SAFIR

Safe and High Quality Food Production using Low Quality Waters and Improved Irrigation Systems and Management (SAFIR)

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A Specific Targeted Research Project

under the Thematic Priority ' Food Quality and Safety '

Work Package 7 • Crop and Farm Management Modelling (ManMod)

D7_1&2: Decision support system for irrigation with low quality water: system, underlying models and tests

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Contents

1 INTRODUCTION

The objective of work package 7 is to develop a decision support system for irrigation management at farm level by integrating aspects of existing dynamic models to take into account crop quality, irrigation water quality, irrigation techniques and environmental impacts of the improved irrigation systems.

The work package includes seven partners: DHI (work package leader), DIAS, KVL, BRGM, CAU and CAAS. The work package has two deliverables, namely

- D7_1 Platform developed for the DSS based on integration of existing models and databases and documented in a report. April 2009 Prototype Confidential
- D7_2 DSS-prototype available and documented. August.

As we decided not to keep parts of the description confidential and because both deliverables concerns the same prototype DSS, the descriptions of both the platform and the prototype have been joined and are included in this report.

The deliverable consists of two different systems. From the beginning it was decided to develop a system that integrates a number of modules describing water quality, irrigation/fertigation, plant growth, risk and fate of heavy metals and microbes as well as calculates economic key figures. During the work it became clear that to set up this model system, certain initial analyses are required.

The initial analyses were then programmed into a separate system (NUBALIR) that can be run alone as a web application. Shortly described, the initial analysis provides an overview of irrigation requirement (quantity and number of irrigations) for the chosen crop and irrigation system during different growth phases. It also calculates the expected fertiliser requirement, the need for initial fertilisation, the addition of N and P through the use of wastewater and it indicates the excess nutrients that may be present if wastewater is used towards the end of the growing season. The calculations may be done for a dry, a normal and a wet year, allowing the user to choose the fertilisation strategy to apply in reality or in the runs with the management model. This system is described in Chapter 1.

The prototype management model estimates the water quality based on initial water quality and choice of filters before the system enters the irrigation system and the system allows irrigation and fertigation of the selected crop, depending on a number of rules. Heavy metals and microbes are added with the irrigation water, and after harvest, the statuses of these as well as the related risks are estimated. Costs of irrigation and fertiliser are compared to the income of the sold produce. The system allows the user to test production, related risk and costs of different types of irrigation systems and water qualities.

2 OVERVIEW OF THE DSS NUBALIR

2.1 Why was it made, what does it do

Before the start of a season, the weather conditions are unknown. The farmer does not know whether it will rain during the first month after planting or whether he has to irrigate from the first day. Without rain, it may be relatively easy to tailor-make a fertigation strategy that feeds the plant with nitrogen day by day. However, if rainfall makes irrigation unnecessary in parts of the season, the nutrients have to be supplied in advance to carry the plant through. If fertigation is supplied during such periods, the plants are basically over-irrigated. Therefore, there is a need to look at the conditions in (a) dry, normal and wet year(s) to see how the growing season usually behaves and how much this influences the choice of fertilisation strategy. In a wet year it may be better to supply a rather large part of the fertiliser in the beginning of the season, while in a dry year continuous fertigation may be the optimal solution. Which strategy that is optimal in a given year can be decided only after the season. The choice made by the farmer is therefore influenced both by his experience with yearly variations and his willingness to gamble.

Shortly described, NUBALIR provides an overview of irrigation requirement (quantity and number of irrigations) for the chosen crop during different growth phases. It also calculates the expected fertiliser requirement, the need for initial fertilisation, the addition of N and P through the use of wastewater and it indicates the excess nutrients that may be present if wastewater is used towards the end of the growing season. The calculations may be done for a dry, a normal and a wet year, allowing the user to choose the fertilisation strategy to apply in reality or in the runs with the management model.

2.2 Description of programme and calculations behind (Technical user guide)

NUBALIR is developed for table potatoes (middle late), processing tomatoes and fresh tomatoes and may run for wet, dry and normal climates at the SAFIR experimental sites (Figure 2.1).

It is based on simple FAO principles for calculation of crop development. Figure 2.2 shows crop parameters for middle late potatoes.

Figure 2.1 Sites at which the DSS NUBALIR runs.

Latitude range		60-40						40-20						20-0					
Growth phases		0	I	II	III	IV	V	0	I	II	III	IV	V	0	I	II	III	IV	V
	Days		25	30	45	30			30	35	50	30							
spring	Kc	0.4	0.4	1.1	1.1	0.7		0.4	0.4	1.15	1.15	0.75							
<121	root depth	0	20	40	60	60		0	20	40	60	60							
	Days		30	35	50	30													
mid-summer	Kc	0.4	0.4	1.1	1.1	0.7													
121-151	root depth	0	20	40	60	60													
	Days								25	30	45	30			25	30	30	20	
late summer	Kc							0.4	0.4	1.15	1.15	0.75		0.4	0.4	1.15	1.15	0.75	
>151	root depth							0	20	40	60	60		0	20	40	60	60	

Figure 2.2 Crop parameters for middle-late potatoes, from FAO(Doorenbos and Kassam, 1979, Doorenbos and Peruitt, 1992)

Standard wet, dry and normal climate data (ET0, precipitation and air temperature) are fixed table values for the sites. The water balance is calculated for the four growth phases I-IV as

Delta_SM = P – ET0*kc

where Delta_SM is the change in soil water content, P is precipitation and ET0*kc is reference evapotranspiration multiplied with the crop coefficient kc. Whenever Delta_SM is lower than a given deficit irrigation is suggested to replenish this deficit. Threshold deficit is determined from the type of irrigation, furrow, sprinkler and drip and soil type; see the web application for more details (www.safir4eu.org). The amount of plant available water (Field capacity minus wilting point) is soil specific and estimated from hydraulic parameters obtained from HYPRESS interpretation of the texture of the soil.

The amount of phosphorous and nitrogen needed is crop specific, see Table 2.1 below.

Table 2.1. Nutrient balance for potato, fresh and processing tomato

Potato				
Expected Yield	T/ha	55		
Dry matter content	%	21		
N-content	%	1.3		
P-content	%	0.25		
Total N-content		150	kg/ha	
Total P-content		29	kg/ha	
Additional requirement, N		20	%	for roots and
Additional requirement, P		30	%	residues, for P additional due to low uptake efficiency

Fresh tomato				
Expected Yield	T/ha	90		
Dry matter content	%	5.8		
N-content	%	2.8		
P-content	%	0.55		
Total N-content		146	kg/ha	
Total P-content		29	kg/ha	
Additional requirement, N		20	%	for roots and
Additional requirement, P		30	%	residues, for P additional due to low uptake efficiency

Processing tomato				
Expected Yield	T/ha	120		
Dry matter content	%	5.8		
N-content	%	2.8		
P-content	%	0.55		
Total N-content		195	kg/ha	
Total P-content		38	kg/ha	
Additional requirement, N		20	%	for roots and
Additional requirement, P		30	%	residues, for P additional due to low uptake efficiency

The demand for nutrients are distributed over the four growth phases (Table 2.2)

Table 2.2. Crop uptake of N and P distributed over growth phases

Typical demand distribution %	I	II	III	IV
N	25	75	100	100
P	25	75	100	100

Based on user inputs, which defines the location on the globe, the crop, crop yield, soil, Nmin in soil, irrigation system and strategy and nutrient concentration in the available waste water, balances for water, nitrogen and phosphorous are calculated. Surplus or additional need for nitrogen and phosphorous are then calculated for the four growth phases and for the season as a whole. If additional N and P is needed the user is guided if fertigation (add of additional nutrients to the irrigation water) is possible or the additional need must be put at the beginning of the season. Fertigation is possible if the current concentration of N and P in waste water do not exceed the upper threshold known to damage the crop. The threshold for nitrogen is 80 mg/l, and for P 12 mg/l.

2.3 Practical user guide, including examples.

Figure 2.3 shows the main input site to NUBALIR, for a more clear view see the www.safir4eu.org homepage.

Input is needed on which crop to grow at the selected site, the yield level and size of the field. Two irrigation strategies may be selected, namely “full irrigation” or “deficit irrigation”. For the latter, irrigation is calculated as a fraction of crop evaporation. The irrigation system needs to be defined as well as percent loss along the supply chain. The soil needs to be characterized to enable calculation of plant available water and also to calculated elements in the nitrogen balance. Finally the nutrient concentration in the applied wastewater needs to be given.

Figure 2.3. Input page for NUBALIR

Several outputs are possible, namely

1. Graphics/ha for the four plant phases,
2. Graphics for the complete growing season.
3. A table showing water and nutrient balances for the total grown area, and finally
4. a page where advice on supplemental fertilization with phosphorus and nitrogen is given.

These output are rather easy to read and understand on just one example is given below (Figure 2.4).

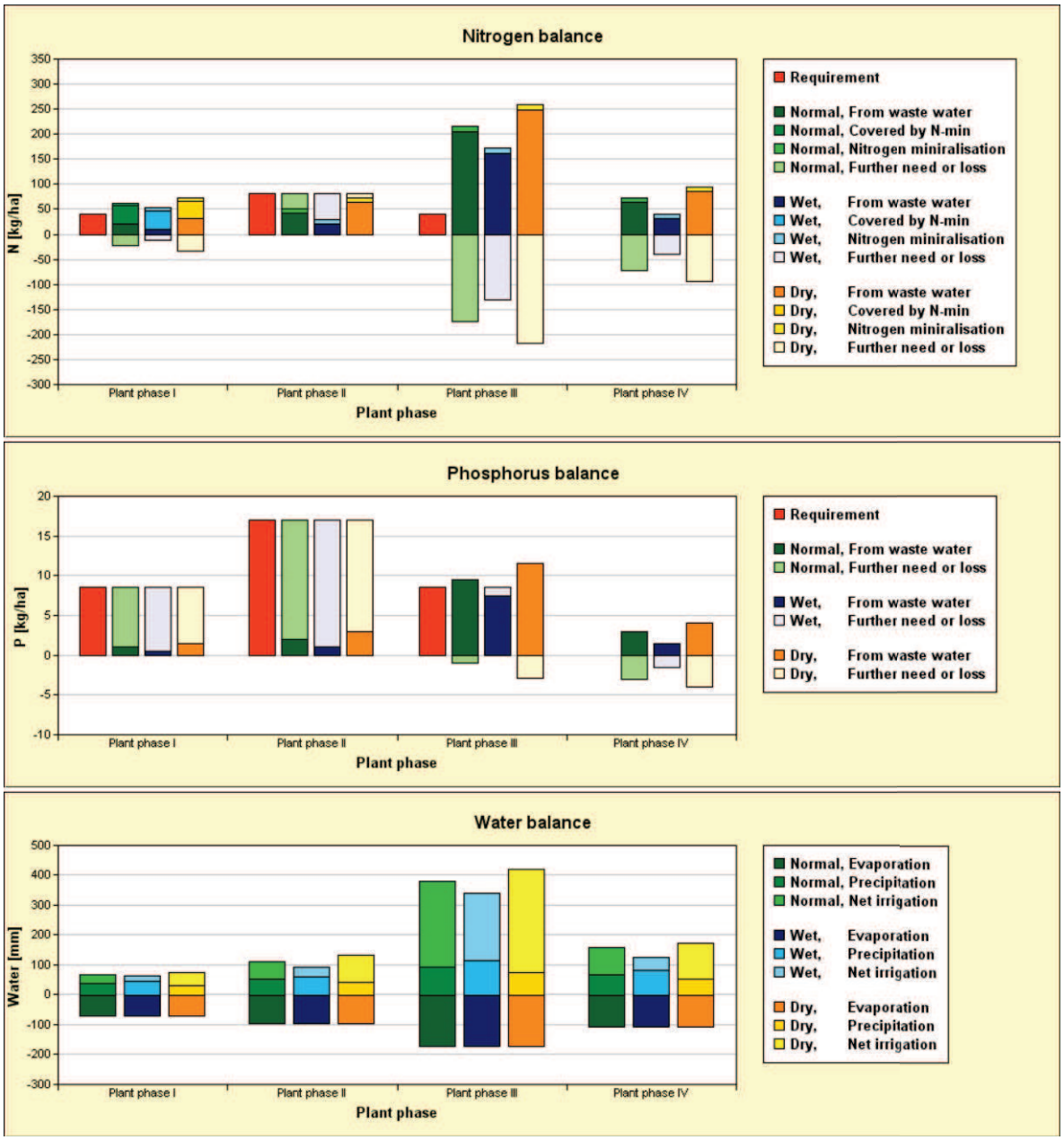


Figure 2.4 Calculated nitrogen, phosphorus, and water balance for the four growth phases.

Figure 2.4 shows the consequence for the nitrogen and phosphorus balance of using the selected waste water for irrigation. Negative values show the amount leached from the root zone. Additional need is shown positive and advice on how to distribute the additional amount is given when selecting “Need for fertilizer” at the input page. The bottom figure shows the water balance.

3 THE PROTOTYPE MANAGEMENT MODEL

3.1 Why was it made and what does it do

The prototype management model allows the user to test different combinations of water (including wastewater), filter methods, irrigation techniques and fertiliser strategies and evaluate water use, fertiliser use, crop growth, risks with respect to heavy metals and microbes and expected profit. The model can, of course, be run for different climatic conditions. The main use is therefore to analyse such systems before investments are made or when preparing a strategy for the season.

The key element in the model is the "plant-soil atmosphere"(PSA)-model Daisy, which is shown in Figure 3.1 as a grey box. Daisy simulates plant growth as well as movement of water, N-compounds, and if required, heavy metals and pathogens in the soil. The irrigation and fertigation module repeatedly questions the Daisy model with respect to the status on water and nitrogen, and determines whether water and fertilizer should be added. This module in turn requests water from the water source administration module, which keeps track of water sources, filters, storage, and criteria for selection of one or the other source. Heavy metals and microbes follow the flow of water to the soil column. At harvest the content of heavy metals in the soils and the concentration of microbes in the soil and on the crop are evaluated and the risk to consumers and farmers assessed. The costs of input and output are also evaluated.

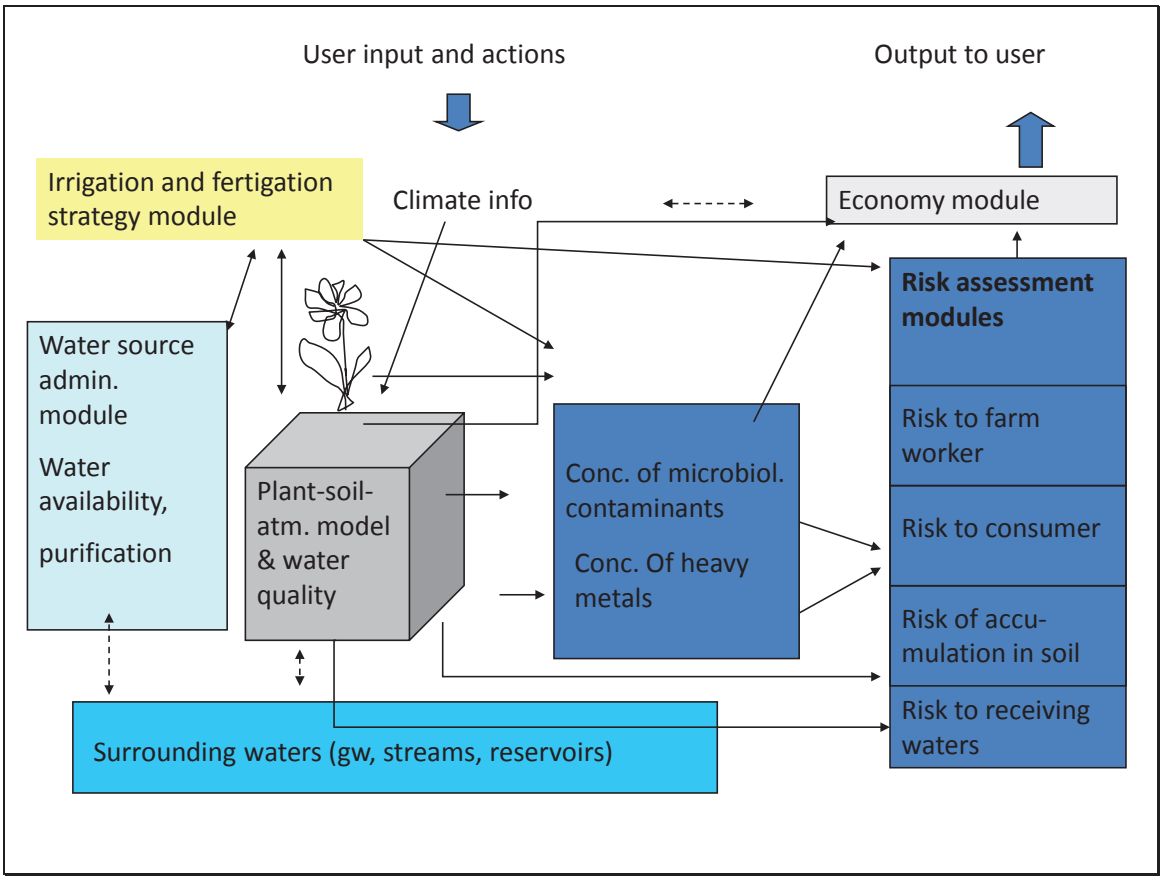


Figure 3.1: ***Overview of the prototype management model made within the Safir project. The plant-soil-atmosphere model used in the project is the Daisy model (Abrahamsen and Hansen, 2000).***

The prototype management model produced in SAFIR is in the first place intended to be a planning tool at farm level.

As a planning tool SAFIR DSS can help the farmer to:

1) Decide if the use of treated waste water as an additional or as the only water source for his irrigation is an option based on:

    a. Possibility to supply enough water from the water sources at the right time,

    b. Productivity – how much produce per hectare,

    c. Economy – how expensive is alternative solutions,

    d. Safety of the produce – can any heavy metals, vira, bacteria etc. on the produce harm the consumers,

    e. Safety for the farmer workers – can any heavy metals, vira, bacteria etc. in the soil or on the produce harm the farm workers,

    f. Impact on the environment – are the concentrations of polluting species in the soil too high,

2) Decide if further treatment of the treated waste water is necessary and test alternative purification methods like sand filters, membrane technology and UV light on the irrigation water quality **and** on the issues a. to e. listed above,

3) Test various irrigation strategies on the issues a. to f. listed above,

4) Test various fertigation strategies on the issues a. to f. listed above.

It would, however, be possible to develop the model into an on-line dynamic decision support system able to run from day to day to guide the farmer on whether to irrigate or fertigate on a given day by running it stepwise and updating the system with actual rainfall, irrigations and fertilizer additions, see Chapter 3.9.5. The models included allow this, but a shell for doing this has not been developed during the SAFIR project.

As a dynamic, on-line tool where weather, water quality, and other information continuously is fed into the database the SAFIR DSS can furthermore help the farmer to:

1) Decide when and how much to irrigate and fertigate based on up-to-date calculations of the conditions in the soil and in the crop – also taking into account the projected weather and water quality conditions in the water sources

2) Make projections of the issues a. to f. listed above at any time during the growth season.

3.2 Water source system

The water source administration system (WAM), placed to the far left on Figure 3.1 delivers water on request to the irrigation-fertigation strategy module (IFM) and the "Plant/soil/atmosphere model" (PSA-model), which in this case is Daisy (Abrahamsen and Hansen. 2000). The interaction between the modules is:

1. The IFM receives information from the PSA about crop development stage, soil moisture content and nitrogen content.

2. Based on this information and the irrigation and fertigation strategy defined by the user, the IFM calculates how much water that should be supplied to the PSA and if fertigation should be added.

3. IFM passes this request for water on to the WAM, which abstracts water from upstream sources, sends dirty waste water through filters and calculates concentrations of nutrients, microbes and heavy metals in the water that finally is delivered to the PSA.

3.2.1 Characteristics of the physical system

The water source administration system was designed based on an analysis of the treatments used in the SAFIR project. An overview of the treatments is shown in Figure 3.2.

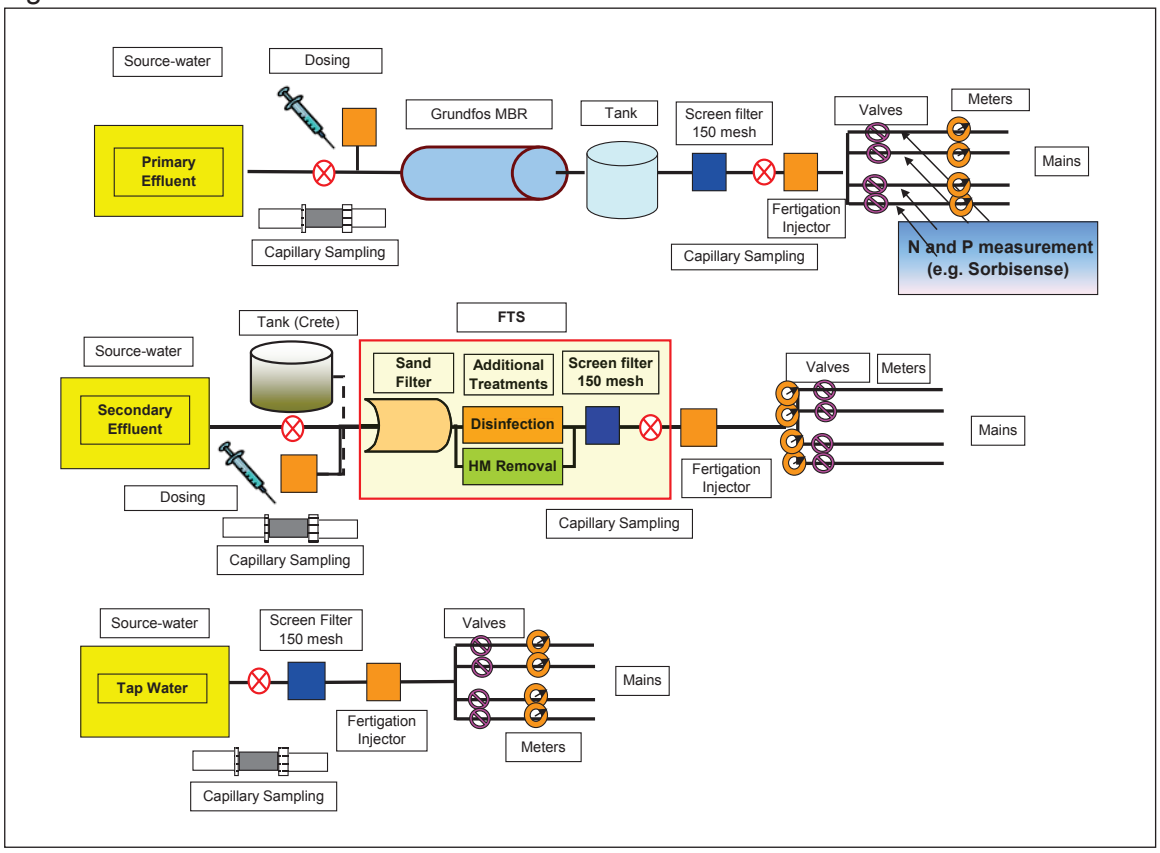


Figure 3.2: Schematic over treatment systems used in the field campaigns. Figure made by Adriano Battilani as part of the work in work package 1.

