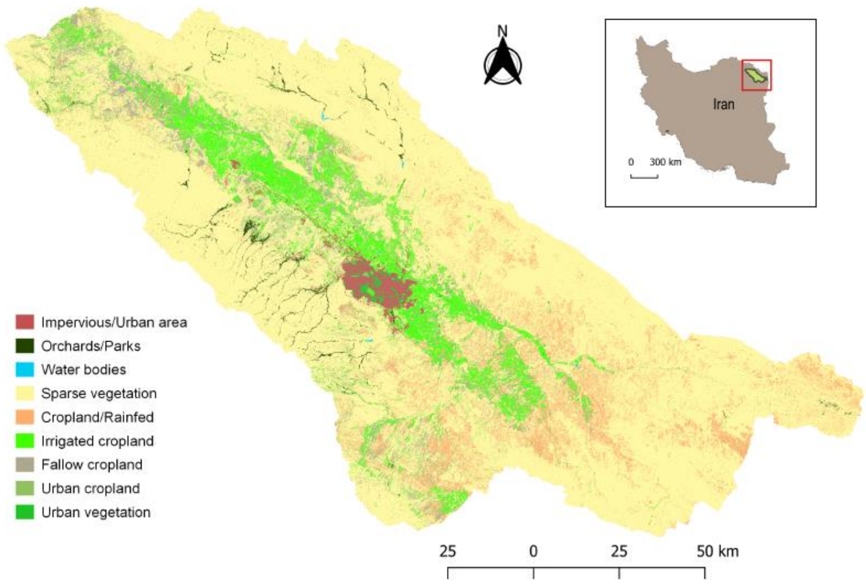


**Figure 14. Irrigated cropland in the Mashhad basin, Iran (Pareeth et al., 2019).**

A drip irrigation system of 5000 hectares is selected for REWAS application (Figure 15). We assume that only wheat is grown in the irrigation system. The growth season of wheat is between October and June with irrigation starting in March.

**Figure 15. Typical drip irrigation system for wheat, Mashhad basin, Iran.**

Reference scenario is the current irrigation used in the farm with a season application of 450 mm. The application is changed to 90 mm (Intervention A). In Figure 16 the input data in REWAS is shown for two measured scenarios (reference and intervention A). The inflows are rainfall and irrigation, and the outflows are crop transpiration, soil evaporation, drainage and percolation. Rainfall remains constant for each scenario (171 mm). For reference scenario (irrigation 450 mm) the crop yield is 5320 kg/ha, the crop transpiration is 382 mm, the drainage is 119 mm, and the percolation is 55 mm. For intervention A (irrigation 90 mm) the crop yield is significantly reduced to 3200 kg/ha. For intervention A percolation is 11mm and drainage is 15 mm. With a decrease in irrigation application a reduction in outflows and a decrease in crop yield is obtained.

| INPUT DATA | | | |
|---|---|---|---|
| | | Scenario | |
| | | Reference | Intervention A |
| **FIELD** | Units | | |
| Rainfall | (mm) | 171 | 171 |
| Irrigation | (mm) | 450 | 90 |
| Crop Transpiration | (mm) | 382 | 185 |
| Soil Evaporation | (mm) | 65 | 50 |
| Drainage | (mm) | 119 | 15 |
| Percolation | (mm) | 55 | 11 |
| Yield | (kg/ha) | 5320 | 3200 |

**Figure 16. Input data for REWAS (INPUT DATA) example in Iran.**

In Figure 17 further input data is provided including the size of the irrigation system (5000 ha) and recoverable flow fractions. Based on observations, we assume a 70% recoverable flow fraction equal for drainage and percolation.

| | | | |
|---|---|---|---|
| **SYSTEM** | | | |
| Area | (ha) | 5000 | 5000 |
| | | | |
| **RECOVERABLE FLOW FRACTION** | | | |
| Recoverable drainage fraction RD | (%) | 70% | 70% |
| Recoverable percolation fraction RP | (%) | 70% | 70% |

**Figure 17. INPUT DATA: Size of the irrigation system (5000ha) and recoverable flow fractions in Iran.**

In Figure 18 intermediate results for total inflows and total outflows are shown at field and system level. Intermediate calculations are made to convert the units of water (from mm to MCM) and crop production (from kg/ha to Mkg), and to obtain recoverable flows from drainage and percolation. The equations used to obtain these variables are shown in section 4.

| INTERMEDIATE RESULTS | | | |
|---|---|---|---|
| | | Scenario | |
| | | Reference | Intervention A |
| **FIELD** | | | |
| InflowTotal | (mm) | 621 | 261 |
| OutflowTotal | (mm) | 621 | 261 |
| | | | |
| **SYSTEM** | | | |
| Rainfall | (MCM) | 8.6 | 8.6 |
| Irrigation | (MCM) | 22.5 | 4.5 |
| Crop Transpiration | (MCM) | 19.1 | 9.3 |
| Soil Evaporation | (MCM) | 3.3 | 2.5 |
| Drainage | (MCM) | 6.0 | 0.8 |
| Percolation | (MCM) | 2.8 | 0.6 |
| Production | (Mkg) | 26.6 | 16.0 |
| | | | |
| DrainageTotal | (MCM) | 6.0 | 0.8 |
| DrainageRecoverable | (MCM) | 4.2 | 0.5 |
| DrainageNonRecoverable | (MCM) | 1.8 | 0.2 |
| PercolationTotal | (MCM) | 2.8 | 0.6 |
| PercolationRecoverable | (MCM) | 1.9 | 0.4 |
| PercolationNonRecoverable | (MCM) | 0.8 | 0.2 |
| | | | |
| Inflow Total | (MCM) | 31 | 13 |
| Outflow Total | (MCM) | 31 | 13 |

**Figure 18. INTERMEDIATE RESULTS for REWAS tool: FIELD, SYSTEM and REUSE SYSTEM in Iran.**

In Figure 19 the water accounting and water productivity results at field level (farmer's perception) and real impact at system level are shown. The percentage of real water savings is 10%, and not the apparent savings of 26%. The percentage of water savings is much lower than expected due to the influence of recoverable flows. The water productivity with intervention A (1.36 kg/m³) is higher than the reference scenario (1.19 kg/m³). This means that even though with intervention A the crop production is lower than with reference conditions, the water consumed with intervention A is much lower than the water consumed with reference conditions.

| RESULTS | | | |
|---|---|---|---|
| | | Scenario | |
| | | Reference | Intervention A |
| **RESULTS FIELD** | | | |
| Consumption, beneficial BC | (mm) | 382 | 185 |
| Consumption, non-beneficial NBC | (mm) | 65 | 50 |
| Return flows | (mm) | 174 | 26 |
| Storage change CS | (mm) | 0.0 | 0.0 |
| Water Productivity WP | (kg/m³) | 1.19 | 1.36 |
| Apparent Water Savings FWS | (mm) | - | 163 |
| **Percentage of Apparent Water Savings %FWS** | **(%)** | **-** | **26%** |
| | | | |
| **RESULTS SYSTEM** | | | |
| Consumption, beneficial BC | (MCM) | 19.1 | 9.3 |
| Consumption, non-beneficial NBC | (MCM) | 3.3 | 2.5 |
| Return flows, recoverable RF | (MCM) | 6.1 | 0.9 |
| Return flows, non-recoverable NRF | (MCM) | 2.6 | 0.4 |
| Storage change CS | (MCM) | 0.0 | 0.0 |
| Water Productivity WP | (kg/m³) | 1.19 | 1.36 |
| Real Water Savings RWS | (MCM) | - | 3.0 |
| **Percentage of Real Water Savings %RWS** | **(%)** | **-** | **10%** |

**Figure 19. RESULTS for REWAS tool: RESULTS FIELD and RESULTS SYSTEM in Iran.**

**BOX 4. Non-recoverable return flows**

If you can prevent non-recoverable return flows from happening, then you can make significant real water savings. Where there is saline groundwater, any deep percolation is unrecoverable. For example, saline shallow water table is common over very large areas of public surface irrigation systems in China (He Tao, Dujiangyan, most of the lower Yellow river systems to name a few); about 30% of Punjab in Pakistan and likely much more in Sindh; and parts of Punjab and Haryana in northern India. The real water savings in these cases should be focused in field intervention which can reduce percolation flows and increase drainage flows which can be recoverable. In REWAS, the recoverable flow fraction from percolation (RP) would be close to zero and the recoverable flow fraction from drainage (RD) would be relatively high given the environmental conditions.