The following elements were identified:

- Water sources: e.g. Tap water, river water, waste water.
- Filters to purify dirty water (removal of heavy metals, chemicals or microbes)
- Reservoirs for storage

- Addition of fertilizers
- Irrigation devices: Sprinkler, surface drip, subsurface drip or furrow

3.2.2 Input data to the water source administration module

Defining a flow source with chemical compounds

By default a water source includes no chemicals. For each water source a list of chemicals present in the water is created.

- The properties of each chemical (e.g. its mole weight) should be stored in a table.
- A number of sources that contain e.g. NO_3 can refer to the NO_3 record in the table.
- The user can add new records of chemicals to the chemicals table when needed.

After making the list of chemicals for the source, time series for flow of water and concentrations of chemicals must be specified. Optionally, a time series for the price per m^3 water can be specified. The model is able to run without price specification.

Defining a filter

A filter is a device that partly or fully removes some chemical species. In this context the term "filter" is used both for simple physical filters as a sand filter and advanced membranes that enforce chemical reactions.

Properties of a filter:

- flow capacity ([m3/h])

A list of chemical reactions that the filter enforces must be created, and then the effect on each chemical is specified:

- Reduction by a factor: specify a "pass through rate" for the chemical
- Chemical reaction: Define a chemical reaction

The table below illustrates the concept for various compounds through a fictive filter.

Table 3.1: Example showing calculations done to produce output concentrations for a fictive filter.

Compound	Fraction passing through	Output concentration
Water	0.999	0.999 * original quantity
NO_3^-	1	1 * NO_3^-
NH_4^+	1	1 * NH_4^+
PO_4^{--}	0.8	0.8 * PO_4^{--}
Organic P	0.3	0.3 *organic P
organic matter	0.3	0.3 * organic matter
[other salts?]	1	1 * [other salts]
[heavy metals]	0.3	0.3 * [heavy metals]
[xenobiotics]	0.5	0.5 *[xenobiotics]
[microbiological contaminants]	0.1	0.1*[microbiological contaminants

Specifically for the MBR/biobooster, process descriptions were required. In the MBR, ammonia nitrifies. This means that 86 % of the NH_4-N becomes NO_3-N. The rest is build into the biomass or denitrifies simultaneously. The resulting NO_3-N-concentration is therefore a sum of the original NO_3-N-concentration and a fraction of the original NH_4-N.

An additional process description that was not implemented, but observed in the field experiments were to apply a fraction when the input concentration was large and a constant maximum concentration, when the input concentration was low. Table 3.2 shows the factors some of the factors derived for the Bio-booster.

Table 3.2: Fractions or equations required to describe the filtering effect of the MBR/bio-booster.

Compound	Fraction passing through	Output concentration
Water	1	0.999 * original quantity
NH_4^+	0.04	0.04 * NH_4^+ or max 0.5 mg/l
NO_3^-	1	1 * NO_3^- + 0.86* NH_4^+
COD	0.1	0.1*COD or max < 50 mg/l
TOT-N	0.54	0.54*TOT-N

Compound	Fraction passing through	Output concentration
PO_4^{--}	0.56	0.56 * PO_4^{--}
E.Coli	0.0001	4 log units (see microbial calc.)
It special modules are added to the MBR, concentrations may be reduced further:		
ToT-N		<10 mg/l
NO3-N		<10 mg/l
Tot-P		<1 mg/l

Defining a tank

A tank is used for storage of water, for instance when water is a scarce resource. A tank shall request water from its upstream source until it is full (or reaches at a defined level) regardless of the current irrigation demand.

Properties of a tank

- Volume [m^3]
- Outflow capacity [m^3/h] (we cannot empty a full tank in a second)
- Evaporation of water
- Decay of some species (e.g. microbes)

3.2.3 Output from the Water source administration module

From each source (flow source, filter, tank, and water manager) a time series of the actual abstraction/outflow can be generated. Also concentration of chemical compounds is logged.

The output time series logs the total amount of water supplied in the time step in [kg]. Concentrations are logged in [ppm] which corresponds to [mg] of the constituent per [kg] water.

3.2.4 Design

Representation of water that carries chemicals

In a given time span (typically one time step of the PSA model) the Water Source Administration Module shall deliver MAX(requested water, available water).

The PSA model works with time integrated quantities, which means the amount of water supplied in one time step (in [m^3] or kg). The source information will typically be given as a flow time series (in [m^3/h]), which is an "instant" quantity. Likewise for the nutrients, where the PSA model input is an amount in [kg] and the source information typically is a time series of concentration (e.g. [mg/l]).

When the Irrigation and Fertigation Strategy Module asks WAM for water in a given time span, WAM must deliver a mass of water ([m^3] or [kg]) and the masses of the chemicals (in [kg]) that the water carries. The IFM must then calculate the quantities for the PSA: irrigation depth in [mm] and Nitrogen in [kg/ha] based on information of the size of the field.

Representation of sources

In the simplest case a single source (with or without chemicals) delivers water for the irrigation. In more complicated applications the water is abstracted from two or more sources, water from different sources run through different treatments and finally the treated water is mixed before the "resulting" water is delivered to the irrigation system.

Similarities and differences between the source types are shown in Table 3.3.

Table 3.3: Similarities and differences between sources of different type

Type of Sources	Functionality	Upstream source	Chemical compounds present in the water	Concentration of chemical compounds	Price	Physical characteristics
FlowSource	"Origin" of water	Cannot have upstream source. Flow information stems from a time series of "available water"	Information about which chemicals must be specified for each flow source	Concentration specified in time series	A price per m^3 abstracted water can be specified in a time series file	Defined in the flow and concentration time series
Tank	Storage on the way from abstraction to irrigation	Exactly one upstream source	Compounds from upstream source + reaction products	Evaporation increases concentration Some reactions might take place during the stay in the tank. e.g. decay of coli bacteria	The price per m^3 increases if the water evaporates	Storage volume [m^3] Outflow rate [m^3/h]
Filter	Treatment of water	Exactly one upstream source	From upstream source + reaction products	A list of reactions that the filter enforces must be specified.	The filtering cost per m^3 should be added to the "inflow" price	Flow rate [m^3/h]
WaterManager	Mix water from two or more sources	A list with two or more upstream sources. The list must be prioritized	All chemicals from the list of upstream sources	Calculate concentration of all chemical compounds in the water-mix	No cost for mixing	None; the WaterManager is not a physical device

3.2.5 Access to input data

General

Regardless of how the input data is stored (e.g. as xml-files, pfs-files or a database) the input data needs to be accessed both from the user interface and from the engine. The user interface needs write access in order to store the parameter configuration that the user enters. The engine needs read access to the input data in order to carry out the computations.

It has been decided to store the parameter configuration for the SAFIR prototype management model in a Microsoft Access 2000 Database. The advantage of this approach is that for instance a long list of chemicals and their properties can be defined in advance in the table SAFIR_Chemical. When setting up a system the user can use these predefined chemicals when configuring the flow sources. Also typical chemical reactions and the physical properties of various filters can be predefined. Advanced users can add chemicals and chemical reactions themselves.

A number of irrigation strategies and irrigation equipment can also be predefined in the database and the user can change this information or add new records.

In the following sections the design of the tables in the database is described.

Access to Water Source Administration data

Figure 3.3 shows the database design for the water sources administration module. Each box corresponds to a data table. In the following a short description of each data table is given. See Figure 3.5 for an application example.

The table SAFIR_Sources shown in Figure 3.3 is the table that collects all information about the sources: Upstream flow sources, filters, tanks, and water managers are all listed in this table. The field `SourceID` is the key to further information about the source:

- For a flow source the flow data is specified in the record in the `SAFIR_FlowSource` table that contains the same `SourceID`.

- For a filter the physical properties of the filter are specified in the record in the `SAFIR_Filter` table that contains the same `sourceID`.

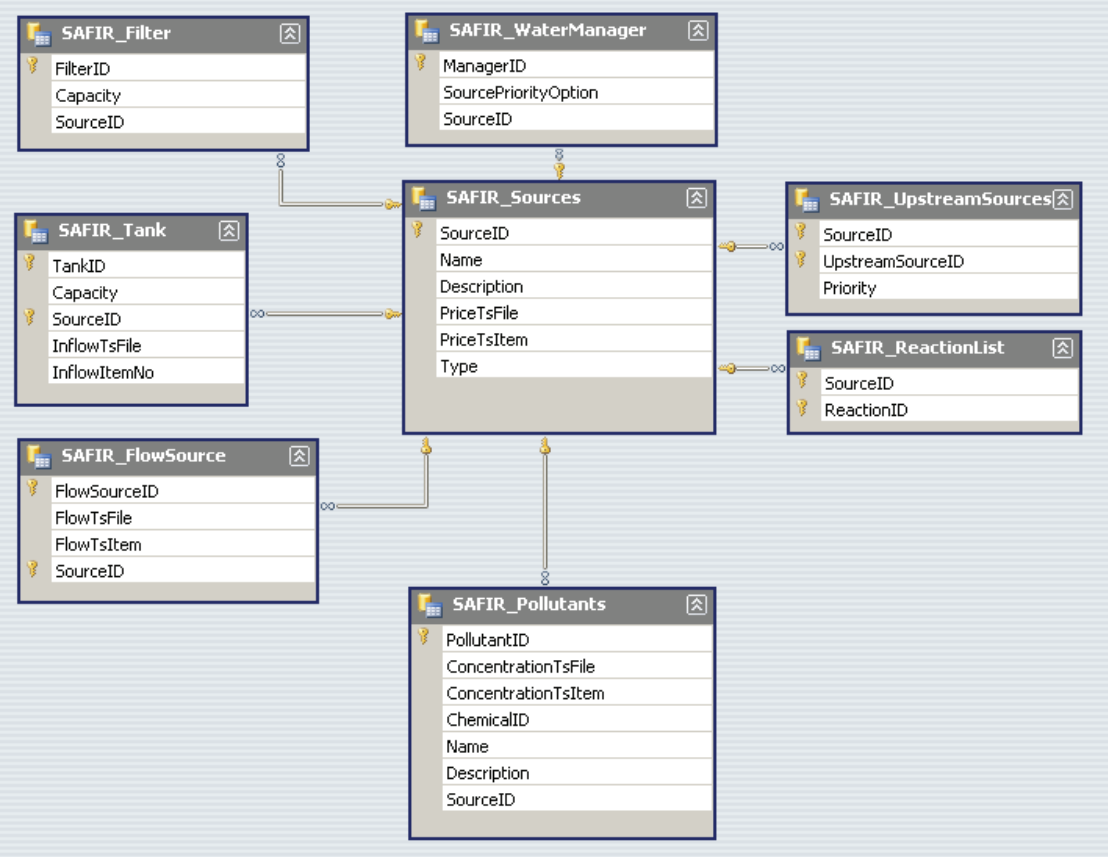


Figure 3.3: Data base design for the Water Source Administration module

Table 3.4: Fields in the SAFIR_Sources table

Field Name	Type	Functionality of input
SourceID	integer	Refers the SourceID of the other tables
Name	string	A user specified name of the source/filter/tank/ water manager
Description	string	User specified description that supplements the Name
PriceTsFile	string	Path to dfs0-file with price of the water in [Currency/m^3]
PriceTsItem	integer	Item number in the specified dfs0-file
Type	integer	

The table SAFIR_FlowSources shown in Figure 3.3 and in Table 3.5 holds the records of flow data (time series of flow) for each flow source.

Table 3.5: Fields in the SAFIR_FlowSources table

Field Name	Type	Functionality of input
FlowSourceID	integer	Unique identifier for the flow source
FlowTsFile	string	Path to dfs0-file with flow data
FlowTsItem	integer	Item in the dfs0-file
SourceID	integer	Referred by SAFIR_Sources in the "total list of sources". Referred by SAFIR_pollutants in order to connect concentrations time series of pollutants to a source.

The table SAFIR_Pollutants shown in Figure 3.3 and Table 3.6 lists concentration time series for a chemical and connects it to a (flow) source by referring the SourceID.

Table 3.6: Fields in the SAFIR_Pollutants table

Field Name	Type	Functionality of input
PollutantID	integer	Unique identifier for the pollutant
ConcentrationTsFile	string	Path to dfs0-file with concentration data
ConcentrationTsItem	integer	Item in the dfs0-file
ChemicalID	integer	Refers to the definition of the chemical in the SAFIR_Chemical table
Name	string	User specified name (usually a repetition of the name of the chemical?)
Description	string	User specified description (usually a repetition of the description of the chemical?)
SourceID	integer	Refers to the SourceID in the SAFIR_Source table

The table SAFIR_Filter shown in Figure 3.3 and Table 3.7 holds the physical properties of a filter.

Table 3.7: Fields in the SAFIR_Filter table

Field Name	Type	Functionality of input
FilterID	integer	Unique identifier for the filter
Capacity	double	The flow capacity of the filter in [m^3/h]
SourceID	integer	An ID for the SAFIR_WaterSources table

The table SAFIR_ReactionList shown in Figure 3.3 and Table 3.8 holds the purification properties of the filters by listing pairs of sources and chemical reactions / reduction / decay.

Table 3.8: Fields in the SAFIR_ReactionList table

Field Name	Type	Functionality of input
SourceID	integer	ID of the source that "hosts" the reaction. This source must be a filter.
ReactionID	integer	ID of the reaction in the SAFIR_Reaction table

The table SAFIR_Tank shown in Figure 3.3 and Table 3.9 describes the physical properties of a tank.

Table 3.9: Fields in the SAFIR_Tank table

Field Name	Type	Functionality of input
TankID	integer	Unique identifier for a tank
Capacity	double	The Capacity of the tank in [m^3]
SourceID	integer	An ID for the SAFIR_WaterSources table
InflowTsFile	string	Path to dfs0-file with inflow data
InFlowTsItem	integer	Item number in dfs0-file

In the prototype the tank object has only been loosely defined, but the definition in Table 3.9 is insufficient. It must be possible to specify upstream sources (e.g. flow sources or filters) as inflow to the tank – not only a time series. Furthermore the tank must possess an "OutflowCapacity" as it cannot be emptied instantly.

Access to Chemistry data

Figure 3.4 shows the database design for the input to the Chemistry component.

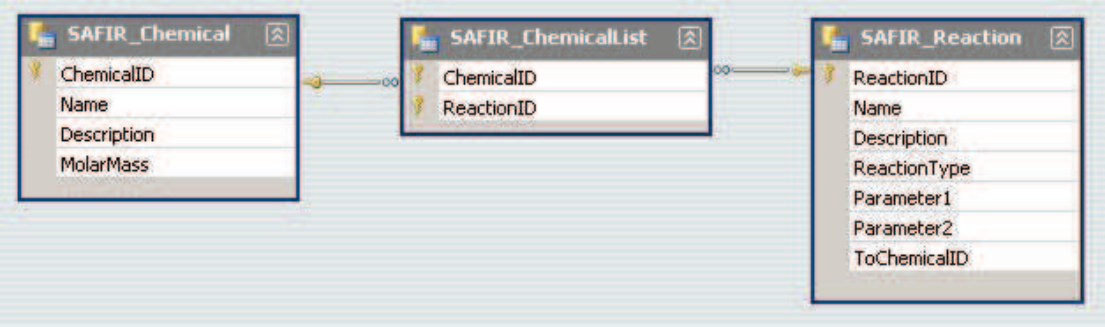


Figure 3.4: Database design for specifying chemicals and associated reactions

WAM – example of database

Figure 3.5 shows a screen dump of a database that configures water source administration of water from two sources:

1. A clean water source without any pollutants (not very likely as even tap water has small concentrations of e.g. nitrate, but it is used as a simple test example)

2. A secondary waste water source that contains Nitrate (NO3), Ammonium (NH4), Phosphor (PO4) and coli bacteria (E.Coli). The secondary waste water is sent trough a (sand) filter which reduces the amount of E.Coli to 0.63 of the original amount.

The (cheap) secondary waste water has first priority when water for irrigation is requested, but the delivery is limited by the filter capacity. Thus the remaining demand is requested from the clean water source.

The two sources (clean water and secondary waste water) are specified in the table SAFIR_FlowSources. In this table the name of the .dfs0-file that contains the time series and the item number in the time series file is specified. Each source has a unique SourceID.

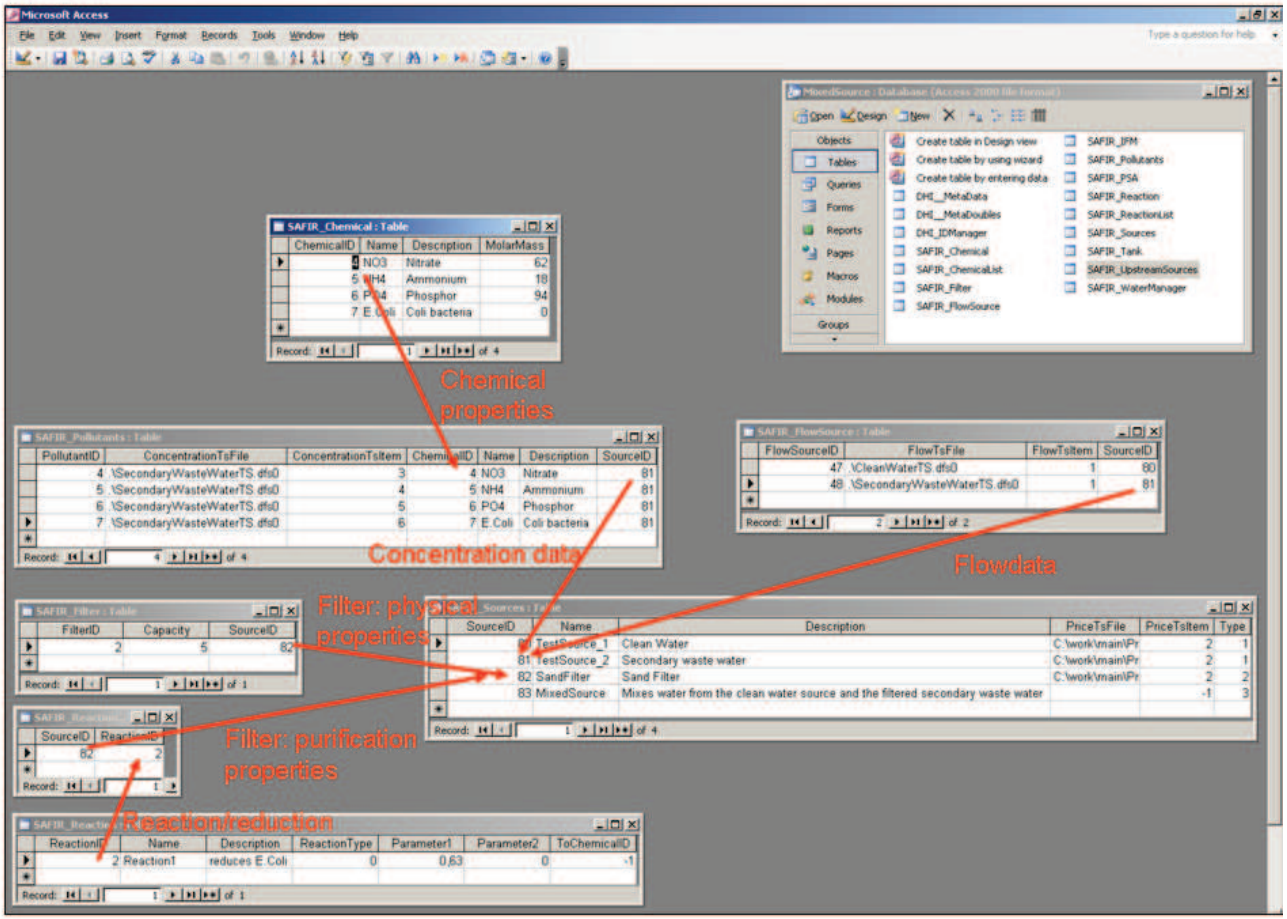


Figure 3.5: ***Screen dump from the SAFIR configuration database, showing the set up for mixing water from two sources: A clean water source and a filtered secondary waste water source.***

3.2.6 *Parameterisation for the prototype*

Water sources

Each of the water sources specified in the database table “SAFIR_sources” must link to a time series file in DHI format i.e. in *.dfs0 c.f. Figure 3.6. Water sources can be several and e.g. include clean water, primary waste water (PWW) or secondary waste water (SWW).

	Time	1:flow [m^3/s]	2:price [undefined]	3:Nitrate [mg/l]	4:Ammonimum [mg/l]	5:Phosphor [mg/l]	6:E.Coli [mg/l]	7:Pb [mg/l]
0	01-12-1970 00:00:00	0.75	0.02	5	5	8	0.00025	0.002
1	02-12-2020 01:00:00	0.75	0.02	5	5	8	0.00025	0.002

Figure 3.6 Example on a time series file describing secondary waste water

Water sources in the time series are characterized by an item that specifies the flow in m^3 per second and subsequently a number of items containing the concentrations of the constituents in the water source e.g. the content of nutrients heavy metals and E.Coli. All constituents defined in the time series, must be denied in the database table “SAFIR_chemical”. All concentrations in the time series must furthermore be specified in mg/l (ppm), which for E.Coli is somewhat arbitrary in the sense that E.Coli normally is considered in colonies or CFU i.e. a normal unit for E.Coli is cells per liter. In order to calculate the E.Coli into concentration [mg/l], is used the E.Coli cell weight given as 1x10-9 mg/cell.

Tanks

A tank object is not operational in the prototype c.f. 3.2.2, however, the description must include the tank volume and die-off of E.coli and other relevant processes e.g. denitrification of nitrogen.

According to the SAFIR Deliverable 5.4-report “Survival and transport of helminth eggs and faecal coliforms in soil and agricultural produce” (Ensink and Fletcher, 2009) E. coli survives in (drinking) water for between 4 and 12 weeks, depending on environmental conditions (temperature, microflora, etc.).

Using a temperature function to modify die-off rates, a T90-value of 40 days results in approximately the right spread die-off rates, at least between 10 and 25 C°. The temperature function is equal to what is used in the Daisy model to adjust decomposition rate coefficients as a function of soil temperature.

For the Italian site, which is the test site for the prototype, the average temperature over the irrigation season is approximately 15 degrees. It is therefore recommended to use the corresponding die-off coefficient in the simulation of die-off in tanks.

Table 3.10: Die-off coefficients for E.coli in water as a function of temperature.

T	5	10	15	20	25	30
reduction factor (T=10)	0,5	1	1,5	2	2,8	4
reduction factor (T=20)	0,25	0,5	0,75	1	1,4	2

days-1	k(mod)	0,0144	0,0288	0,0432	0,0576	0,0806	0,1151
Days	T90	160	80	53	40	29	20
reduction per day, %		1,43	2,84	4,23	5,59	7,74	10,87

Filters

Filters must be characterised by a capacity, the type of process taking place and the relevant parameters for the process. Most filtration processes are described as a fraction of the input concentration that leaves the filter. Table 3.11 shows the parameters derived on the basis of the field trials of SAFIR and reported in deliverable 1.4. It should, however, be noted, that when the individual removal percentages for heavy metals in gravel filter and heavy metal removal device are combined, it underestimates the full effect seen in the system. On the other hand, the reduction in microbes assigned to the gravel filter and the heavy metal removal device leaves only a small reduction to the UV-lamp.

Specifically with respect to microbes, the method of description is compatible with the WHO-approach to description of measures reducing the risk to microbes. Table 3.12 shows decades of reduction in load due to different cleaning processes estimated by WHO (2006). In our case, the decades are just converted to fractions (e.g. 2 decades equals a fraction of 0.01).

Table 3.11: Description of filters according to figures reported in Deliverable 1.4.

	unit	MBR	gravel filter	UV lamp	heavy metal removal device
Capacity	m3/day	8.4	5	10.5	
COD	mg/l	0.1			
DOC	mg/l	0.1	1	1	
TOC		0.4	0.85	1	
NH4		0.04	1.00	1	
Cl		0.70	1.00	1	
NO3		conc*1+0.86 * input NH4-conc.	1.00	1	
PO4		1.00	1.00	1	
NO2		1.00	1.00	1	
Al		0.25	0.50	1	
As		0.183	0.59	1	0.65
Cd		0.182	0.64	1	0.78
Cr		0.033	0.52	1	0.75
Cu		0.072	0.54	1	0.67
Pb		0.012	0.63	1	0.47
NTOT		0.54	1.00	1	
PTOT		0.56	1.00	1	
E.coli		0.0001	0.1	0.4	0.15

Table 3.12: Log unit reduction or inactivation of exreted pathogens achieved by selected wastewater treatment processes. From WHO guidelines.

Treatment process	Log unit pathogen removals			
	Viruses	Bacteria	Protozoan (oo)cysts	Helminth eggs
Low rate biological processes				
Waste stabilisation ponds	1-4	1-6	1-4	1-3
Wastewater storage end treatment reservoirs	1-4	1-6	1-4	1-3
Constructed wetlands	1-2	0.5-3	0.5-2	1-3
High-rate processes				
Primary treatment				
Primary sedimentation	0-1	0-1	0-1	0-<1
Chemically enhanced primary treatment	1-2	1-2	1-2	1-3
Anaerobic upflow sludge blanket reactors	0-1	0.5-1.5	0-1	1.5-1
Secondary treatment				
Activated sludge + secondary sedimentation	0-2	1-2	0-1	1-<2
Trickling filters + secondary sedimentation	0-2	1-2	0-1	1-2
Aerated lagoon+settling pond	1-2	1-2	0-1	1-3
Tertiary treatment				
Coagulation/flocculation	1-3	0-1	1-3	2
High-rate granular or slow-rate sand filtration	1-3	0-3	0-3	1-3
Dual media filtration	1-3	0-1	1-3	2-3

Treatment process	Log unit pathogen removals			
	Viruses	Bacteria	Protozoan (oo)cysts	Helminth eggs
Membranes	2.5->6	3.5->6	>6	>3
Disenfection				
Chlorination	1-3	2-6	0-1.5	0-<1
Ozonation	3-6	2-6	1-2	0-2
Ultraviolet radiation	1->3	2->4	>3	0

3.3 Irrigation/fertigation strategy module

An "irrigation strategy" is a set of rules concerning *when* to supply water and *how much* water to supply. As such the modelling of irrigation strategies is the modelling of actions, not of physical installations. However the execution of an irrigation strategy will depend on the physical installations, e.g. capacity of the irrigation system, capacity of purification filters, and available water from the sources.

Traditional irrigation strategies let the soil moisture content of the field decrease to a specified level and then supply the water needed to fill the root zone fully or partially. The soil moisture content that triggers irrigation and to what limit the root zone is filled during irrigation depends on the crop, the development stage and the personal experience of the farmer.

The modelling of irrigation strategies are coupled to a model of water sources and to a model of field and crop. Figure 3.7 shows a sketch of the concept. In this way a large number of scenarios with different irrigation strategies can be run in a short time. At the end of each simulation parameters such as crop quality and total costs of irrigation can be evaluated and a decision of which irrigation scheme to use can be made.

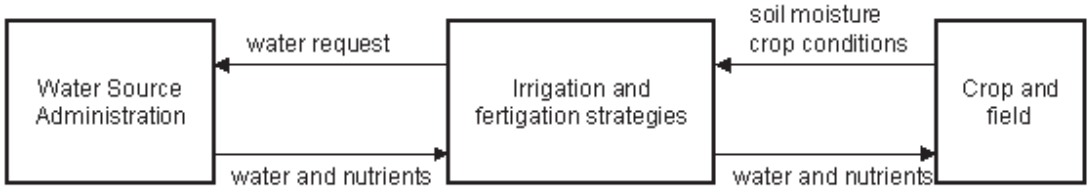


Figure 3.7: Conceptual sketch of how the model of the irrigation and fertigation strategy interacts with the model of water sources and the model of crop and field.

Fertigation is the use of fertilizers, which are dissolved in the irrigation water. Especially if waste water is used for irrigation the water might already carry some nutrients and this load might or might not fulfil the demand of the crop. Fertigation strategies are very similar to irrigation strategies in that a lower limit that triggers a fertigation demand is defined and the

amount of fertigation should bring the crop to some specified upper limit. The fertigation is subject to some physical restrictions:

1. Because the fertilizer is dissolved in the water fertigation can only take place while irrigating – which may cause extra irrigations.

2. The amount of fertilizer that can be dissolved in a given water volume has an upper limit.

3. There might be an upper limit to the concentration of fertilizer in the irrigation water in order not to damage the roots or leaves.

3.3.1 Characteristics of the physical system

In the SAFIR field experiments, the irrigation methods used were furrow, sprinkler, surface drip and subsurface irrigation. In addition, crops were irrigated using different strategies such as full irrigation, deficit irrigation and deficit irrigation using partial root drying. Partial root drying is further complicated by the fact that irrigation is done at one side of the plant at a time, with a specified rule to determine when to change from one side to the other.

The DSS, however, does not act exactly as prescribed in the Safir field trials. The experiments were carried out based on calculation of the reference evaporation or a fraction of this, while the idea for the DSS from the beginning of the project has been to guide irrigation according to pressure potentials in the soil.

Strategies of irrigation may change over the season and the changes depend on both type of crop and crop stages. In general, the plants should be well supplied with water up to flowering, while reductions in water application can be made from this period onwards.

Irrigation

Irrigation can be described in different ways in the SafirDSS; either as a prescribed irrigation scheme, based on relative water content or as a prescribed irrigation depth.

In the *prescribed irrigation scheme* option, the irrigation depth (in [mm]) is specified as a time series. If the demand cannot be fulfilled in one time step (due to limiting factors as irrigation system capacity or water availability) the remaining demand is requested during the next time step. The prescribed irrigation scheme can, among other applications, be used for testing of the Water Source Administration Module without coupling to the PSA, because the water request does not depend on information from the PSA.

If irrigation is based on *relative root zone water content* irrigation is triggered when the relative water content reaches a user defined lower limit (threshold). This lower limit depends on the crop development stage and will typically be reduced over time while the crop gets more resistant to water stress. A table that relates lower limit values to crop development stages is used to define the trigger values for "start irrigation". A table that relates upper limit values to crop development stage is used to define values for "stop irrigation". If the relative water content is defined to be 1.0 at field capacity and 0.0 at wilting point, full irrigation during irrigation stage 1 can be simulated by setting "stop values" to 1, i.e. irrigate until field capacity is reached.

If irrigation is based on *prescribed irrigation depth* irrigation is triggered when the relative water content in the root zone reaches a lower limit as described above. When irrigation is triggered, water that fulfils a prescribed irrigation depth is requested. The prescribed irrigation depth might be dependent on the crop development stage and in that case a table relating development stage to irrigation depth must be supplied.

The irrigation also depends on the irrigation strategy (full, deficit, regulated deficit, prd) **and** the *irrigation method* (sprinkler, furrow, drip) **and** on the *crop* (potatoes, fresh tomatoes, processing tomatoes).

The capacity of the irrigation equipment (and to some extent the soil type) determines the time between two irrigations – and therefore also to some extent the threshold to be used. Sprinkler and furrow irrigation add much water (at least 30 mm during one irrigation) and the irrigation is therefore spaced to “make room” for this amount. Drip irrigation is very frequent and aims at replacing “today’s” (read yesterdays) evapotranspiration only. The lower threshold for drip irrigation is therefore not as low – less room is required to store the small amount of water. However, for clay soils, the soil structure still makes it attractive to irrigate with slightly larger amounts, equal to a few days evapotranspiration.

The term *full irrigation* is quite well defined but the terms *deficit irrigation* and *regulated deficit irrigation* have caused some confusion. Deficit irrigation means that the irrigation depth at all the times is a fraction of the amount that would have been required for the full irrigation. In *regulated deficit irrigation* the evaporated amount is replaced, but the threshold in the soil is lower than it would have been for full irrigation (at least for some growth stages). It could be kept constant during the season, but usually, it is kept constant for a period of time and moved downwards or upwards when going from one growing/irrigation stage to another. The main difference is that *deficit irrigation* normally refers to Ep so just a part of it is replenished, while *regulated deficit irrigation* aims to keep the soil tension (available water content) in a defined soil layer at a certain level in order to impose some stress only when the vegetation is the dominant sink. *Deficit irrigation* calculated on Ep basis causes increasing soil water depletion during the season.

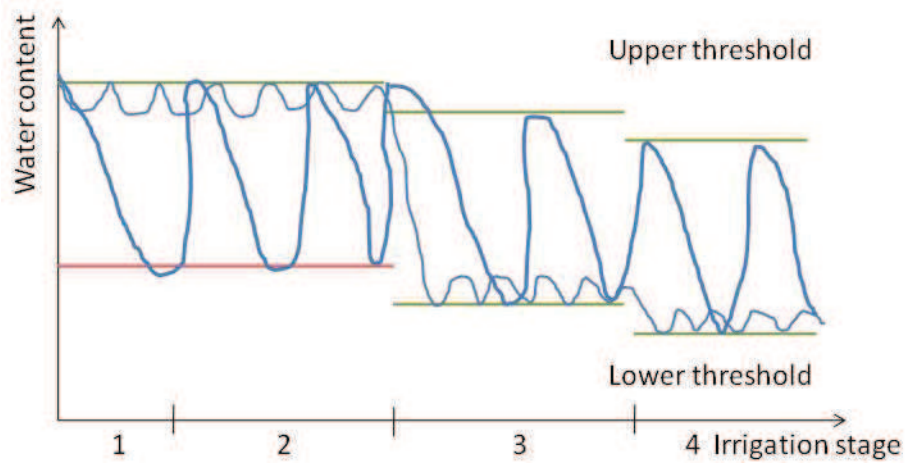


Figure 3.8: ***Schematic illustration of full irrigation with sprinkler equipment compared with deficit irrigation with drip equipment for regulated deficit irrigation. Large variations in water content compared to small variations in water content in the soil.***

The prototype management model deals with 4 irrigation stages, which are defined for each of the crops the DSS is developed to handle, i.e. potatoes, processing tomatoes and fresh tomatoes. The irrigation stages are linked both to Daisy growth stages and to other types of development as for instance the root depth, the temperature sum and others c.f. paragraph 3.3.4.

Fertigation strategy

The fertigation strategy is based on the N-balance in the crop. Phosphorus fertilisers is not considered because Daisy cannot handle phosphorus and so the conditions in the plant cannot be monitored during the simulation NUBALIR can be used to decide on the amount of P to apply before planting. The P-application with irrigation water is monitored in the irrigation/fertigation module and can thus be compared to a previously defined P-requirement.

The fertigation strategy will be based on three variables from Daisy, i.e. actual N content in the plant ($N_{act)}$, potential N content in the plant (N_{Pt}) and critical N content in the plant (N_{Cr}). These variables summarise the nitrogen content in the plant root, leaves, fruits and stem and are good indicators on the plants condition. If N_{act} lies between N_{Pt} and N_{Cr} the plant is growing optimally, so the strategy is simply to try to fulfil this requirement.

If all water supplied to the field was irrigation water, the implementation of this approach would be simple. However, in reality it rains from time to time, and if the plants rely on fertigation alone, there may be times, where fertigation is required when the moisture content is still adequate, and this can lead to over-irrigation. NUBALIR analyses typical seasons and calculates whether an initial dose of fertilizer is required to minimize such problems. Fertilizer may thus be applied as an initial dose, through fertigation or through a mixture of the two.

The analysis carried out by the module is the following:

If $N_{Act} > N_{Cr} + \Delta N_{Cr} * N_{days}$ no action is required

If $N_{Act} \leq N_{Cr} + \Delta N_{Cr} * N_{days}$ then initiate fertigation.

ΔN_{Cr} is the daily N-requirement that will keep the plant at the critical level (and thus avoid that the level falls below). To obtain this value, the model monitors the daily changes in N_{Cr}. N_{days} is the typical distance between two irrigations. For many drip installations this will be every day or every second day. The selected strategy is most appropriate for drip irrigation; if N_{days} become large, the ability to predict the requirement becomes poor.

The amount to be added is calculated as:

Addition = $N_{Cr} - N_{Act} + \Delta N_{Cr} * N_{days}$ + “Security factor”

Initially, the security factor was set to be $f*(N_{Pt}-N_{Cr})$, where f is a factor between 1 and 0, developing towards 0 during the season. However, the approach had the disadvantage that in the beginning of the growing season, where the uptake increases fast, the ΔN_{Cr} “undershoots” the development and the difference between N_{Pt} and N_{Cr}) is minute. Presently, the security factor is a number of kg’s that is reduced over the growing season, starting with approximately 5 kg and ending with 0, but the value can be changed by the user.

The need for N can trigger irrigation with the minimum quantity of water required to dissolve the fertilizer and avoid damage to roots. For sprinkler irrigation it is important to dilute the mother solution in order not to burn the leaves.

In all cases an initial content of N in the water is taken into account before dosing the fertigation solution.

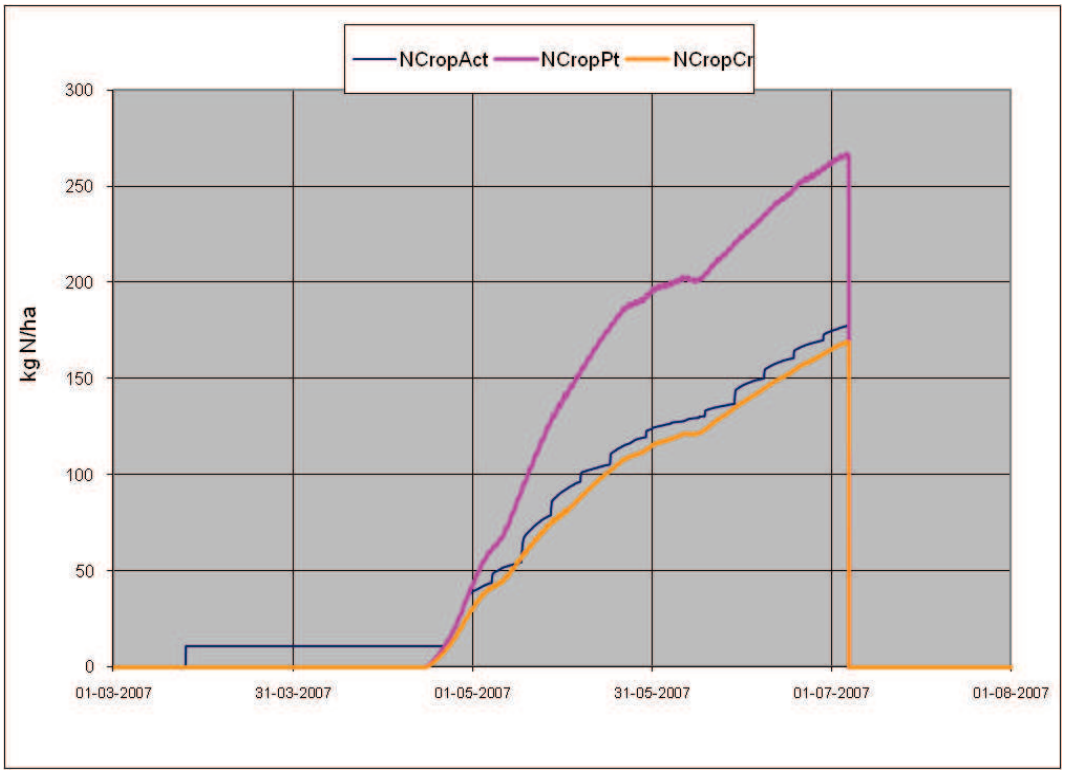


Figure 3.9: ***The IFM monitors the critical N content of the crop and predict the N requirement for a specified forecast period. Fertilizer is applied according to the prediction.***

Preferably the N_{Act} -value, particularly towards the end of the growing season, should not exceed N_{Cr}, because this is a sign of excess fertilization and perhaps also excess nitrate in the soil that may leach after harvest. However, if wastewater is used all through the season, such an excess may build up due to the content of ammonia and nitrate in the wastewater. For both tomatoes and potatoes an excess may influence the yield negatively.

3.3.2 Input data to the Irrigation/Fertigation module

The module receives input data from four different sources.

1. First of all, information concerning area to be irrigated, which irrigation strategy to use, trigger criteria for irrigation and how these should change over the season, which fertilizer strategy to use etc. is supplied directly to this module via the Access database.

2. Time series that allow the user to apply certain constrains, within which the DSS operates.

3. The information about the conditions in the soil or in the plant is supplied from the PSA model “Daisy” during the model simulation. The module asks for the value of control variables via OpenMI (Gijsbers, 2004 Gregersen et al. 2005, Gregersen et al. 2007), which is a system that allows communication between different models. The module decides on the basis of the plant-soil conditions and the strategy set up irrigation or fertigation should be carried out. This is specified as a condition: If the condition is true (e.g. "relative root zone deficit > 0,75") then the assigned strategy is executed.

4. However, before the irrigation can be carried out, the module has to request the water source administration module whether water is available and in what quality. This information influences whether the irrigation can be carried out and may adjust the fertigation strategy in case the supplied water already contains nitrogen.

Direct input to the module

Figure 3.10 shows the database design for the input to the Irrigation and Fertigation Strategy Module. Information about irrigation equipment and irrigation strategy is specified in these tables, whereas the fertigation strategy has to be specified in additional time series files c.f. paragraph **Error! Reference source not found.**.