A second case where non-recoverable flows can be recovered is water logging – as in about 25-30% of the irrigation command area in Sindh. Mostly this water is not recoverable and sits in place and evaporates – resulting in a large non-beneficial loss and prevents agriculture from being done. This happens more due to poor (or more properly distorted) water management than application efficiency and field irrigation management per se – although they go hand in hand. The true non-recoverable portion of water logging will vary from place to place and pathway to pathway. Hence, it may not have the same potential for real water savings as with high saline water table.

## 5.2 Irrigation system in the Ca basin, Vietnam

The Ca basin is a transboundary basin between Laos and Vietnam. The basin is located in the north of the Vietnam and north of Laos. We focus on irrigated areas in the Vietnam part of the basin, specifically in the Nghe An province near the city of Vinh. Rice makes up the majority of vegetation cover. Rice paddies are defined as irrigated or flooded fields, or low land paddy fields where rice is intensively planted for more than 1 cycle per year. Rice is planted in three seasons: Mua (or monsoon), He-Thu (or Summer-Autumn) and Dong-Xuan (or Winter-Spring). A typical vertical cross-section through a puddled rice field shows a layer of 0-0.10 m ponded water.

The total area of the Nghe An province is 16,490 km². The provinces Eastern border is coastline with high mountain ranges in the west. The monsoon tropical climate supports a rich biodiversity. The total population of Nghe An was over 3.5 million in 2019. The total irrigated rice area is 1,520 km² (Figure 20).

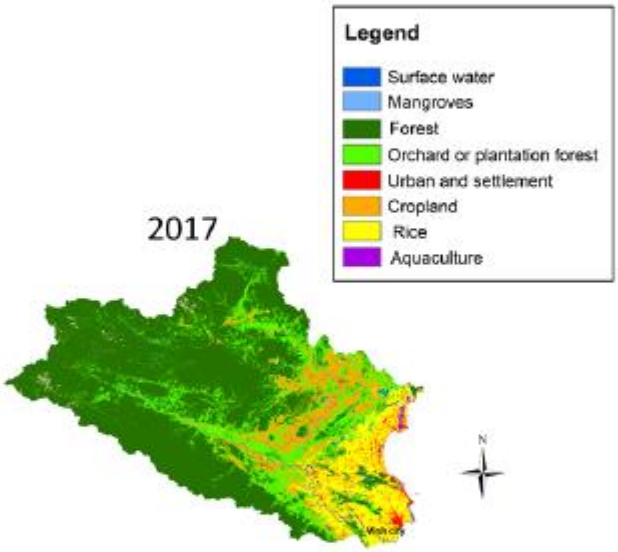


**Figure 20. Land use and irrigated rice in the Nghe An province, Vietnam.**

Local measurements for paddy rice for the growth season between February and June (winter/spring season) are shown in Figure 21. Different outflows and crop yields are obtained for irrigation application reference (910 mm) and irrigation application intervention A (182 mm). The inflows are rainfall and irrigation, and the outflows are crop transpiration, soil evaporation, drainage and percolation. Rainfall remains the same for each scenario (211 mm). For reference scenario (irrigation 910 mm) the crop yield is 5240 kg/ha, the crop transpiration is 399 mm, the drainage is 330 mm and the percolation is 232 mm. In intervention A (irrigation 182 mm) the crop yield is significantly reduced to 3813 kg/ha. With a decrease in irrigation application a reduction in outflows and a decrease in crop yield is obtained.

| INPUT DATA | | | |
|---|---|---|---|
| | | Scenario | |
| | | Reference | Intervention A |
| **FIELD** | Units | | |
| Rainfall | (mm) | 211 | 211 |
| Irrigation | (mm) | 910 | 182 |
| Crop Transpiration | (mm) | 399 | 230 |
| Soil Evaporation | (mm) | 160 | 90 |
| Drainage | (mm) | 330 | 47 |
| Percolation | (mm) | 232 | 26 |
| Yield | (kg/ha) | 5240 | 3813 |

**Figure 21. Input data for REWAS (INPUT DATA) in Vietnam.**

In Figure 22, further input data is provided including the size of the irrigation system (5000 ha) and recoverable flow fraction. We assume equal recoverable flow fraction for drainage and percolation of 90%.