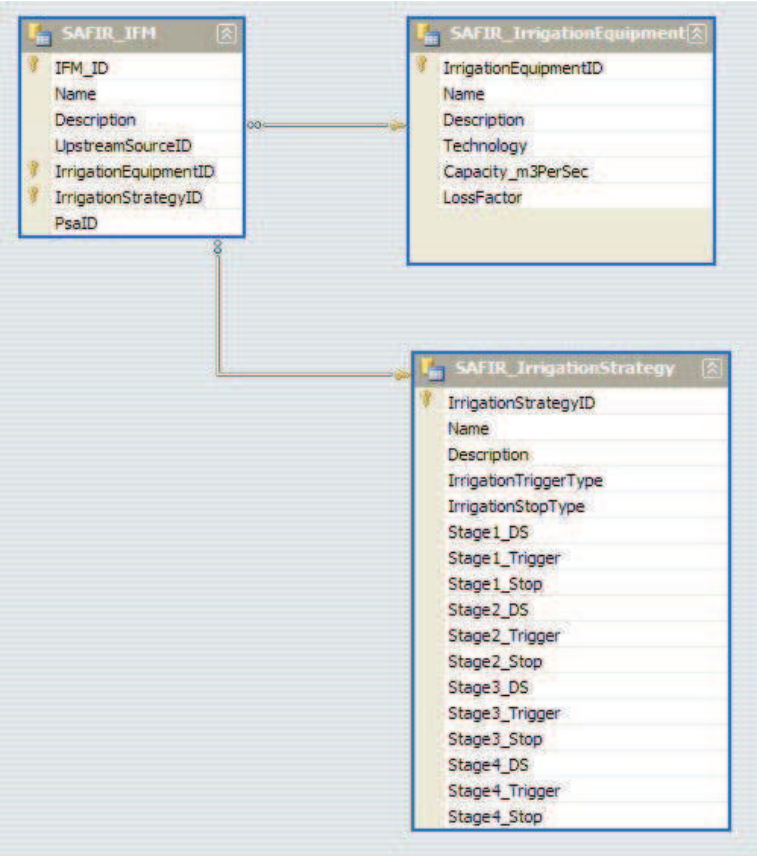


Figure 3.10 Data tables for irrigation and fertigation strategies

SAFIR_IFM is the table in which the main setup for a SAFIR run is defined. This table holds keys to source information (UpstreamSourceID), specification of

irrigation equipment (IrrigationEquipmentID), specification of irrigation strategy (IrrigationStrategyID) and a key to the plant-soil-atmosphere model (PasID).

Table 3.13 Data table for SAFIR_IrrigationEquipment

Field Name	Type	Functionality of input
`IrrigationEquipmentID`	integer	ID which is referred to from SAFIR_IFM
`Name`	string	Short name for equipment configuration
`Description`	string	Description of equipment, e.g. “subsoil dripline”
`Technology`	integer	0: Furrow (not an option with current daisy openMI version(1: Sprinkler (not an option with current daisy openMI version) 2: Surface drip (not an option with current daisy openMI version(3: Subsurface drip (only option with current daisy OpenMI version)
`Capacity_m3PerSec`	double	Flow capacity of equipment in [m_3/s]. Setting a small flow capacity puts a limit to how fast water can be distributed to the field.
`LossFactor`	double	A real number in the interval [0,1], where 0 corresponds to zero loss. The loss is the fraction of the requested water that never reaches the field. Losses can be due to e.g. evaporation in sprinkler equipment or due to leakage.

Table 3.14 Data table for SAFIR_IrrigationStrategy

Field Name	Type	Functionality of input
IrrigationStrategyID	integer	ID which is referred to from SAFIR_IFM
Name	string	Shot name for strategy
Description	string	Description of strategy, e.g. “relative deficit irrigation of potatoes”
IrrigationTriggerType	integer	0: RelativeDeficit 1: SpecifiedDepletion 2: Prescribed 3: FixedInterval
IrrigationStopType	integer	0: RelativeDeficit 1: PrescribedDepletion 2: PrescribedApplication
stage1_DS	double	The development stage where growth stage 1 starts
stage1_Trigger	double	threshold value where irrigation should start
stage1_Stop	double	threshold value where irrigation should stop
stage2_DS	double	The development stage where growth stage 2 starts
stage2_Trigger	double	threshold value where irrigation should start
stage2_Stop	double	threshold value where irrigation should stop
stage3_DS	double	The development stage where growth stage 3 starts
stage3_Trigger	double	threshold value where irrigation should start
stage3_Stop	double	threshold value where irrigation should stop
stage4_DS	double	The development stage where growth stage 4 starts
stage4_Trigger	double	threshold value where irrigation should start
stage4_Stop	double	threshold value where irrigation should stop

Time series

The time series enable the user to specify a range of constrains within which the management model operates, including:

a. FertilizerTS.dfs0 - Specifies the flow of the fertigation source [m^3/s] and the concentration [mg/l] of its constituents including the NO_3 and NH_4 and other constituents.

b. TriggerTS_FertilizerPeriod.dfs0 - Specifies the period (days) for which the fertilizer demand is estimated (N_{days}).

c. TriggerFertilizerFactor.dfs0 - Specifies an extra amount [kg] of fertilizer given at each fertilizer application (Security factor).

d. TriggerTS_FertilizerNoIrr.dfs0 - Specifies the amount of fertilizer deficit [kg/ha] that the DSS accumulate, before fertilization starts without irrigation. (If irrigation is initiated before, fertilizer is also applied)

e. TriggerTS_IrrigationPeriod.dfs0 - Specifies the minimum period [days] between two consecutive irrigations

Coupling to the plant-soil-atmosphere model Daisy

It is the aim that the design of the Decision Support System to be able to let any plant-soil-atmosphere model plug into the DSS, if it is OpenMI compliant. OpenMI is a model wrapper that standardizes operations as "performing one time step" and gives runtime read and write access to model variables. A condition is, of course, that the model calculates the variables required for the exchange.

The coupling to the PSA-model is made on code level that means the main time loop of the Decision Support System accesses to the PSA-engine via method calls provided by OpenMI. In the SAFIR-project, the only PSA-model that was made OpenMI compatible was Daisy.

Figure 3.11 shows the database design for the input to the plant-soil-atmosphere component.

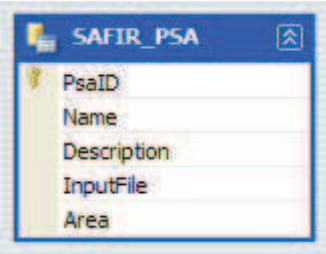


Figure 3.11: Data table for linking to the PSA model.

Daisy has no area information, all quantities are described per unit area (for instance irrigation demand in [mm], Nitrogen demand in [kg/ha]).

This means that the SAFIR_PSA data table include a field with area information in order to calculate the demands in absolute values.

Table 3.15: Data fields in the SAFIR_PSA table

Field Name	Type	Functionality of input
PsaID	integer	used to refer a SAFIR_PSA record from another table.
Name	string	User specified name of the PSA-model
Description	string	User specified description of the PSA-model which supplements the name
Area	double	The area (in [m^2]) of the modelled field
InputFile	string	Path to PSA-input-file

The data exchanged between the IFM-module and Daisy during the simulation are the following:

The Daisy model supplies:

- Water present in the root zone [mm]
- Water at field capacity [mm]
- Water at wilting point [mm]
- Critical N-content in the plant [kg/ha]
- Potential N-content in the plant [kg/ha]
- Actual N-content in the plant [kg/ha]
- Daisy's crop development stage [ ]

The Daisy model receives:

- Irrigation water to apply in the time-step (hourly) [mm]
- N-content of the added water, distributed on ammonia and nitrate [ppm]
- Heavy metal content (one or more) added with the water [ppm]
- E.coli added with the water [ppm]. The E.Coli concentration is based on an assumption of 1E-09 mg/cell.

From the water source administration module

The IFM module requests the water source administration module for the water required for irrigation. The IFM receives back time series of water supplied (which may be less than requested), including quantity and quality information. This information is, in turn, used to calculate fertigation requirement and mm of water than can be supplied.

3.3.3 Output

The main output of the IFM module is the information to the PSA model concerning irrigation and fertigation supplied, as well as the content of heavy metals or pathogens present in the water. However, in addition, the module sums up the application of other compounds of interest, such as P. Although this value is not passed to Daisy via the dynamic coupling, it may be of interest for the user when judging the overall value of wastewater application.

3.3.4 Parameterisation of the prototype

The following descriptions of irrigation strategies are based on the conclusions from a number of discussions among plant scientist within the SAFIR project (Finn Plauborg, Adriano Bataliani and others). The compiled descriptions are expected to be optimal irrigation strategies for various irrigation methods. The optimal irrigation strategy is understood as the strategy where plants physiologically have the best conditions with given equipment and irrigation method. It is also understood as the strategy that experienced farmers are aiming at.

Irrigation of Potatoes

Irrigation stages

Irrigation stage 1 last from transplanting until the root depth is 20 cm. In reality the soil should be wetted to field capacity just before transplanting either due to irrigation or due to precipitation.

Irrigation stage 2 lasts until 80% of all tubers are bigger than 2 cm, which also corresponds to reaching DAISY growth stage 1. In fact this also corresponds to a temperature sum of about 200.

Irrigation stage 3 lasts until DAISY growth stage 1.5 is reached. At this point 50% of the tubers measure more than 50 cm. Furthermore, the stage corresponds to a temperature sum of about 450.

Irrigation stage 4 continues to harvest, which corresponds to DAISY growth stage 1.7. In Table 3.16 the definition of the irrigation stages is shown as an overview.

Table 3.16: Definition of irrigation stages for potatoes

	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**
End of stage	Root depth equal to 20 cm	80% of tubers > 2 cm	50% of tubers > 5 cm	Harvest
Other indicators		Temperature sum 200	Temperature sum 450	Last 14 days
Daisy growth stage expected		1.0	1.5	1.7
Daisy growth stage, actual, Italy	-0.5	0.8	1.1	1.2
Daisy growth stage, actual,Denmark	0	1.3	1.5	1.7

Optimal irrigation strategy

During **stage 1**, irrigation should be controlled based on lower and upper threshold values for pressure or water content in the soil. The upper threshold is typically equal to field capacity since it is too early to stress the plants. The calculation of the optimal irrigation amount should be scaled to upper 20 cm of the soil, i.e. if the root depth is less, the irrigation amount will still be calculated based on a depth of 20 cm and the content between lower and upper threshold values. For all types of irrigation, the lower threshold value is calculated with a view to the minimum amount of water that can be supplied by the irrigation system. This amount is larger for sprinkler and furrow irrigation, than for drip. In Table 3.18, the lower threshold values for sprinkler and furrow irrigation are identical, while for drip irrigation the threshold has to be scaled according to required irrigation depth. E.g. if the irrigation depth is 5 mm or 10 mm the lower threshold should be -16 kPa and and -25 kPa respectively (for a selected soil type) to bring the pressure to -10 after irrigation.

During **stage 2**, irrigation is controlled as during stage 1 except that the water content in the soil is calculated based on actual root depth. The upper threshold water content is defined to be a bit lower than field capacity.

During **stage 3**, full irrigation is still governed by an upper and a lower threshold though the thresholds are a bit lower. The same goes for regulated deficit irrigation,

except the thresholds have been lowered further. The suction values given in Table 3.18 are guide-values only, as illustrated in the following example:

To move between suction in the soil and mm irrigation water, a retention curve is required. For this example, retention curves for sandy, loamy and clayey soils are generated using the pedotransfer function “HYPRES”. The upper and lower threshold values given for regulated deficit irrigation in stage 3 in Table 3.18 can be re-calculated to 25, 28 and 21 mm of irrigation water for the three soils, respectively. If the upper threshold is kept constant, the lower suction value should have been 70, 57 or 90 kPa, respectively, to make room for 30 mm of water, if this is the minimum amount of water that can be supplied by the irrigation system per irrigation. For drip irrigation, it is simpler. Keeping the lower threshold constant, it can be calculated for a loamy soil that 5 mm will decrease the suction from 57 to 45 kPa and 10 mm from 57 to 36 kPa. These values then become the upper thresholds. See also Annex 1.

Deficit irrigation should be controlled by ΣEp since last irrigation and a fraction less than 1 should be given in order to the define irrigation depth.

For partial root drying the irrigation amount is calculated according to one of the three strategies based on the moisture content on the wet side of the plant. The whole amount/ha is added in half the drippers, leading to double amount per dripper. The side is changed when moisture content on the dry side of the plant reaches the threshold value for relative water content, in most cases equal to -80 kPa.

During **stage 4**, full irrigation is still governed by an upper and a lower threshold though the upper and lower limits are yet a bit smaller. Deficit irrigation and regulated deficit irrigation are controlled in the same manner as in stage 3. The same goes for partial root drying.

An overview of strategies and thresholds are shown in Table 3.18.

Irrigation of Processing tomatoes

Irrigation stages

Irrigation stage 1 last from transplanting until the root depth is 20 cm. Optimally, the water content in the soil should be close to 80% of field capacity just before transplanting due to transplanting machines not being able to work in too wet soils.

Irrigation stage 2 lasts until Daisy growth stage 1.2. Flowering of first cluster should take place during irrigation stage 2, but deficit irrigation only starts after flowering of fourth to fifth cluster. In fact this also corresponds to a temperature sum of about 400.

Irrigation stage 3 lasts until Daisy growth stage 1.5 is reached. This is also when 4th to 5th cluster is set.

Irrigation stage 4 continues to close to harvest or close to Daisy growth stage 1.60. In Table 3.17 the definition of the irrigation stages is shown as an overview.

Table 3.17: Definition of irrigation stages for processing tomatoes

	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**
End of stage	Root depth equal to 20 cm	Fruit setting 4-5 cluster	10 % red fruit	Harvest (no irrigation last 7-20 days)
Other indicators	Last 7-14days	Temperature sum 400 at end of stage	Lasts 40-45 days	
Daisy growth stage expected		1.2	1.5	1.7
Daisy growth stage actual, Italy	0.6	1.44	1.5	2

*Table 3.18: **Controlling factors for various irrigation strategies and irrigation methods for potatoes. Upper and lower thresholds are given in kPa. Bold figures are target values while values in italics should be scaled according to irrigation method and preferred amount. Scaled and fraction: see text***

Irrigation stage		Full irrigation			Deficit irrigation			Regulated deficit irrigation and PRD			
		Sprinkler	Furrow	Drip	Sprinkler	Furrow	Drip	Sprinkler	Furrow	Drip	threshold
1	Upper	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	-
	Lower	*-30*	*-30*	*-16*	*-30*	*-30*	*-16*	*-30*	*-30*	*-16*	
2	Upper	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	-
	Lower	*-52*	*-52*	*-23*	*-52*	*-52*	*-23*	*-52*	*-52*	*-23*	
3	Upper	**-16**	**-16**	**-16**	na	na	na	-21	-21	scaled	
	Lower	*-52*	*-52*	*-20*	na	na	na	**-57**	**-57**	**-35 (IT)** **-50 (DK)**	**-80**
	Fraction	na	na	na	**0.70**	**0.70**	**0.70**	na	na	na	
	Freq.	na	na	na	every 5th day (min. 30 mm)	every week (min. 30 mm)	every 2. day (min. 3 mm)	na	na	na	
4	Upper	**-20**	**-20**	**-20**	na	na	na	-25	-25	scaled	
	Lower	*-75*	*-75*	*-0.23-*	na	na	na	**-80**	**-80**	**-85 (IT)** **-80 (DK)**	**-120 (It)** **-80 DK**
	Fraction	na	na	na	**0.5**	**0.5**	**0.5**	na	na	na	
	Freq.	na	na	na	every 5th day (min. 30 mm)	every week (min. 30 mm)	every 2. day (min. 3 mm)	na	na	na	

Optimal irrigation strategy

During **stage 1**, irrigation should be controlled based on lower and upper threshold values for pressure or water content in the soil. The upper threshold is typically equal to field capacity since it is too early to stress the plants. The calculation of the optimal irrigation amount should be scaled to upper 20 cm of the soil, i.e. if the root depth is less, the irrigation amount will still be calculated based on a depth of 20 cm and the content between lower and upper threshold values. For all types of irrigation, the lower threshold value is calculated with a view to the minimum amount of water that can be supplied by the irrigation system. This amount is larger for sprinkler and furrow irrigation, than for drip. In Table 3.19, the lower threshold values for sprinkler and furrow irrigation are identical, while for drip irrigation the threshold has to be scaled according to required irrigation depth. E.g. if the irrigation depth is 5 mm or 10 mm the lower threshold should be -16 kPa and and -25 kPa respectively (for a selected soil type) to bring the pressure to -10 after irrigation. See also Annex 1.

During **stage 2**, irrigation is controlled as during stage 1 except that the water content in the soil is calculated based on actual root depth. The upper threshold water content is defined to be a bit lower than field capacity.

During **stage 3**, full irrigation is still governed by an upper and a lower threshold though the water content thresholds are a bit lower. Deficit irrigation should be controlled by Ep since last irrigation and a fraction less than 1 should be given in order to define irrigation depth. Regulated deficit irrigation is controlled by a lower threshold (which is set lower than for full irrigation) and the soil should be replenished to an upper threshold based on soil type. The calculations and limits build into this approach are identical to what was described for potatoes.

During **stage 4** the tomatoes are still developing. For full irrigation, irrigation takes place as in stage 3. For deficit and regulated deficit the fractions and thresholds are lowered.

For partial root drying the irrigation amount is calculated according to one of the three strategies based on the moisture content on the wet side of the plant. The whole amount/ha is added in half the drippers, leading to double amount per dripper. The side is changed when moisture content on the dry side of the plant reaches the threshold value for relative water content.

An overview of strategies and thresholds are shown in Table 3.19.

*Table 3.19: **Controlling factors for various irrigation strategies and irrigation methods for processing tomatoes. Upper and lower thresholds are given in kPa. Bold figures are target values while values in italics should be scaled according to irrigation method and preferred amount. Scaled and fraction: see text. Based on Italian data.***

Irrigation stage		Full irrigation			Deficit irrigation			Regulated deficit irrigation and PRD			
		Sprinkler	Furrow	Drip	Sprinkler	Furrow	Drip	Sprinkler	Furrow	Drip	threshold
1	Upper	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	
	Lower	*-30*	*-30*	*-16*	*-30*	*-30*	*-16*	*-30*	*-30*	*-16*	
2	Upper	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	
	Lower	*-52*	*-52*	*-23*	*-52*	*-52*	*-23*	*-52*	*-52*	*-23*	
3	Upper	**-16**	**-16**	**-16**	na	na	na	*-21*	*-21*	scaled	
	Lower	*-52*	*-52*	*-20*	na	na	na	**-57**	**-57**	**RDI/PRD -35/-85**	**-120**
	Fraction	na	na	na	**0.70**	**0.70**	**0.70**	n	na	na	
	Freq.	na	na	na	every 5th day (min. 30 mm)	every week (min. 30 mm)	every 2. day (min. 3 mm)	na	na	na	
4	Upper	**-20 or -16**	**-20 or -16**	**-20 or -16**	na	na	na	*-26*	*-26*	Scaled	
	Lower	*-75*	*-75*	*-0.23-*	na	na	na	**-85**	**-85**	**-85 (IT)**	**-180**
	Fraction	na	na	na	**0.5**	**0.5**	**0.5**	na	na	na	
	Freq.	na	na	na	every 5th day (min. 30 mm)	every week (min. 30 mm)	every 2. day (min. 3 mm)	na	na	na	

Irrigation of Fresh tomatoes

Fresh tomatoes are more difficult than processing tomatoes and potatoes because fruits are harvested several times during the growing season and because different sorts of tomato plants requires different irrigation strategies.

Irrigation stages

Irrigation stage 1 lasts from transplanting until the root depth is 20 cm. Optimally, the water content in the soil should be close to 80% of field capacity just before transplanting due to transplanting machines not being able to work in too wet soils.

Irrigation stage 2 lasts until Daisy growth stage 1.2. Flowering should basically be finished and 1st truice developed. In the practical experiments, irrigation was reduced by a small amount for the first 2 weeks of the following period. The differences in soil moisture and Daisy-calculated growth stage, were, however, som small that the 2-week period has not been included in these recommendations.

Irrigation stage 3 last until Daisy growth stage 1.6 is reached. This is also when 4th to 5th cluster is set.

Irrigation stage 4 continues to close to harvest or close to Daisy growth stage 1.7. In

Table 3.20 the definition of the irrigation stages is shown as an overview.

Table 3.20: Definition of irrigation stages for fresh tomatoes

	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**
End of stage	Root depth equal to 20 cm	1st. Truice developed/ followed by 2 weeks	middle period	Last 14 days
Other indicators	Lasts 7-14days			Harvest
Daisy growth stage expected		1.2/ 1.3	1.6	1.7
Daisy growth stage actual, Crete	0.5	1.3*/ 1.4	1.6	1.8

* 1.3 is used in the DSS, concluded from an analysis of the actual moisture conditions obtained in the experiments.

Optimal irrigation strategy

In the prototype management model fresh tomatoes are handled as the other crops. The practice existing on the Italian test site is that irrigation is controlled by a prescribed amount of water per plant for each of the four stages i.e. 300 cl/plant/day in stage 1, 600 cl/plant/day in stage 2, 900 cl/plant/day in stage 3 and 600 cl/plant/day in stage 4.

An overview of strategies and thresholds are shown in Table 3.21.

Table 3.21: ***Controlling factors for various irrigation strategies and irrigation methods for fresh tomatoes. Upper and lower thresholds are given in kPa. Bold figures are target values while values in italics should be scaled according to irrigation method and preferred amount. Scaled and fraction: see text. Based on data.from Crete.***

Irrigation stage		Full irrigation			Deficit irrigation			Regulated deficit irrigation and PRD			
		Sprinkler	Furrow	Drip	Sprinkler	Furrow	Drip	Sprinkler	Furrow	Drip	threshold
1	Upper	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	
	Lower	*-30*	*-30*	*-16*	*-30*	*-30*	*-16*	*-30*	*-30*	*-16*	
2	Upper	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	**-16**	
	Lower	*-52*	*-52*	*-23*	*-52*	*-52*	*-23*	*-52*	*-52*	*-23*	
3	Upper	**-16**	**-16**	**-16**	na	na	na	*-21*	*-21*	scaled	
	Lower	*-52*	*-52*	*-20*	na	na	na	**-57**	**-57**	**-22 (2 wks)** **-34**	**-80**
	Fraction	na	na	na	0.8 (2 wks) 0.7	0.8 (2 wks) 0.7	0.8 (2 wks) 0.7	na	na	na	
	Freq.	na	na	na	every 5th day (min. 30 mm)	every week (min. 30 mm)	every 2. day (min. 3 mm)	na	na	na	
4	Upper	**-20**	**-20**	**-20**	na	na	na	*-26*	*-26*	Scaled	
	Lower	*-75*	*-75*	*-0.23-*	na	na	na	**-51**	**-51**	**-51**	**-80**
	Fraction	na	na	na	**0.5**	**0.5**	**0.5**	na	na	na	
	Freq.	na	na	na	every 5th day (min. 30 mm)	every week (min. 30 mm)	every 2. day (min. 3 mm)	na	na	na	

3.4 Plant/soil/atmosphere model

3.4.1 OpenMI compatible version of Daisy

To couple information from the agro-ecologic system model Daisy to other models, a new coupling interface through OpenMI has been developed. The coupling is used for the DSS, but can also be used to link Daisy with other models, e.g. for watershed simulations.

OpenMI is a framework for connecting simulation models. Simulations models are models that can predict the state of a system after a specified time step, given the state of the system at the beginning of the time step, e.g. transport of pesticides in the soil after a rain event. The new state can then be used as a basis for predicting further ahead. OpenMI allows the user to let the prediction of one model depend on the state predicted by another model. An example could be that the groundwater levels and pesticide concentration predicted by a groundwater model depends on percolation and soil use management simulated by an overlying agro-ecologic system model.

OpenMI allows each model to specify the possible inputs and outputs as well as the mechanisms for connecting these. These mechanisms can be divided into three areas:

1. Conversion between mismatched physical dimensions, such as m/s and mm/h.
2. Conversion between mismatched time steps (say one model use hourly time steps and the other 100 second time steps).
3. Conversions between mismatched geometries, such as a 3D groundwater model with a grid that perhaps contains a number of columns of a 1D/2D agro-ecologic system model.

The time step and geometry conversions can involve both integrations and interpolations, and are therefore not always exact, which may or may not be acceptable depending on the application. OpenMI will run the models in parallel, letting each model predict further ahead as its output is needed by the inputs of other models. Daisy is a good match to OpenMI; it is a simulation model with a time step of one hour, and a 1D/2D geometry.

Detailed information about OpenMI can be found at the homepage: http://www.openmi.org.

Introduction to the programmatic access to Daisy

The core functionality of the Daisy program is written in the C++ programming language, and made available through application programming interfaces for multiple languages. The primary API is for C++, and found in the daisy.dll file. The C++ API is used both by the command line executable (daisy.exe) and the native graphical interface (daisyw.exe).

On top of the C++ API, there is an API for the C programming language. The C programming language is often considered the lowest common denominator for programming languages, as most other languages are able to access functionality through a C API. The C API is also exported in the daisy.dll file. On top of the C API, we have build a C# (or more generally, .NET) API. It is available through the file

daisy_dotnet.dll. And on top of that, we have the OpenMI API available in daisy_OpenMI.dll. The C# and OpenMI APIs will be described in the next section.

The command line executable, daisy.exe, may be the most popular interface to Daisy from other programs. TextPad, DaisyGIS, and PI@ntInfo access Daisy through this interface.

OpenMI components

In the Daisy OpenMI interface three OpenMI components are defined: "DaisyOpenMI-Components", "DaisyWrapper", and "DaisyAccess" as displayed in Figure 3.12. Below a brief description of each component is given.

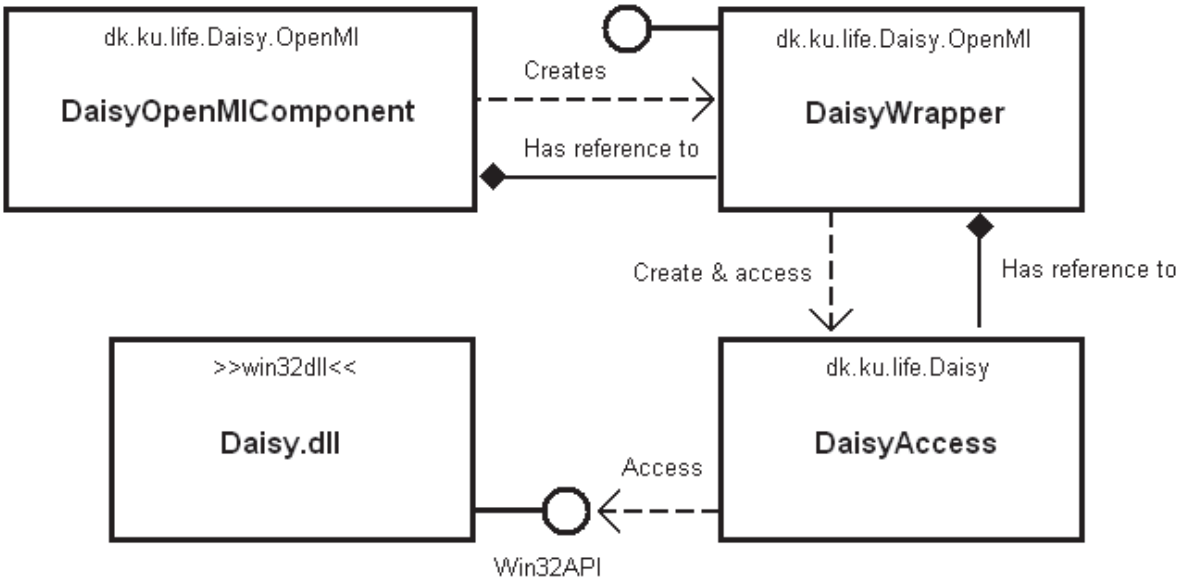


Figure 3.12: Overview of linkable components in the Daisy OpenMI interface.

Daisy Access

The component "DaisyAccess" contains five classes: "DLL", "AList", "Column", "Scope", and "Daisy". The "DLL" class implements all relevant C API functions from the daisy.dll, and makes them available for the other four classes. The "AList" associates parameter names with parameter values, which is used for looking up specific parameter values from the Daisy setup file. The "Column" class contains the functions related to the geographical location of each Daisy column defined. The "Scope" class can look into the defined scopes, logs and input and output exchange items defined in the model setup (see section 0). Finally, the Daisy class has access to the Daisy model and can start, terminate and run the model stepwise.

Daisy Wrapper

The wrapper component controls the bookkeeping associated with handling input and output exchange items and the interpolation in time and space. The wrapper class initializes the Daisy model, has a time stepping subroutine to step through each time step, and makes specific values readable or writeable from the engine core model Daisy.

Daisy OpenMI Component

The Daisy OpenMI Component is the linkable component that is going to be accessed by other models. The class creates a new “DaisyWrapper” and assigns the wrapper to a protected field variable called “_daisyApiAccess”.

User interface

Two concepts have been introduced in the Daisy user interface to support the OpenMI interface: an “extern” log to exchange output exchange items and an “exchange” scope to exchange input exchange items.

Exchange output items through extern logs

A parameterization of the “extern” log model specifies the state Daisy makes available for output through OpenMI. It is almost identical to the way a “table” log file parameterizations are defined in Daisy, and the parameterizations are activated in the same way, by listing them in the output parameter (described in section 0).

First we define a log named “OpenMI_output” of the type “extern”. A specific column is allocated to the log and the “when” parameter specifies that the results are stored every hour.

```
(deflog OpenMI_output extern

(parameter_names column)

(declare column String "Name of column to log output")

(when (hourly)))
```

It is convenient to group specific parameters and separate others; i.e. parameters related to crop production (dry matter production, development stage, etc.) are separated from parameters related to the lower boundary of the soil-water system (water and solute fluxes).

A log named “Lower_boundary_output” is inherited from the above “OpenMI_output” and is thus also of the type “extern”. This standard log is included in the file “OpenMI.dai” which is part of the Daisy distribution, and stores the parameters “Matrix percolation” and “NO3 flux”. The data are made available through OpenMI as output exchange items.

```
 (deflog Lower_boundary_output OpenMI_output

 (entries
```

```
(flux_bottom      (tag "Matrix percolation")
                  (description "This is the amount of water leaving Daisy through the soil
                  bottom.")
                  (path column "${column}" SoilWater q)
                  (spec fixed SoilWater q)
                  (negate true))
(flux_bottom      (tag "NO3 flux")
                  (description "This is the amount of NO3 leaving Daisy through the soil
                  bottom.")
                  (path column "${column}" SoilNO3 J)
                  (spec fixed SoilNO3 J)
                  (negate true))))
```

To all the logs of type “OpenMI_output” a specific column must be attached to the output parameters, accessed by the “${column}”. The “spec” and “path” parameters specify how to find the type and value of the state variable within the internal hierarchical structure of Daisy. Daisy calculates fluxes as positive when the flow is upward; however, percolation and leaking is conventionally considered positive for downward flow. When the “negate” is set to “true”, the sign value is multiplied with -1, and the fluxes logged are then positive when the flow is downward.

Another standard log named “Crop_soil_content”, also part of the Daisy distribution, is defined in the same way as “Lower_boundary_output” and stores parameters related to the plant state (development stage, dry matter, and nitrogen content in the crop at different conditions), management (amount of nitrogen removed by harvest each time step), and the soil state (Amount of organic N, NH_4^+, NO_3^- in the root zone, and water content in the root zone at different conditions).

It is easy to add more output exchange items in a new log or extend the above mentioned logs to include more parameters, as long as they correspond to states that can already be logged by Daisy.

Exchange input item through exchange scopes

On the input side, it is possible to define “exchange” scopes, and activate it by listing it in the exchange parameter (described in section 0). The syntax is new, but the concepts are very similar to the extern log on the output side.

```
(defscope OpenMI_input exchange
  "An exchange table for a specific column."
  (declare column String "Name of column to log input.")
```

```
  (column "*")

  (entries (name (name column) (value "${column}"))))
```

A specific column is allocated to the scope. Hence, Daisy facilitates simulation of multiple soil columns, defined with geographical coordinates, at the same time. Using “*” in column parameter value, stores data for all columns. The “entries” parameter contains a list of different methods to select state variables. To get the state of ground water table and NO_3^- concentration in the groundwater the “number” method is used. If no input of the state parameter is given through OpenMI the parameter, obtains the state of “value” with the dimension listed in “dimension”.

```
(defscope Lower_boundary_input OpenMI_input

 (entries &old

     (number (name "GroundWaterTable")

             (description "Ground water table. Value zero corresponds to soil surface,
                     negative values are below surface.")

             (value -100)

             (dimension [cm]))

     (number (name "NO3 conc. groundwater")

             (description "NO3 concentration in groundwater.")

             (dimension [g/cm^3]))))
```

To actually have the input items affecting the simulation it is now possible to look up certain values of input items in one of the activated scopes. The possible input items are listed in the “OpenMI.dai” file, which is part of the Daisy distribution, and include, besides the above “Lower_boundary_input”, also a “fertigation” exchange item.

```
(defscope fertigation OpenMI_input

 (entries &old

  (number (name "Overhead Irrigation")

          (description "Irrigation of soil and leaves by sprinkling")

          (dimension [mm/h]))

  (number (name "Surface Irrigation")

          (description "Irrigation of surface soil by tubes")

          (dimension [mm/h]))
```

```
  (number (name "Subsoil Irrigation")
          (description "Irrigation by tubes inside the soil")
          (dimension [mm/h]))
  (number (name "NO3 input")
          (description "Amount of NO3-N applied")
          (dimension [kg N/ha/h]))
  (number (name "NH4 input")
          (description "Amount of NH4-N applied")
          (dimension [kg N/ha/h]))
))
```

The “fertigation” item receives orders for irrigation (overhead, surface, and subsoil irrigation) and fertilization (NO3 and NH4). These orders are handled by the action model “OpenMI_fertigation”, thus linking the input items received by OpenMI into Daisy.

```
(defaction OpenMI_fertigation extern_fertigation
  "Control fertigation through OpenMI."
  (surface "Surface Irrigation")
  (overhead "Overhead Irrigation")
  (subsoil "Subsoil Irrigation")
  (NO3 "NO3 input")
  (NH4 "NH4 input")
)
```

Adding more input exchange items in the user interface is just as easy as to add output exchange items. But to make Daisy actually use these items in the next time step often requires changes in the Daisy program code.

Applications and use

The DAISY model code is open software and distributed through the homepage http://code.google.com/p/daisy-model/. In relation to the Daisy OpenMI interface two examples of setup files for OpenMI have been made located in the “sample” directory. The setup files includes two input files, the “log.dai” and the “OpenMI.dai” (which both are located in the “lib” directory) to access the traditional log files and the OpenMI input and output exchange items, respectively.

Exchanging lower boundary

The setup file “OpenMI_simple.dai” illustrate the definition of two columns “Field A” and “Field B” where the ground water table is given by a ground water model through OpenMI. The “Field B” is inherited from “Field A” meaning that they contain the same horizon with identical textural, hydraulic and physical properties. The options of defining textural, hydraulic and physical properties as well as the state of organic matter in the columns is not described in this context, but references is made to Abrahamsen and Hansen (2000) and Jensen et al. (2001).

```
(defcolumn "Field A" default
   (Soil (horizons (-20 [cm] Ap) (-2.5 [m] C))
   (location (-10 100))
   (scope name "Lower_boundary_input_A")
   (SoilNO3 (C_below "NO3 conc. groundwater"))
   (Groundwater pipe  (pressure_table extern
                           (value "GroundWaterTable")
                           (initial_value -200 [cm])))))

(defcolumn "Field B" "Field A"
   (location (100 100) (90 100) (90 90))
   (scope name "Lower_boundary_input_B")
   (Groundwater extern          (table "GroundWaterTable")
                           (initial_table -200 [cm])))
```

“Field A” is drained given by the groundwater model “pipe”. However, the pressure table at the lower boundary is imported through the OpenMI input exchange item “GroundWaterTable” defined in “Lower_boundary_input _A”. The groundwater model in “Field B” is “extern” which points to the “GroundWaterTable” defined in “Lower_boundary_input_B”.

“Field B” has a different location than “Field A”. The “location” parameter contains a list of (x y) coordinates, intended to identify the location of the column on an externally defined map. This is most relevant when coupled with a GIS system, for example through the OpenMI interface. A location with only one (x y) coordinate defines a point in the OpenMI terminology. A location with more than two (x y) coordinate defines a polygon in the OpenMI terminology as illustrated in the “Field B” which labels the corners of a triangle.

Activating the output exchange items

The “extern” log models are activated by listing them in the “output” parameter:

```
(output         (Lower_boundary_output (column "Field A"))
                (Lower_boundary_output (column "Field B"))
                ("Soil Water Potential" (column "Field A")))
```

Here the “Lower_boundary_output” is attached to each column. An ordinary log file defined in “log.dai” is also listed in the output parameter.

Activating the input exchange items

Both fields have the lover boundary defined by the exchange item “Lower_boundary_input” but the input item is specific for each column:

```
(defscope Lower_boundary_input_A Lower_boundary_input (column "Field A"))
(defscope Lower_boundary_input_B Lower_boundary_input (column "Field B"))
```

The input exchange item “Lower_boundary_input_A” and “Lower_boundary_input_B” are inherited from the exchange scope “Lower_boundary_input” and a specific column is attached. Thus, the ground water table may not be at the same state in each field.

The “exchange” scopes are activated by listing them in the “exchange” parameter:

```
(exchange  (Lower_boundary_input_A)
           (Lower_boundary_input_B))
```

Here the two scopes storing ground water table and NO_3 concentration is exchanged.

Exchanging management related to fertigation

The setup file “OpenMI_management.dai” illustrates an example of fertigation from an extern scope. The manager is running until there is no input from the scope “fertigation” defined in section 0. The manager call the “OpenMI_fertigation” model which reads from the extern scope “fertigation” and turn the input into action. The definition of drip line placement in the soil is defines by the depth “from -5 [cm]” “to -15 [cm]”.

```
(manager                (while (wait false)
```

```
                    (OpenMI_fertigation     (scope name fertigation)
                    (from -2 [cm]) ;; Drip line placement.
                    (to -12 [cm]))
        (MyMan)
))
```

The manager also calls the “MyMan” activity which also is defined in “OpenMI_management.dai” which term the time for plowing, sowing and harvesting of grass and spring barley.

```
(defaction MyMan activity
  (wait (at 1987 3 20 1))       (plowing)
  (wait (at 1987 4 5 1)) (prong  (sow "Grass")
                         (sow "Spring Barley"))
  (wait (at 1987 9 5 1))        (harvest "Spring Barley")
  (wait (at 1987 10 10 1))      (harvest "Grass"  (stub 8.0 [cm]) (stem 1.00 []))
  )
```

The harvest of spring barley removes the whole crop. The harvest of grass leave 8 cm stub but harvest everything above the stub.

3.5 Treatment of heavy metals

Heavy metals may or may not be present in the irrigation water. If present, the concentration in the water should be specified, together with the relevant filtering factors related to the presence of a sand filter, a heavy metal removal device etc. as described in Chapter 3.2. The final concentration of heavy metals in the irrigation water will be calculated.

In order to describe the fate of heavy metal(s) in the soil, the compound(s) has to be defined in the Daisy model and an initial concentration specified together with the Freundlich sorption isotherm for the compound in the given soil. The content of heavy metal in the irrigation water will be added to Daisy through OpenMI. Daisy will then calculate the concentration in the soil and water, including leaching. It has not been attempted to calculate plant uptake of the heavy metals. It is, however, possible, to describe an uptake as passive uptake with the water or as a fraction of this, as for pesticides, if wished, but the Daisy model is not able to distribute the uptake to roots, leaves, stems and storage organs. Instead of calculating uptake and redistribution of the metals in the plant, it was decided to use the WHO guidelines on acceptable concentrations in the soil to judge the risk for consumers due to heavy metals in the irrigation water. Input concentrations may be evaluated with respect to damage to crops while the concentration in the soil is evaluated to judge the risk for consumers of the produced crop and due to ingestion of soil. Concentrations in leaching water indicate the risk to the environment.

3.5.1 The parameterization of the sorption isotherm

A detailed discussion of this issue is carried out in Pettenati and Surdyk (2009) (Deliverable D4.3 of the Safir project), and the main issues from this report is summarized below. The concept of sorption isotherms is widely used to describe the partitioning of organic or inorganic compounds between soil water and soil. It describes the dependence of fixed (sorbed) concentrations of a given compound and its concentration in the liquid phase at thermodynamic equilibrium (synthesis in Limousin *et al*., 2007). Sorption isotherms relate the remaining solute i in concentration C_i after equilibration of a solution with a solid phase to the concentration A_i of compound i on the solid particles:

$$A_i = f(C_i)$$

where A_i is the adsorbed concentration of compound I ($mol.kg^{-1}$, $g.kg^{-1}$…), C_i is its solute concentration at equilibrium ($mol.L^{-1}$, $g.kgw^{-1}$…). This general function can have several forms. Concave isotherms, reaching a plateau or not, are described by the empirical Freundlich model ($A_i = K_f * C_i^n$) with the distribution coefficient K_f and a dimensionless non linear sorption coefficient n. A special case (n=1) is the linear function $A_i = K_d \cdot (C_i)$ with 0 origin, where K_d is the ''distribution coefficient'', an isotherm that is frequently used, due to its simplicity. Other forms of sorption isotherms have been encountered (e.g. sigmoidal). In the following, the Freundlich isotherm is used as it represents the general case most widely encountered in experimental studies. This choice was also motivated by the analysis of the modeling results, indicating that for the investigated concentration range, a linear function (K_d) would have induced an oversimplification (see discussion below).

Strictly spoken, the sorption isotherm concept is limited to sorption-desorption processes but the typical experimental approach for determining K_f and n (or K_d if n=1) values (batch experiments in which solutions with variable concentrations of the compound of interest are brought in contact with a given soil) will not distinguish the actual mechanisms of water-soil interactions. Sorption-desorption processes are predominant for organic compounds, even if biodegradation may play an important role, whereas for inorganic compounds, like heavy metals, other processes may prevail, in particular dissolution-precipitation reactions. Experimental determinations of sorption isotherms currently treat the water soil system as black box: Within the liquid phase, only the total concentration of a given compound is taken into account, independently of the aqueous speciation, within the solid phase, no distinction of reactive mineral species is made. Nevertheless, the partitioning of a compound between the liquid and the solid phase is the result of a complex superposition of several competing reactions between aqueous species and mineral phases so that the measured sorption isotherms describe in fact not one single reaction but may result from a superposition of several of them. This may contribute to the extremely high variability observed for experimental (K_f, n) or K_d values of heavy metals, depending on experimental conditions, key parameters as pH, and soil types (Zhu, 2003; Carlon *et al*., 2004).

Nevertheless, the isotherm approach has the advantage to be straightforward, relatively simple to implement in water and solute transport models, so that reactions with the solid phase can be taken into account to some degree, and widely used in soil sciences, risk assessment, agronomy. This is the reason why it was decided to use it to implement a heavy metal module in the integrated modeling approach of SAFIR WP7 using DAISY.

An attempt was made to produce transfer-functions for Freundlich parameters for Pb for the Crete site to illustrate the concept. A detailed description of these experiments carried out for Pb is given in Pettenati and Surdyk (2009).