| | | | |
|---|---|---|---|
| **SYSTEM** | | | |
| Area | (ha) | 5000 | 5000 |
| | | | |
| **RECOVERABLE FLOW FRACTION** | | | |
| Recoverable drainage fraction RD | (%) | 90% | 90% |
| Recoverable percolation fraction RP | (%) | 90% | 90% |

**Figure 22. INPUT DATA: Size of the irrigation system (5000ha) and recoverable flow fractions in Vietnam.**

In Figure 23, intermediate results for total inflows and total outflows are shown at field and system level. Intermediate calculations are made to convert the units of water (from mm to MCM) and crop production (from kg/ha to Mkg), and to obtain recoverable flows from drainage and percolation. The equations used to obtain these variables are shown in section 4.

| INTERMEDIATE RESULTS | | | |
|---|---|---|---|
| | | Scenario | |
| | | Reference | Intervention A |
| **FIELD** | | | |
| InflowTotal | (mm) | 1121 | 393 |
| OutflowTotal | (mm) | 1121 | 393 |
| | | | |
| **SYSTEM** | | | |
| Rainfall | (MCM) | 10.6 | 10.6 |
| Irrigation | (MCM) | 45.5 | 9.1 |
| Crop Transpiration | (MCM) | 20.0 | 11.5 |
| Soil Evaporation | (MCM) | 8.0 | 4.5 |
| Drainage | (MCM) | 16.5 | 2.4 |
| Percolation | (MCM) | 11.6 | 1.3 |
| Production | (Mkg) | 26.2 | 19.1 |
| | | | |
| DrainageTotal | (MCM) | 16.5 | 2.4 |
| DrainageRecoverable | (MCM) | 14.9 | 2.1 |
| DrainageNonRecoverable | (MCM) | 1.7 | 0.2 |
| PercolationTotal | (MCM) | 11.6 | 1.3 |
| PercolationRecoverable | (MCM) | 10.4 | 1.2 |
| PercolationNonRecoverable | (MCM) | 1.2 | 0.1 |
| | | | |
| Inflow Total | (MCM) | 56 | 20 |
| Outflow Total | (MCM) | 56 | 20 |

**Figure 23. INTERMEDIATE RESULTS for REWAS tool: FIELD, SYSTEM and REUSE SYSTEM in Vietnam.**

In Figure 24 the water accounting and water productivity results at field level (farmer's perception) and real impact at system level are shown. The percentage of real water savings is 11%, and not the apparent savings of 50%. The percentage of water savings is much lower than expected due to the influence of recoverable flows. The water productivity in intervention A (1.19 kg/m³) is higher than the reference (0.94 kg/m³). This means that even though with intervention A the crop production is lower than with the reference conditions, the water consumed with intervention A is much lower than the water consumed with reference conditions.

| RESULTS | | | |
|---|---|---|---|
| | | Scenario | |
| | | Reference | Intervention A |
| **RESULTS FIELD** | | | |
| Consumption, beneficial BC | (mm) | 399 | 230 |
| Consumption, non-beneficial NBC | (mm) | 160 | 90 |
| Return flows | (mm) | 562 | 73 |
| Storage change CS | (mm) | 0 | 0 |
| Water Productivity WP | (kg/m³) | 0.94 | 1.19 |
| Apparent Water Savings FWS | (mm) | - | 559 |
| **Percentage of Apparent Water Savings %FWS** | **(%)** | **-** | **50%** |
| | | | |
| **RESULTS SYSTEM** | | | |
| Consumption, beneficial BC | (MCM) | 20.0 | 11.5 |
| Consumption, non-beneficial NBC | (MCM) | 8.0 | 4.5 |
| Return flows, recoverable RF | (MCM) | 25.3 | 3.3 |
| Return flows, non-recoverable NRF | (MCM) | 2.8 | 0.4 |
| Storage change CS | (MCM) | 0.0 | 0.0 |
| Water Productivity WP | (kg/m³) | 0.94 | 1.19 |
| Real Water Savings RWS | (MCM) | - | 5.9 |
| **Percentage of Real Water Savings %RWS** | **(%)** | **-** | **11%** |

**Figure 24. RESULTS for REWAS tool: RESULTS FIELD and RESULTS SYSTEM in Vietnam.**

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