The work resulted in pedo-transfer-functions to determine K_f and n as a function of information on the specific soil to be modeled. The developed functions were:

For Pb:

$$K_f = \exp(-19.02 + 2.74 \times pH0 + 143.72 \times Fe0) \times 1.009$$

$$n = -0.874 + 0.168 \times pH0 + 8.576 \times Fe0$$

Where

pH0 represents the pH of the injected concentration (in this case the irrigation water) before the interaction with the soil. This is a very influent parameter because many geochemical reactions are controlled by pH like the creation of charge surface of adsorbent. A difference of one unit of pH can profoundly influence the geochemical signature of the solid-solution system. pH is unitless.

FeO represents the quantity of ferrihydrite ($Fe(OH)_3$ in solution, 10 l of water per kg soil was used in the experiments) . A number of unoccupied sites available for Pb atoms at the ferrihydrite surface is associated with a given quantity of ferrihydrite. The higher the quantity of ferrihydrite, the higher the number of sites, which could be occupied by a Pb atom. The ratio “sites/FeO” is never linear because of competition between Pb and other atoms for unoccupied sites. FeO is given in mol/L.

1.009 is a bias-correction factor known as the smearing estimator (Helsel and Hirsh, 1992) to show K_f in original unit (Kg/L) and applied to the exponential form of the model. The smearing estimator is the average of the exponential model residuals: $\sum \exp(r_i)/n$ =1.009.

The equations have been implemented in a spreadsheet that calculates the parameter values to be included in the Daisy model based on the pH and chemistry of the local soil and irrigation water. However, the equations are valid for sites with a similar mineralogy to the Crete field experiment-site only. In the test example, the equations have been used to derive parameters for the Italian site, but the validity of the parameters here is questionable.

Annex 2 show values for K_d for risk assessment in the U.S.

3.5.2 The Daisy setup for heavy metals

In Daisy,sorption can be specified through a K(organic matter) or a K(clay) in $(cm^3\ g^{-1})^m$ which is then multiplied with the fraction of the constituents. This means that the calculated K_f-value has to be adjusted to the soil in which it is applied. This can be done within the spreadsheet mentioned above by entering the description of the soil for which the calculation is done.

The Freundlich parameters for the compound are specified in the Daisy input file “OpenMI_management.dai” before the model run is executed. In addition, the initial concentration of the heavy metal in the soil must be specified.

```
(defchemical Pb heavy_metal

 "Lead (Pb)"

 (Ms 25e-6 []) ;Approx. background concentration in CER soil [g Pb/g soil]

 (adsorption Freundlich (m 1 [])(K_clay 2.62e5 [(g/cm^3)^-m])))
```

3.5.3 Risk assessment related to heavy metals.

Table 3.22 compiles WHO (2006)-guidelines regarding safe use of wastewater, excreta and greywater for irrigation and the resulting concentration in soils. Table 3.23 shows figures from a later review by Battilani (pers.com), which takes plant toxicity into account to a higher degree than the WHO-figures. Generally the figures in Table 3.23 are equal to or lower than the WHO-guidelines. These figures will be the base for evaluation of simulation results regarding heavy metals.

Five figures are considered when evaluating the risk related to heavy metals:

i. The concentration in the irrigation water,
ii. The initial concentration in the soil
iii. The final concentration in the soil, and
iv. The increase in concentration due to irrigation with waste water
v. Concentration in leaching water, if relevant

Concentration in irrigation water is evaluated in relation to thresholds given in Table 3.23. If the concentration in the irrigation water is below the limit for prolonged use, it is flagged “safe” (highlighted with green), if the concentration is between the limit for prolonged use and acute toxicity it is flagged “caution” and highlighted with orange. Concentrations above the limit for acute toxicity are flagged dangerous by a red highligh.

At the end of the simulation, the content in the root zone is evaluated and presented. Somewhat arbitrarily, the use is considered safe if the soil concentration is less than 70 % of the maximum tolerable soil concentration. Caution is required if the concentration is rising to between 70 and 100 % of the maximum tolerable soil concentration, and particularly in this range, it is important to look at the increase in concentration over a growth season. The use is unsafe if the concentration exceeds the maximum concentration. The colour coding is similar to the above.

In some cases, the concentration of heavy metal in infiltrating water or drain water may pose a problem. The concentration in leaching water is therefore presented graphically. However, if the simulation only covers the growth season, the amount of water leaching may be minute and not really represent average conditions for a year.

Table 3.22: WHO guidelines regarding safe use of wastewater, excreta and greywater for irrigation and the resulting concentration in soils.(WHO, 2006.)

Compound	Recommended maximum concentration in irrigation water (mg/l)		Degree of restriction on use			Maximum tolerable soil conc. of various toxic chemicals in soil based on human health protection (mg/kg)
			None	Slight to moderate	Severe	
Ag						3
Al	5	Can cause non-productivity in acid soils (pH<5.5, but more alkaline soils at pH>7.0 will precipitate the ion and eliminate any toxicity				
Antimony (Sb)						36
Arsenic (As)	0.1	Toxicity to plants varies widely, ranging from 12 mg/l for Sudan grass to less than 0.05 mg/l for rice.				8
Ba						302
Be	0.1	Toxicity to plants varies widely, ranging from 5 mg/l for kale to 0.5 mg/l for bush beans.				0,2
B			<0.7	0.7-3.0	>3.0	1,7
Cd	0.01	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/l in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.				4

Co	0.05	Toxic to tomato plants at 0.1 mg/l in nutrient solution. Tends to be inactivated in neutral and alkaline soils.				
Cr	0.1	Not generally recognized as an essential growth element. Conservative limits recommended due to lack of knowledge on its toxicity to plants.				
Cu	0,2	Toxic to a number of plants at 0.1-1.0 mg/l in nutrient solutions.				
F	1	Inactivated by neutral and alkaline soils.				635
Fe	5	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead Sprinkling may result in unsightly deposits on plants, equipment and buildings	<0.1 drip irr	0.1-1.5 (drip irr)	>1.5 (drip irr).	
Hg						7
Li	2.5	Tolerated by most crops up to 5 mg/l, mobile in soil. Toxic to citrus at low concentrations (<0.075 mg/l). Acts similarly to boron.				
Mn	0.2	Toxic to a number of crops at a few-tenths to a few mg/l, but usually only in acid soil.	<0.1 drip irr	0.1-1.5 (drip irr)	>1.5 (drip irr).	
Mo	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concetrations of available molybdenum.				0,6
Ni	0.2	Toxic to a number of plants at 0.5-1.0 mg/l, reduced toxicity at neutral or alkaline pH.				107

Pb	5	Can inhibit plant cell growth at very high concentrations.				84
Se	0.02	Toxic to plants at concentrations as low as 0.025 mg/l, and to				6
Thallium (Tl)						0,3
V	0.1	Toxic to many plants at relatively low concentration				47
Zn	2	Toxic to many plants at widely varying concentrations, reduced toxicity at pH>6.0 and in fine textured or organic soils.				

Table 3.23 Limiting contents of a number of chemical compounds in irrigation water and soil based on a literature review carried out by A. Battilani (pers. com).

	Irrigation water		
	Prolonged use	Acute phytotoxicity	Concentration in soil
	mg l^{-1}	mg l^{-1}	mg kg^{-1}
Arsenic	0.1	2.0	8.0
B	0.5	Crop dependent, 0.5->6	nd
Cd	0.01	0.05	1.0
Cu	0.2	5.0	150.0
Cr (VI)	0.1	1.0	nd
Fe	0.2	20.0	nd
Mn	0.2	10.0	nd
Hg	0.002	0.002	1.0
Mo	0.01	0.05	nd
Ni	0.2	2.0	50.0
Pb	2.0	5.0	84.0
Zn	2.0	5.0	150.0

3.6 Calculations of microbial contamination in soil and on crop

Microbes may or may not be present in the irrigation water. If present, the concentration of E. Coli in the water should be specified, together with the relevant filtering factors. The final concentration in the irrigation water will be calculated as described in Chapter 3.2.6.

When irrigation starts, the contaminated water may end up directly on the produce or in the soil. It is therefore necessary to consider what happens to the E.coli in each of these cases.

In order to describe the fate of the microbes in the soil, microbes have to be defined in the Daisy model and an initial concentration specified together with parameters for die-off and filtration. The concentration of E.coli in the irrigation will be transferred to Daisy via OpenMI. Daisy will then calculate the concentration in the soil and water, including leaching.

In case of water directly on the produce, a die-off rate is required to calculate the contamination at harvest.

Exposure assessment is relevant in two instances, 1. For the farm workers and 2. for the consumers eating the produce.

The basis for a risk assessment for farm workers is the no. of E.coli/g soil. For the consumers the situation is slightly more complicated. For tomatoes lying on the ground and potatoes in the ground, the risk is associated with the contamination on the surface of the crop and thus the E.coli/g soil * the amount of soil attached to the crop. For tomatoes hanging in free air, contamination from irrigation water is expected to occur only if the field receives sprinkler irrigation and the contamination will be linked to the amount of water sticking to the tomato. The actual contamination is time-dependent because a certain die-off will take place from irrigation to harvest.

The contamination figures are fed into the microbial risk models (see chapter 3.7).

Calculations of the contamination on tomatoes above the soil are done through post-processing of the data from the IFM-module.

For calculation of contamination on soil, the microbes are then transferred via OpenMI to the Daisy model, where it is treated as a pesticide. Daisy is able to describe sorption, filtration and decay of pesticides, but only the last two functions are employed for microbes. A 1st order decay is assumed, which depends on moisture and temperature conditions in the soil. In the following, the use of adsorption and filtration functions for bacteria and vira are discussed.

3.6.1 Die-off in the air/on the crop.

The description of die-off of bacteria is based on work done in WP5 of the project (Deliverable 5.4, Ensink and Fletcher, 2009). Information on die-off rates of E.coli in air (on crop), in water and in soils were collected and forms the basis for the rates suggested for implementation in DAISY.

The suggested T90 for E.coli on aerial parts of a plant is 4 days. According to Deliverable 5.4, research has shown that exposure to sunlight and high temperatures have a detrimental effect on the survival of *E. coli* in soil (and similarly on the crop). During experiments *E. coli* survival, expressed as t90 (the time it takes for 90% of bacteria to deactivate) was found to be 3 days in summer and 14 days in autumn and winter (Feachem et al., 1983). Studies in Canada reported a 33% reduction in *E. coli* concentrations per day at 15°C and a 25% reduction at 10°C (Bell and Bole, 1978).

On the basis of these figures, rates of degradation were estimated, assuming that the 4 days (standard) were obtained at 20 degrees. Modifications as a function of temperature are shown in Table 3.24 and are equal to the modification that DAISY assumes for chemical reactions in the soil.

Table 3.24: Die-off rates for E.coli on tomatoes as a function of temperature. The reduction factor scale used depends on whether the die-off rate is originally defined at 10 or 20°C

	T	5	10	15	20	25	30
reduction factor (T=10)		0,5	1	1,5	2	2,8	4
reduction factor (T=20)		0,25	0,5	0,75	1	1,4	2
days-1	k(mod)	0,1439	0,2878	0,4317	0,5756	0,8059	1,1513
days	T90	16	8	5,3	4	2,9	2
reduction per day, %		13,4	25,0	35,1	43,8	55,3	68,4

While E.coli is the model organism, the following citations from Ensink and Fletcher (2009) are relevant when judging the exposure to other organisms:

The survival of Ascaris and Taenia eggs on produce tends to be relatively short, predominantly as a result of a greater exposure to drying heat and direct sunlight (WHO, 2006; O´Lorcain and Holland, 2000). Nematode and cestode eggs have shown the longest survival on crops with particular surface properties. Smooth surface vegetables, like for example tomatoes and aubergines, tend to be free from helminth egg or harbour very small concentrations, even if irrigation water with high concentrations of helminth eggs are used (Rhallabi et al., 1990; Stien et al., 1990). In contrast, low growing, hairy, sticky, rough or crops with crevices tend to show higher concentrations of helminth eggs per gram of produce (Ensink et al., 2007, Ayres et al., 1992 and Amoah et al., 2005), most likely as a result of their ability to hold on to water. This ability to hold on to water creates a more favourable environment for the survival of helminth eggs, bacteria, protozoa and viruses (Stine et al., 2005). Research in Israel found lettuce to retain on average 10.8 ml of water, while a smooth surface cucumber retained only 0.36 ml (Shuval et al., 1997). The manner in which irrigation water is applied is further suggested to play an important role in the contamination of agricultural produce, with crops cultivated under basin irrigation showing lower concentrations as compared to those irrigated by watering cans, in which water is directly applied to the crop (Ensink et al., 2007, Ayres et al., 1992 and Amoah et al., 2005). Helminth egg concentrations on crops tend to have shown low concentration, with concentrations ranging from 0.0002 eggs per plant to 2.7 eggs per gram of produce (Rhallabi et al., 1990; Stien et al., 1990, Ayres et al., 1992, Amoah et al., 2005, Stott et al., 1994). Rainfall has shown a mixed impact with one study suggesting that eggs are washed off agricultural produce following rainfall (Ayres et al., 1992) , while another study suggested that the splashing caused by rainfall could contaminate produce with helminth eggs found in soil (WHO, 2006).

The survival of helminth eggs on agricultural produce is therefore dependant on the type of irrigation application, environmental conditions and the type of crop. Ascaris eggs tend to survive longest on produce, and can, under the right conditions survive for over 60 days, though normally would be expected to be inactivated within 30 days (WHO, 2006).

For bacteria, the following citations from Ensink and Fletcher (2009) concerns differences due to crop choice and irrigation systems:

The survival of bacteria on crops is determined very much by similar factors as those stipulated for helminth eggs. Past studies for example have found differences in coliform concentrations between low-growing leafy vegetables and vegetables with a smooth, waxy outer surface (Rosas et al., 1984, Armon et al., 1994). In Pakistan, high concentrations of E. coli ($1.8x10^7$ CFU 100 ml^{-1}) were found in water used for irrigation, however relatively low concentrations of E. coli were found on irrigated produce (1.9 E. coli g^{-1})(Ensink et al., 2007). These low concentrations were contributed to high temperatures (ranging from 35°C to 45°C) and low humidity (as low as 40%). Studies conducted on produce quality in Ghana, Israel and Mexico found faecal coliform concentrations at least 100 times higher as compared to those found in the Pakistan study (Amoah et al., 2005, Rosas et al., 1984, Armon et al., 1994). The irrigation water application method likely played a pivotal role as in these irrigation water was applied from above through sprinklers or watering cans, while in the study in Pakistan irrigation water was applied through furrows, minimising contact between plant and wastewater. High daily temperatures combined with low humidity promote a rapid die-off of E. coli, which can be as high as 2 Log_{10} per day(WHO, 2006). In general, survival of faecal coliform and E. coli will depend on a number of factors; type of crop, climatic conditions and manner in which irrigation water is applied. Studies in Portugal showed a survival of 7-12 days of E. coli on spray irrigated lettuce (Vaz da Costa Vargas et al., 1996). Rainfall can have an important impact on produce quality – during dry periods much lower E. coli concentrations were reported as compared to after rain showers, the splashing of raindrops and thereby transferring contaminated soil onto agricultural produce was considered the main reasons for this (Bastos and Mara, 1995). On crops the WHO reports a usual survival of less than 15 days for faecal E. coli and salmonella spp. and a maximum survival of up to a month (WHO, 2006).

3.6.2 *Considerations concerning modelling of pathogens in soil in the prototype management model*

At present, there are no experiences with simulating pathogens with the Daisy model. It is therefore of interest to evaluate the possibilities and challenges when considering to do so for the prototype management model. The expected approach is to use functionalities and processes already included in the model, and to parameterize them to obtain a reasonable description of the transport.

Literature studies concerning retention in the soil during transport

The most comprehensive and recent review of studies of retention in soil and aquifers is produced by Pang (2009). For studies carried out within the upper meter of the soil, his analysis is based on the assumption that they are carried out with constant velocity of infiltrating water:

$$V = \frac{dx}{dt}$$

$$\frac{dC}{dt} = \frac{dC}{dx}\frac{dx}{dt} = \frac{dC}{dx} * V = -kC$$

If λ = k/V,

$$\frac{dC}{dx} = \lambda C$$

So, in this case, λ is inversely related to velocity. The removal rates are the observed rates of removal of microbes in column- and lysimeter experiments and thus include all possible processes (die-off, sorption, straining etc.). The table that summarizes the microbial removal rates for different soils found by Pang (2009) is included as

Table 3.25.

On the basis of the studies investigated, he concluded:

1. Microbial removal rates are generally in the order of 10^0 log/m (i.e., a few log/m) for most soil types, 10^1 log/m or greater for allophanic and pumice sand soils, but could be down to 10^{-1} log/m for clayey soil, clay loam, and clayey silt loam.

2. Of all soil types investigated in this study, allophanic and pumice sand soils have the greatest capacity to remove both bacteria and phages. This is because allophanic clays have a net positive charge when soil pH is below 6.0, which is their isoelectric point (Cooper and Morgan, 1979). The pH values for allophanic and pumice topsoils in the field are typically < pH 6, therefore they have an affinity for net negatively charged bacteria and phages. In addition, allophane has a very large surface area, 700 to 900 $m^2 g^{-1}$ (Aislabie et al., 2001), further enhancing microbial removal with the volcanic soil media.

3. Volcanic soils are followed by fine sandy loam, sandy loam, and loamy sand for efficiency in microbial removal. Fine sandy loam is very effective at removing bacteria probably due to straining, but it is relatively ineffective at removing phages. 4. Silt loam, shallow and deep silt loams have moderate capacities in microbial removal.

4. Silt loam, shallow and deep silt loams have moderate capacities in microbial removal.

Table 3.25: Summary of microbial removal rates for different soils (Table 10 from Pang, 2009).

Soil texture	Source	Q	pH	CEC	Clay	OC	K_s	Microbe	λ based on C_p Mean	Min.	Max.
		mm/h		cmol/kg	———%———		mm/h		———Log/m———		
Pumice soil	DSE	5	5.7–6.2	6–21	1–3	0.4–8.1	30–60	*Salmonella* phage	16.61	15.75	17.46
								Complete removal in fecal bacteria			
Allophanic soil	DSE	5–10	5.8–6.0		20–25	1.5–6.5	200–1200	Fecal coliforms	5.48	5.22	5.75
								E coli	5.34	5.04	5.63
								Enterococci	5.16	5.05	5.28
								Complete removal in *Salmonella* phage			
Fine sandy loam	DSE	5	5.5–6.4	8.7–11.3	10–20	0.5–2.0	17–43	*Salmonella* phage	2.98	2.40	3.28
								Fecal coliforms	9.34	8.88	9.56
	SW sludge	7.64	5.1–5.6					Poliovirus	5.26	4.97	5.54
Fine-very fine sand	SW	1.33–2.63	6.2–7				5.67–6.69	PRD1	9.19	5.02	13.68
Medium sand	SE	0.21–1.13	0.07			0.017	27.6	MS2 or PRD1	10.85	6.82	20.00
Recent sandy soil	DSE	5	5.0–5.7	3–19	2–6	0.6–6	100–200	*Salmonella* phage	2.46	2.08	2.89
								Fecal coliforms	2.34	1.96	2.77
Loamy sand	SE	0.09	4.8–4.9	2.3–2.5	7–10	0.6		Fecal coliforms	4.02	1.38	6.66
		0.09	4.8–4.9	2.3–2.5	7–10	0.6		Fecal streptococci	3.72	1.37	6.07
	Trace	1.83				1-2		*Salmonella* phage	3.76	2.74	4.87
Sandy loam	SE	0.04–0.07	4.8–6.2	4.7–6.2	12–18	0.8–3.4		Fecal coliforms	3.70	2.63	5.13
	DSE	25–flood	5.00		5.90	6.20	123	Fecal coliforms	2.78	2.24	3.31
	SE	0.04–0.07	4.8–6.2	4.7–6.2	12–18	0.8–3.4		Fecal streptococci	3.87	2.24	5.17
Bare sandy loam	Cow manure	61	5.9–6.5			0.8–2.6		Fecal coliforms	2.41		
Vegetated sandy loam	Cow manure	61	5.9–6.5			0.8–2.6		Fecal coliform	1.60		
Silty sands and gravel	SW						8.64	f2 bacteriophage	2.19	1.31	2.86
								Fecal coliform	8.28		
								Fecal streptococci	4.81	2.31	8.58
Silt loam	DSE	5	5.7–6.1	9.0–15.4	1.2–24	1.6–23	4–50	*Salmonella* phage	2.30	2.07	2.69
	DSE	5	5.7–6.1	9.1–15.4	12–24	1.6–4.1	4–50	Fecal coliforms	2.47	2.27	2.79
	DSE	25–40	4.1–4.7		7.6–13	6.1–7.2	33–110	Fecal coliforms	6.00	4.27	7.14
	DSE	flood	4.1–4.7		7.6–10.8	6.1–7.2	33–110	Fecal coliforms	4.11		
Deep silt loam	DSE	5	5.6–5.9	6.7–15.2	15–24	0.3–3.1	14.5–385	*Salmonella* phage	1.99	1.56	2.56
	DSE	variable	4.1–5.8		5.9–13.0	6.1–7.2	33–250	Fecal coliforms	4.00	0.12	6.25
Shallow silt loam over gravels	DSE	5	5.6–5.9	8.3–11.7	12–24	0.8–2.2	114–723	*Salmonella* phage	1.98	0.99	2.53
								Fecal coliforms	4.04	2.42	6.49
Stony silt loam	Cow manure	71	5.0			0.3–2.0		Fecal coliform	2.48	1.61	2.69
Silty clay loam	DSE		4.80	20.4–25.9	70–80	1.2–8.0	5–88	*Salmonella* phage	2.80	1.87	4.18
								Fecal coliforms	3.61	2.77	5.16
Silty clay/clay	SE	0.03	5.7	19.2	52.0	0.3		Fecal coliforms	2.44		
		0.03	5.7	19.2	52.0	0.3		Fecal streptococci	2.76		
	Tracer		5.6–5.7				0.04–18.0	*E coli*	0.34	0.32	0.36
Clay	SE	0.03	6.0	16.5	42.0	0.1		Fecal coliforms	3.67		
		0.03	6.0	16.5	42.0	0.1		Fecal streptococci	6.04		
Clay loam	DSE	5	4.9–5.3	9.9–17.2	30–79	0.8–3.0	13–200	*Salmonella* phage	1.80	1.59	2.15
								Fecal coliforms	2.64	2.08	3.17
	SE	0.04	5.2	8.5	28.0	0.7		Fecal coliforms	0.81		
		0.04	5.2	8.5	28.0	0.7		Fecal streptococci	1.75		
	Cow manure	61	5.3–6.5			1.8–3.6		Fecal coliform	0.46		
Clayey silt loam	DSE	5–10	5.7–6.6		30–40	0.4–6.9	200–300	Fecal coliforms	0.55	0.40	0.69
								E coli	0.54	0.42	0.65
								Enterococci	0.27	0.20	0.33
Clayey soil	DSE	5	5.1–6.1	27–32	52–69	0.8–5.4	30–50	*Salmonella* phage	0.97	0.12	2.08
		5–10	4.8–5.5	not given	65–70	0.8–5.5	30–50	Fecal coliforms	0.41	0.00	0.83
								E coli	0.34	0.00	0.69
								Enterococci	0.79	0.72	0.86
Loam	SE	0.07	4.7	5.4	16.0	0.4		Fecal coliforms	4.89		
		0.07	4.7	5.4	16.0	0.4		Fecal streptococci	5.50		
	DSE	25–40	5.80		10.90	7.20	250	Fecal coliforms	0.75	0.43	1.06
Marshland	SW							*E coli*	1.13	0.99	1.28

5. The worst soils for microbial removal are clayey soils and clay loam. Although clay particles are very effective at filtering microbial particles under conditions

of ideal matrix flow (Keswick and Gerba, 1980), clay soils under field conditions are susceptible to shrinking and cracking forming macropores and preferential flow paths (Carlander et al., 2000). Rapid microbial leaching immediately after effluent irrigation is often observed in structured clayey soil, clayey silt loam, and clay loam. Similarly, Carlander et al. (2000) also noted that phage transport was generally more rapid and had a much lower retention in clay soils than in sand soils in their field lysimeter study. This suggests that under field conditions, the effect of soil structure (i.e., macropores) often overrides the effect of texture on microbial removal. A clay soil core with many cracks and channels might favor microbial transport compared with a sandy soil core with a more homogenous pore structure (Guimaraes et al., 1997). With intact soil cores, there is sometimes no relationship between soil texture and microbial transport (Guimaraes et al., 1997; Smith et al., 1985).

6. Removal rates are more variable in soils containing clay and gravels (clayey soil, silty clay loam, clay loam, silt loam over- gravels, and deep silt loam) than fine textured and volcanic soils (silt loam, fine sandy loam, recent sandy soil, allophanic soil, and pumice sand soils).

7. For a specific soil, the removal rate for fecal coliforms is generally greater than that for bacteriophages, but they are within the same order of magnitude. Removal rates for fecal coliforms, *Escherichia coli*, *streptococci,* and *enterococci* are similar.

8. For a particular soil, removal rates determined from experiments with flood irrigation are lower due to a greater transport but less variable than those determined from spray irrigation. This is because soil drainage is greatly in excess of soil moisture for flood irrigation; whereas for spray irrigation the amount applied may or may not exceed the soil moisture deficit, depending on the time of year, irrigation method, irrigation rate, and uniformity of application.

9. For a particular soil, removal rates determined from indoor lysimeters are less variable than those determined from outdoor lysimeters although they are still within the same order of magnitude. Soil structure can change with seasons. This is particularly relevant to the soils with higher clay content in the topsoil as shrinkage cracks can form during summer but can close up during wet seasons.

From this study and several of the works referred to in the review, it is clear that macroporosity plays an important role for the transport, and a description of this must be present in the model. Soils without macropores tend to retain pathogens to a higher degree than the soils with macropores. When evaluating some of the original studies behind the review, it becomes clear that the very low λ-values tend to be associated with flooding, very high irrigation rates and/or soil types with low matrix conductivity, indicating that chance of macropore flow occurrence is high high (McLeod et al. (2001), Aislabie et al. (2001), Jiang et al. (2008)).

This finding is also in line with Artz et al. (2005), who finds macropores to govern the leaching of E.coli from soil. They conclude that small variations in compaction and

presence of pores significantly affect the pathway that cells can take through soils and that preferential flow is the prime determinant of leaching through soil. When evaluating some of the original data sources, it is clear that the pathogens often arrive at the bottom of the soil columns before an added tracer, strongly indicating macropore flow (e.g. Pang, 2008).

Adsorption is mentioned as particularly important for soils with a positive charge. However, most soils that are not volcanic or kaolinitic with low pH have overall negative charges. Other possible mechanisms are not mentioned, but in addition to sorption, straining and die-off are mentioned in the background papers. Pang et al. (2008) estimated a die off of 3.8 % for phages and 5.5 % for bacteria during their experiment. The rates are thus too low to influence the λ-values significantly. There is general agreement that these processes may influence pathogen transport. Gerba et al (1991) reviewed processes and parameterization relevant to describing microbial transport and list and discuss advection, dispersion, adsorption, filtration and decay or die-off.

In the following, these processes will be further investigated.

Field experience obtained in the Safir project

Field experience obtained in the Safir project As part of the Safir project, Forslund et al. (2009a and b) experiments were carried out with addition of bacteria and phages to a) small soil columns and significant amounts of water, leading to macropore flow, and b) on lysimeters, receiving low amounts of water, avoiding saturated flow conditions.

In the first case, the bacteriophage, E. coli and C. parvum were detected already one day after slurry was applied irrespective of application method. The highest bacteriophage concentration was seen on day 4 when about 10% of the water in the soil pores was exchanged. After 148 days, the bacteriophage was still detectable (100 plaque forming units per ml). The highest concentration of chloride was detected on day 13 corresponding to 0.5-0.6 pore volume, indicating a predominance of bypass flow over matrix flow in the soil cores. E. coli was detected in low concentrations (1-10 colony forming units per ml) throughout 3½ month for both application methods. The concentration of C. parvum oocysts was highest on day 1, but oocysts were detected during a 1½ month period and remained viable after transport through soil.

In the second experiment, phage 28B was detected at low concentrations (2 pfu/mL) in leachate from both sandy loam and coarse sand lysimeters two weeks after irrigation was started. After 27 days, phages continued to be present in similar concentrations in leachate from lysimeters containing coarse sand, while no phages were found in lysimeters with sandy loam. None of the three added bacterial pathogens were found in any leachate samples during the entire study period. All bacterial pathogens and phage 28B were found on potato samples harvested just after the application of test organisms was terminated.

In general, the findings of these trials are in agreement with the experiments reviewed by Pang (2009).

Die-off in soil.

Microbial die-off is described as 1.order decay, resulting in an equation of the form:

$C = C_0 * e^{-kt}$.

Ensink and Fletcher (2009) quote a number of authors on measured die-off rates in soils. Bacterial die-off is more rapid in hot, dry climates as compared to cool, cloudy and rainy climates. Bacterial survival, for example, is marked longer at 4°C as compared to 20°C (Höglund et al., 2000). Bacterial die-off shows an exponential trend, with 90% to 99% of bacteria dying within a relatively short time, while few might survive for several days, sometimes months.

The given examples were:

- in Australia a T99 for *E. coli* was reported to be 1 day in dry soil, while the same soil in saturated condition reported a t90 of over 3 weeks (Chandler and Craven, 1978).
- The same authors further reported a T90 for *E. coli* of 2.5 days under 10% soil moisture conditions and a T90 of 18 days under 30% moisture conditions (Chandler and Craven, 1980).
- Survival of *E. coli* in soil is promoted by nutrition. Soil with high organic matter content provides an environment more favorable to *E. coli* survival as compared to soils with low organic matter contents. In soils receiving animal manure, the T90 for *E. coli* was reported to be 8.5 days as compared to 4 days in soils which did not receive manure (Dazzo et al., 1973).
- E.coli can survive for up to a maximum of 70 days, but after 10 days 90% of *E. coli* and other faecal coliforms have disappeared. Under hot and arid conditions a complete elimination of all faecal coliform bacteria in soil can be expected within 14 days (Faechem et al., 1983).
- The report recommends to use a T90 of 25 days for E.coli and 35 for Salmonella.

In order to accommodate the findings, it was attempted to create a dependency of the die-off on temperature and moisture. The earlier shown temperature dependency is kept and is still equal to the one used in the Daisy model for decomposition, except it is normalized to 20 ˚C rather than 10˚C. The effect of moisture content is suggested to follow the figures given inTable 3.26, although these figures may underestimate the effect of drying slightly. If the field receives much manure, the die-off-rates may be halved.

Table 3.26: Die-off rates for E.coli in soil as a function of temperature and suction, expressed as T90-values and die-off rate coefficients.

	Temp,˚C	0	5	10	15	20	25

soil (pF)	factor	factor	0	0,25	0,5	0,75	1	1,4
		T90						
0	0,6			166,7	83,3	55,6	41,7	29,8
1	0,8			125,0	62,5	41,7	31,3	22,3
2	1			100,0	50,0	33,3	25,0	17,9
3	3			33,3	16,7	11,1	8,3	6,0
4	5			20,0	10,0	6,7	5,0	3,6
5	7			14,3	7,1	4,8	3,6	2,6
6	9			11,1	5,6	3,7	2,8	2,0
7	11							
		Die-off rates, days-1						
0	0,6		0,0000	0,0138	0,0276	0,0414	0,0553	0,0774
1	0,8		0,0000	0,0184	0,0368	0,0553	0,0737	0,1032
2	1		0,0000	0,0230	0,0461	0,0691	0,0921	0,1289
3	3		0,0000	0,0691	0,1382	0,2072	0,2763	0,3868
4	5		0,0000	0,1151	0,2303	0,3454	0,4605	0,6447
5	7		0,0000	0,1612	0,3224	0,4835	0,6447	0,9026
6	9		0,0000	0,2072	0,4145	0,6217	0,8289	1,1605
7	11		0,0000	0,2533	0,5066	0,7598	1,0131	1,4183

Die-off rates for virus were investigated by Yates et al. (1985). They found a relationship of the form

K_i ($\log_{10}$ day^{-1})= -0.018+0.0214*temperature (°C).

In the table below, the rates have been calculated, together with a temperature dependent factor, based on either the rate at 10 or 20 degrees. It is clear that the temperature dependent factor derived from this expression is almost identical to the one used within the Daisy model.

Table 3.27: Die-off rates coefficients for virus in soil as a function of temperature, expressed as T90-values, calculated from Yates et al. (1985).

Temp	0	5	8	10	15	20	25	30

die-off rates	-0.018	0.089	0.1532	0.196	0.303	0.41	0.517	0.624
f(10)	-0.09	0.45	0.78	1.00	1.55	2.09	2.64	3.18
f(20)	-0.04	0.22	0.37	0.48	0.74	1.00	1.26	1.52

Gerba et al. (1991) described die-off of E.coli to be, on average, 0.92 day^{-1}, ranging from 0.15 to 6.39, based on 26 observations presented in Reddy et al. (1981). The values for fecal coliforms, fecal streptococci, salmonella and shigella sp., range between 0.05 and 9.10 day^{-1} according to the same sources. The original data, however, do not appear to come from studies of decay in soil. The same sources also describe die-off as a function of temperature, but only with an increase of about 10 % when going from 5-10 degrees to 15-20 degrees C for E.coli.

Ogden et al. 2001 treated the population of E.coli added to soil with applied slurry according to a dual population approach, resulting in a linear die-off with a half life of 3-4 days (faster at higher temperature and lowest moisture content) for the susceptible part of the population and a half-life for die-off of between 18 and 24 days, with little temperature and moisture dependency for the resistant pool. These half-lives can be translated to 0.100, 0.075, 0.0167 and 0.0120 day^{-1}, respectively. These data are within the range given above.

While E.coli is used as the model organism, data on nematodes may be of interest too, when judging risks. Ensink and Fletcher (2009) collected the following information on this:

Of the different nematode eggs, Ascaris eggs have shown the greatest survival time in soil, though the variability in survival times is great. Studies conducted during hot dry summers have shown a survival ranging from 27-35 days (Rudolfs et al., 1951), while studies conducted during the winter season in Japan have shown a survival of up to 5-6 months (Yoshida, 1920). In rare instances, Ascaris eggs have shown to survive up to 7 years in soil (Golueke, 1983; Parsons et al., 1975), though the 'normal' maximum survival time is set by the WHO guidelines for the safe use of wastewater in agriculture is 2 years (WHO, 2006). At 20 °C it is estimated that it takes 15-100 days for all Ascaris eggs to be inactivated in soil (Schonning et al., 2007).

Filtration

Gerba et al. (1991) include straining, sedimentation, intertial impingement and diffusion in filtration processes. Later authors (DeNovio et al. (2004) and McGechan and Lewis (2002)) discuss these processes in far more detail and under slightly different names. DeNovio et al. (2004) discuss grain attachment, air-water attachment, pore straining attachment and film straining attachment, while McGechan and Lewis (2002) reviewed processes described in relation to industrial use of colloids. These are diffusion, interception, filtration and sedimentation. Pure filtration takes place when particles cannot move through pores with a diameter less than their own, but it is, in practice very difficult to separate from sorption to the soil matrix or deposition within a porous material.

According to Gerba et al. (1991), the relative magnitude of the effect of this process depends on soil, water and microbial factors. For small microbial particles (i.e., vira) in coarse-grained material, filtration is probably negligible. For large bacteria and virus aggregates, on the other hand, physical straining may be an important consideration. Figure 3.13 shows the approximate size of bacteria and virus. It is clear that bacteria are considerably larger than the ions and organic molecules usually transported through the soil with water. They belong to the size range of colloids. Colloids are small particles (constituents) present in the soil, defined on the basis of their size. Unfortunately, there is not total agreement in literature concerning the size of colloids. Stumm (1977) and Puls and Powel (1992) define colloids as particles smaller than 10 µm, while Brady and Weil (1999) define colloids to be less than 2 µm. These authors do not define a minimum size for colloids. Other authors define a minimum and a mazimum size for colloids, e.g. Buffle and Leppard (1995) who consider colloids to be beween 1 nm and 1 µm, or Kretzschmar and Sticher (1998) where colloids should be between 1nm and 1 µm in at least one direction. Oswald and Ibariaki (2001) use the limits 1 nm to 10 µm, while Ryan and Elimelech (1996) consider them to be from 1 nm to a few µm.

As colloids are defined according to size they may be very different with respect to properties. The colloids may be made up of clay, iron(hydro)oxides, macro-molecules, silicates, bacteria, vira (etc. (Ouyang et al, 1996, McGechan and Lewis, 2002). Some have surface properties that cause them to sorp to soil constituents or solutes.

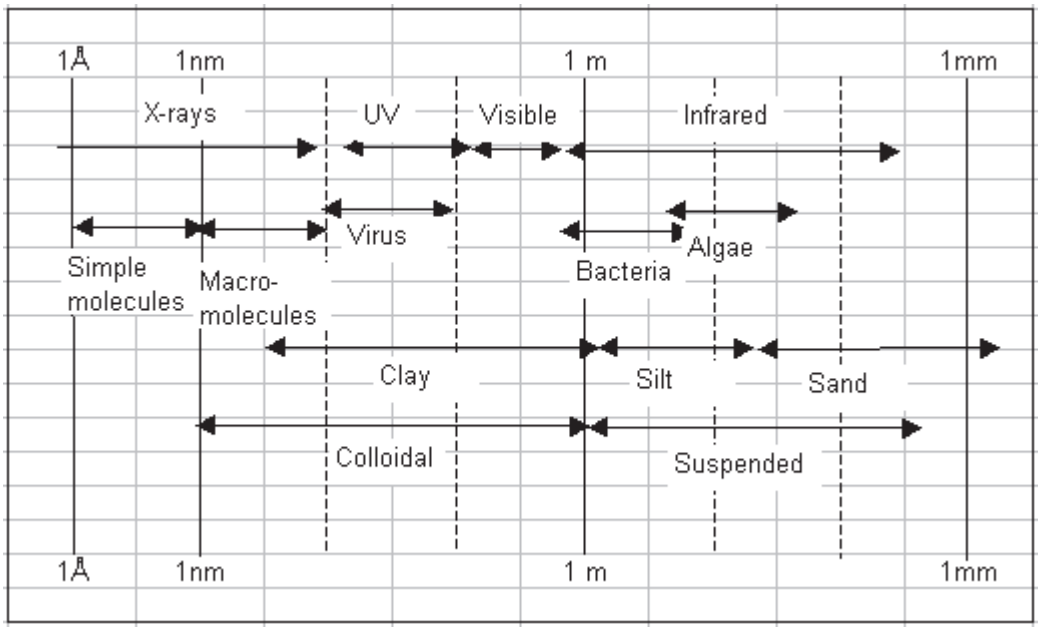


Figure 3.13: Orders of magnitudes of different types of colloids compared to wavelengths of light. Ullum (2001).

In general, under high flow velocities, the amount of bacteria filtered is less than for low flow flow velocities (Wollum and Cassel, 1978). This is probably due to the fact that the larger amount of the total flow quantity is derived from the larger pores, which will transmit a greater portion of the total number of bacterial present. Gerba et al. (1991) also state that the filter efficiency may change with time, as the bacteria

accumulate in the soil, they become part of the filter, thus increasing filter efficiency. Filter mechanisms depend on hydraulic conditions such as flow velocity and flow direction. When these parameters change, the bacteria may be remobilized. The filter factor may also change with time; as the bacteria or other particles accumulate, a filter layer develops which further reduces the diameter of the pores available for microorganism movement (Krone et al. 1958).

The basic equation used in all filtration theory to represent removal of particles (mass concentration c with distance z was first empirically observed by Iwasaki (1937) as:

$$-\left(\frac{\partial c}{\partial z}\right) = \lambda_f c$$

C is the observed concentration of the filtered colloids, z is the distance, λ_f is the filtration factor or coefficient.

This equation has been used by numerous researchers over time, generating information that λ_f depends on particle size and properties, packing geometry, flow rate, electrolyte composition and surface potential of particle and surfaces. Assuming that transport by dispersion can be neglected, the filtration coefficient λ_f can be described as a function of the deposition rate coefficient, k_d, as $\lambda_f = k_d/v_p$

This is identical to the equation used by Pang (2009) in the study of general retention.

Pang et al. (2008) analyzed straining as an explanation of retention seen in a series of lysimeter trials with 10 soils. He assumed that straining occurs when the ratio of the colloid to medium grain diameter, Dp/d, is >0.5% (Bradford et al., 2004), and will be significant when the ratio is >8% (McDowell-Boyer et al.,1986). He found that straining could occur during transport of fecal coliforms through all of the lysimeters (Dp/d > 0.69%), and could be significant in clayey soil, clay loam, and silt loam (Dp/d ≥ 10%). Based on these criteria, straining could also occur in the transport of phages in clayey soil and clay loam (Dp/d = 0.7–3%). He mentioned that the criteria for straining described above were developed from media with uniform grain sizes and that these criteria do not consider the effect of soil aggregates and macropores. Although the grain diameter may be small in aggregated soils, the effective diameter may be a lot larger because the grains are clumped and the microbes are not interacting with single grains. This statement, however, does not rule out that straining takes place in the part of the soil matrix that contains the smaller pores. He modeled the experiments, using linear adsorption/desorption descriptions, an inactivation (or die-off rate) and no straining functions, and concluded that the modeled adsorption was more or less irreversible (detachment rates only about 1% of the attachment rate).

Matthess et al. (1988) reported filter coefficients of 10-44.6 m^{-1} for enteric bacteria in sandy soil (<2% clay). Jang et al. (1983) reported filter coefficients of 40-93 m^{-1} for sandstone cores, depending on the type of bacteria.

McGechan (2002) concluded after a considerable effort into analysis of pore sizes, flow distribution in pores and microbial sizes that only the largest pathogens can be seriously affected by straining. However, Gannon et al. (1992) found that the length

of bacteria played a role for transport (Significant at the 1% level). Bacterial strains of less than 1.0 µm showed greater leaching than strains with longer cells.

Gargiulo et al. (2007) investigated filtration and adsorption in unsaturated packed columns, using sand of three different sizes (607, 567 and 330 µm) and surface treatment of the bacteria to be able to distinguish between adsorption and filtration. The bacterium used was Rhodococcus rhodochrous, which is a spherical bacterium of 1 µm. It is, however, able to form big three-dimensional aggregates as large as 10-15 µm, but this ability was counteracted by the surface treatment. The peak effluent concentration expressed as c/c_0 was 0.92, 0.7 and 0.02 for the three sizes of sand, respectively. 7, 33 and 98% of the added untreated bacteria were retained in the columns. Modeled retention was, for comparison, 10.6, 35.4 and 97.1 %, and of this 9.7, 27.6 and 96.7% could be attributed to straining. Results for treated bacteria on medium sand resulted in only 20.9 % retained and 17.6 % of this could be attributed to straining. The equations used differ from the formulas discussed above, as straining was made a function of depth from surface and colloid saturation of the soil.

The same authors found that although the sorption processes were much less important that the straining, the sorption parameters used in the model simulation increased when sand size decreased. This observation is in accordance with the expectation that finer sand particles have a larger surface area. After treatment of the surface of the bacteria, the sorption parameters dropped considerably.

Adsorption

Gerba et al. (1991) summarized results of sorption experiments and concludes that adsorption (particularly of vira) usually can be described by a Freundlic isotherm and often can be reduced to a linear isotherm, as 1/n is not statistically different from 1. For bacteria, retardation is usually lower than 1, and as retardation is defined as $R = 1-(\rho_b/\theta)*K_A$, K_A being the sorption coefficient, K_A has to be 0. The reason given for bacteria moving faster than the general water flow is exclusion of these from smaller pores, either due to size or anion exclusion (negatively charged particles are pushed to the center of the pores, where flow velocities are greater). Rotavirus, which is also of interest here, is assigned a K_A-value of 1.1 ml/g in the review.

There seem to be a broad agreement that vira sorp onto soil material and that sorption is particularly important for vira, being the main mechanism for their retention in soil (Goyal & Gerba, 1979; Bitton, 1975). However, they observed large variations in the extent of adsorption between different types and strains of vira under the same conditions. Burge and Enkiri (1978) measured virus sorption by five different soils. Moore et al. (1982) describe the mechanisms by which vira are sorbed in soil, and measured variations in sorption capacity of a range of soil minerals. Murray and Parks (1980) measured sorption of poliovirus on oxide surfaces in soil, showing that the ionic strength, pH and composition of the soil solution had a major effect. Vilker and Burge (1980) and Vilker (1981) have described a mass transfer model of transport of vira through soil which includes sorption according to the Freundlich isotherm equation, but for sorption by the static soil matrix only.

For bacteria it seems to be extremely difficult to separate straining and adsorption, and it does appear to be the conviction of the author of a given article that decides whether retardation has been attributed to one or the other.

Gannon et al. (1991) finds that Enterobacter, Pseudomonas, Arthrobacter, Bacillus, Achromobacter and Flavobacterium are retained in an Anion-exchange ESIC assey (97-100 % of the cells retained), indicating that the cell surfaces are negatively charged and that anion exclusion may take place. Tan et a., (1992) attributed retardation of bacterial movement to adsorption of bacteria unto sand surfaces. As mentioned above, some sorption of bacteria to sand surfaces also took place in the study of Gargiulo et al. (2007), but it was less important that the straining processes. Pang et al. (2008) assumed that the removal of bacteria and phages in his soil columns were due to sorption and he explained the differences with different surface coatings on the particles in the different soil types, but the claim is not substantiated.

According to McGechan and Lewis (2002), Marshall (1971) and Muller and Hickisch (1970) have reviewed the subject of sorption of microorganisms on soil particles, and further information on sorption of bacteria by clay minerals is presented by Filip (1973). However, little new information is available on the subject.

Nobody appears to consider sorption of bacteria (or virus) unto mobile colloids, as is seen for pesticides.

3.6.3 Implementation in the DSS

E.coli on high-growing sprinkler-irrigated tomatoes

The calculation as carried out as post processing, based on the concentration of E.coli in delivered irrigation water and the air temperature. Based on Table 3.24, and the rate given at 20°C, the temperature factor is parameterized as:

If t <0: f = 0

If $0 \leq t \leq 20$: f = 0.05 *t

If t> 20 : f =0.1732*exp(0.07871*t)+0.1624

The rate at 20°C is given in the table as 0.5756 day^{-1} or 1/24 of this, calculated as h^{-1}.

The calculation is done for 1 ml of water assumed to stay on a fruit, and the calculation is carried out from the beginning of the irrigation, although no fruits are present. The high die-off rates ensure that the latest irrigations dominate the calculations. Depending on the no. of mm expected to stay on the crop, the contamination at harvest can be calculated and transferred to the risk assessment sheets.

Daisy calculates the concentration of E.coli in ppm. To move between ppm and cfu a value of $1*10^{-9}$ cfu/mg is used. The formula used is therefore

$No(t) = Ct/1*10^{-9}/1000 + No(t-1)*\exp(k*f*\Delta t)$

Where

- No is the number of E.coli in 1 ml of water at the time t
- Ct is the concentration of E.coli added with irrigation water in ppm (mg/l) at the time t. This figure is divided by the weight of a cell cfu/mg and by 1000 to obtain cfu/ml.
- k is the rate of decay in $hours^{-1}$.
- f is the temperature modification factor
- Δt is the timestep of 1 hour used in the Daisy output files.

The assumed amount of irrigation water staying on 100 g of tomato is 1-1.5 ml of water.

Die-off of E.coli in the soil

For the soil, the functions have to be specified in the Daisy input files. If the die-off rate is specified at 10 degrees and the moisture content at field capacity, no temperature modification factor requires specification. The Daisy default function can be used. Otherwise specification is required. The dependency on moisture content is very different from the Daisy default value and requires specification. An example is given below.

```
(defchemical "E.Coli-base" microbe

  "A Gram negative bacterium."

  (decompose_rate 0.0461 [d^-1])

  (decompose_water_factor (7 [pF] 11) (6 [pF] 9) (5 [pF] 7) (4 [pF] 5) (3 [pF] 3) (2 [pF] 1) (1 [pF] 0.8) (0 [pF] 0.6)))
```

It is important to note that the die-off value to use in Daisy should be in $hours^{-1}$. This may be calculated as the daily rate divided by 24.

Inclusion of filtration and sorption in the Daisy model

Daisy describes filtration of colloids as a 1^{st} order reaction, where the coefficient depends on the geometry of the matrix, the particle size, the flow velocity, the electrolytic composition of the water and the surface potential on particles and pore surfaces. For micropores, the description is equal to the one used by Jarvis (1994) in the MACRO-model. It describes the filtration in the matrix through a simple 1.order reaction, where the filtration coefficient can be expressed as the colloid deposition rate-coefficient (s^{-1}) divided by the velocity of colloid particles in the porous medium ($m\ s^{-1}$)

$F = f_c v c \theta$

where

- F is the filtration (g $m^{-3} h^{-1}$)

- f_c is a reference filtration coefficient (m^{-1})

- c is the concentration (g m^{-3})

- θ is the water content (m^3 m^{-3})

- v is the pore water velocity (m h^{-1})

Daisy include two micropore domains, so it is possible to apply two different f_c-values, if required.

Jarvis (1994) describes the filtration in the macropores as a function of the reference filtration coefficient (m^{-1}) times a weighted pore water velocity, $((v_{ref}/v)^{nf}*v$, where nf is an exponent, multiplied by the colloid content (c*θ).

$$F = f_{ref} v^{nf}{}_{ref} v^{(1-nf)} c \theta$$

where

- F is the filtration (g $m^{-3} h^{-1}$)

- f_{ref} is an empirical reference filter coefficient, m^{-1}

- nf is an empirical constant

- v_{ref} is the pore water velocity at which f_{ref} is measured

For nf = 0, the expression for macropores and matrix are identical, for nf=1, the expression becomes a typical sink term for reactive processes. For 0<nf<1, filtration increases with v, while for nf>1, filtering decreases with increasing pore water velocity.

This description has been used in the MACRO-model and was parameterised by Villholth et al. (2000) and McGechan et al. (2002). McGechan et al. (2002) used these model descriptions to simulate leaching from the soil surface of particulate and colloid-bound phosphorus from slurry. The processes were also implemented and used in the MIKE SHE model (DHI Water and Environment, 2007, Baun et al., 2007).

Table 3.28 Filtration parameters and parameter values in the MACRO model.

Parameter	Parameter value	References
Reference filter coefficient for macropore, f_{ref}	0.5 m^{-1} 2 m^{-1} 1.5 m^{-1}	McGechan et al. (2002)[1] Jarvis et al. (1999)[2] Villholth et al. (2000)[3]
Reference flow velocity in macropores, v_{ref}	50 m h^{-1} 100 m h^{-1} 1 m h^{-1}	McGechan et al (2002) Jarvis et al. (1999) Villholth et al. (2000)
Filter exponent (macropores), n_f	1.8 0.7 2	McGechan et al (2002) Jarvis et al. (1999) Villholth et al. (2000)
Filter coefficient (micropores), f_c	40 m^{-1} 50 m^{-1}	McGechan et al (2002) Villholth et al. (2000) & Jarvis et al. (1999)

1: The soils (field experiments) used in McGechan et al (2002) is a clay loam with arable cropping and newly grass and a silty clay loam with grassland (longtime). The arable soils receive slurry.

2: Silty clay soil (field experiment) (clay in top soil = 46.5%). No tilled soil since 1988. The soil was bare after harvest of spring barley. Particle concentration in peak: 110 mg L^{-1}.

3: The soil (plot 5*5m) used in Villholth et al (2000) is a sandy loam (clay in top soil = 15.5%) from Gelbæk stream area. The soil was ploughed in August the previously year and winter wheat was sown. In April, three irrigation events was conducted (drip irrigation, 30 cm above the surface, 12 mm h^{-1} for 3 hours). Particle concentration in peak: ≈20-130-80 mg L^{-1} respectively in the three irrigation events.

Table 3.29 Filtration parameters and parameter values in Mike SHE (Baun et al., 2007)[1].

Parameter	Parameter value	Soil treatment
Reference filter coefficient for macropore, fref	10^{-7}-$2.5 \cdot 10^{-6}$ m^{-1} ≈ $3 \cdot 10$-6 m^{-1}	Minimally tilled Ploughed soil
Reference flow velocity in macropores, vref	1 m h^{-1}	Minimally &Ploughed soil
Filter exponent (macropores), nf	2	Minimally &Ploughed soil
Filter coefficient (micropores), fc	100 m^{-1}	Minimally &Ploughed soil

1: Intact soil columns (sandy loam, clay content in topsoil = %) with two soil treatment: Minimal tilled and recently ploughed. Model fitted to the first irrigation event (15 mm h^{-1} for two hours). Particle concentration in peak: ≈ 180-300 mg L^{-1} in ploughed soil and ≈ 50-100 mg L^{-1} in minimal tilled soil (surface partly covered by crop residues).

For Daisy, it is assumed that there is no filtration in the macropores. On the basis of the parameter values found by other authors, it seems that the filter coefficient in micropores should be in the order of 40-100 m^{-1} for colloid size-particles. Comparing to

Table 3.25 this equals log-values of 1.6-2. The particles considered as colloids are 0.2 µm in the study by Jarvis et al. (1999) and 0.02 µm for Baun et al. (2007), indicating that higher values may be appropriate for larger colloids such as bacteria. These values are certainly in the range given, but may also be considered conservative, as some of the values in

Table 3.25 are considerably higher.

If Gargiulo (2007) is correct, straining processes and sorption processes occur together, but the first process is more important than the second, at least for bacteria in sandy soil (and with a predominantly negative surface charge). His study, however, was the only one found that included both processes at the same time. Pang et al. (2008) include only die-off and sorption (using a linear isotherm) in his studies. Table 3.30 shows the sorption- and desorption parameters they obtained in their modeling study and the re-calculated removal rates as $\log_{10}$/m. The removal rates are total rates, thus including die-off. The removal rate in $\log_{10}$/m is generally around 2 log units.

Table 3.30 Modelling results from Pang et al. (2008) and Pang (2009) related to sorption data and recalculated as overall removal rates for Faecal coliform bacteria.

Soil type	Rep.	K_{att}, d^{-1}	K_{det}, d^{-1}	K_{tot}, h^{-1}	K_{det}/k_{att}	Removal rate, log_{10}/m*
Waikiwi silt loam	1	9.54	0.06	0.41	0.006	2.35
	2	9.85	0.19	0.42	0.019	2.27
	3	9.90	0.07	0.43	0.007	2.79
Lismore, shallow silt loam over gravels	1	13.71	0.06	0.58	0.005	4.04 (2.42-6.49]
	2	17.2	0.06	0.73	0.004	
	3	25.79	0.10	1.09	0.004	
Templeford, deep silt loam	1	8.00	0.08	0.35	0.011	1.54 (1.28-1.8)
	3	6.84	0.09	0.30	0.013	
Waitarere, recent sandy soil	1	2.1	0.02	0.10	0.009	2.29
	2	1.36	0.01	0.07	0.006	1.96
	3	3.19	0.04	0.15	0.011	2.77

*Peak concentration method, described in Pang (2009)

As E.coli is the model organism used for the risk assessment, it is the only one modeled in the DSS. For information, however, Table 3.31 includes similar figures from the same study for Salmonella phages for information. As mentioned earlier, sorption/desorption is the most likely processes to take place for phages.

Because we are not able to parameterize straining and sorption separately on the basis of existing data, it was decided to include one process only in the DSS simulation. According to Pang et al. (2008), the sorption is almost irreversible, and sorption data appear to be rather soil dependent. Such data have not been collected for the Safir soil sites. It is expected that the overall result of the straning process and an irreversible sorption can be rather similar, if parameterized adequately. We have, on this basis, decided to rely solely on the straining process for the DSS. Initially, a f_c-value of 40 m^{-1} will be used for the micropore-domains.

Table 3.31 Modelling results from Pang et al. (2008) and Pang (2009) related to sorption data and recalculated as overall removal rates for Salmonella phage.

Soil type	Rep.	K_{att}, d^{-1}	K_{det}, d^{-1}	K_{tot}, h^{-1}	K_{det}/k_{att}	Removal rate, log_{10}/m*
Waikiwi silt loam	1	9.02	0.11	0.38	0.012	2.38
	2	8.91	0.04	0.38	0.005	2.36
	3	8.50	0.03	0.36	0.004	2.07
Waikoikoi, silt loam	1	7.91	0.04	0.34	0.005	2.23
	2	9.91	0.02	0.42	0.002	2.69
	3	7.15	0.06	0.31	0.008	2.09
Lismore, shallow silt loam over gravels	1	5.31	0.02	0.23	0.004	1.98 (0.99-2.53)
	2	10.11	0.02	0.43	0.002	
	3	8.64	0.03	0.37	0.003	
Templeford, deep silt loam	1	7.38	0.07	0.32	0.009	2.56
	2	8.15	0.06	0.35	0.008	1.85
	3	7.49	0.10	0.32	0.013	1.56
Waitarere, recent sandy soil	1	2.91	0.07	0.13	0.024	2.41
	2	1.58	0.00	0.07	0.003	2.08
	3	3.37	0.03	0.15	0.008	2.89

How will bacteria behave in Daisy, subjected to filtration?

Bacteria added at the surface will be able to infiltrate with the water. Under dry conditions, most of the bacteria will stay close to the point of application. If it is very wet, and particularly if flood irrigation is applied, macropore flow may be activated and the bacteria may be transported down via macropores (if macropores are defined in the model). In case of drip irrigation, there will be little horizontal transport

from the point of the drip to the area between drips. Although it cannot be directly compared, WHO (2006) considers a protection equal to 2 decades for localized (drip) irrigation on low-growing crops (see Table 3.32). In reality bacteria may be transported with soil splashing onto tomatoes or on shoes. This is not considered in these calculations.

In case of subsurface drip, the bacteria may move down if the soil becomes saturated, but they are not likely to move upwards. If the bacteria were treated as a soluble salt in the model, they would move with water towards the surface due to differences in soil water potential, and when the water evaporates, the "salt" would be left behind on the surface. As the movement in dry soil through the soil matrix will be strongly restricted by the filtering process, the modeled bacteria will stay close to the level where water is added or move downwards.

3.6.4 Output

The situation differs for tomato and potatoes, and depends on the type of irrigation supplied.

High-growing sprinkler-irrigated tomatoes

The basis for calculation of the contamination is the content of E.coli in irrigation water at the time of irrigation. The amount of water sticking to tomatoes after irrigation is set to 1-1.5 ml/100 g. The water die-off rate is applied, and the contamination at harvest is calculated. This value is used directly in the risk assessment sheets (chapter .3.7). Different levels of contamination on tomatoes harvested at different dates make up the range of contamination.

Tomatoes touching the ground

The basis for calculation of the contamination is the content of E.coli in the top soil at the time of harvest. The amount of soil sticking to tomatoes is set to 5-10 mg/100 g. The value is used directly in the risk assessment sheets.

Potatoes

The basis for calculation of the contamination is the content of E.coli at the depth of the potatoes [alternatively, the highest/average concentration in the topsoil, because they are mixed with the soil when dug up]. The average amount of soil sticking to potatoes is estimated to be 10-50 mg/100 g. In reality this is a gross over-estimation because peeling of potatoes decreases to contamination by 2 decades and boiling by 6-7 decades, so the actual risk when eating the potato is extremely small.

Exposure of farmers

The range of concentrations obtained in the topsoil over the season is used as a basis for the calculation of risk to the farmer (see chapter 3.7.)

General considerations

In rough values the acceptable contamination of E.coli is approximately 10^5 E.coli/100 g soil for highly mechanised agriculture, 10^4 E.coli/100 g soil for labour-

intensive agriculture and 10^2 E.coli/100 g soil or 10^2 E.coli/100 ml water when consumer safety is considered. For information and comparison with DSS-results, the WHO-recommended values for pathogen reduction achievable by various health protection measures are listed in Table 3.32.

Table 3.32: Pathogen reduction achievable by various health protection measures. Modified from WHO guidelines

Control measure	Pathogen reduction (log units)	Notes
Sprinkler irrigation	0	
Localized (drip) irrigation (low growing crops)	2	Root crops and crops such as lettuce that grow just above, but partially in contact with the soil
Localized (drip) irrigation (high-growing crops)	4	Crops, such as tomatoes, the harvested part of which are not in contact with the soil
Pathogen die-off	0.5-2 per day	Die-off on crop surfaces that occurs between the last irrigation and consumption. The log unit reduction achieved depends on climate (temperature, sunlight, intensity, humidity), time, crop type, etc.
Produce washing with water	1	Washing salad crops, vegetables and fruit with clean water
Produce disinfection	2	Washing salad crops, vegetables and fruit with a weak disinfectant solution and rinsing with clean water
Produce peeling	2	Fruits, root crops
Produce cooking	6-7	Immersion in boiling or close-to-boiling water until the food is cooked ensures pathogen destruction

3.7 Risk assessment for microbes

3.7.1 Background

The method applied is based on the WHO guidelines for safe use of wastewater, excreta and greywater – in agriculture (WHO, 2006).

The WHO-guideline is based on health based targets:

The starting point for the development of health-based targets related to wastewater use in agriculture is the tolerable additional burden of disease. This is expressed as Disability Adjusted Life Years (DALY) and reflects the time lost because of disability or death as a result of disease.

The disease burden of ≤1 × 10^{-6} DALY loss per person per year (pppy) is converted for each wastewater-related pathogen of concern to the corresponding tolerable risk of disease pppy.

In the WHO guidelines, health targets are based on rotavirus, Campylobacter and Cryptosporidium concentrations. For Helminth eggs, an additional water quality standard of ≤ 1 egg per litre is set.

Rotavirus, Campylobacter and Cryptosporidium concentrations are normally not directly measured in water or soil. Therefore the concentrations of the faecal indicator *E. coli* are used to estimate the concentration of rotavirus, Campylobacter and Cryptosporidium.

Based on the concentration in the water and the calculated health target the required Log reduction in pathogen concentrations in irrigation water is calculated. In practice this will differ between crops, depending on consumption pattern. Assuming a typical *E. coli* concentration of 10^8 in untreated wastewater, the WHO guidelines show that for agricultural workers in (highly) mechanised agriculture a 3 Log reduction *E. coli* concentrations needs to be achieved and 4 Log reduction for labour intensive agriculture conditions. For crops consumed uncooked a 6-7 Log reduction might be required. However, while some of the reduction could be achieved as a result of wastewater treatment technology, natural decay on the crop or in the soil also takes place. Treatments done in the household (washing, peeling) is not included in this model, although it will affect the actual risk to the consumer.

3.7.2 Implementation in the DSS

The risk assessment is carried out with the help of spreadsheets designed to calculate the risk of disease, which for rotavirus, campylobacter and cryptosporidium must not exceed 1*10^{-3}. The spreadsheets are based on formulas and descriptions given in WHO (2006). The in-build dose-response models are:

(a) B-Poisson dose-response model (for Camphylobacter and rotavirus)

$$P_l(d) = 1 - [1 + (\frac{d}{ID_{50}})(2^{\frac{1}{\alpha}} - 1)^{-\alpha}$$

(b) Exponential dose-response model (for Cryptosporidium)

$$P_l(d) = 1 - \exp(-rd)$$

(c) Annual risk of infection

$$P_{l(A)}(d) = 1 - [1 - P_l(d)]^n$$

where

$P_I(d)$ = risk of infection in an individual exposed to (via ingestion in this case) a single pathogen dose d.

$P_{I(A)}(d)$ =annual risk of infection in an individual from n exposures per year to the single pathogen dose d.

ID_{50} = the median infective dose, 6.17 for rotavirus, 896 for Campylobacter.

α and r = pathogen "infectivity constants". α = 0.253 for rotavirus and 0.145 for Campylobacter, r = 0.0042 for Cryptosporidium.

The value of $P_{I(A)}(d)$ is in the range 0-1. If it is equal to 1, infection is certain.

Within the spreadsheet, the daily dose for consumers is calculated as a function of E.coli on the produce, the amount consumed per day, the reduction in contamination as a function of time between harvest and consumption, and the disease infection ratio.

Similarly, a risk for farmers is calculated based on an assumed quantity of soil ingested per day, the number of working days per year and the disease infection ratio.

Figure 3.14 and Figure 3.15 show a view of the first and second sheet of the spreadsheet "QMRA-MC_UnrestrictedIrrigation_2". The spreadsheet is made for lettuce and had to be adjusted for the crops used for SAFIR. The upper part of the spreadsheets is identical, while the lower part refers to parameter values for pathogens, described earlier on. The resulting values should preferably all be lower than 10^{-3}, as this signifies an acceptable disease-risk.

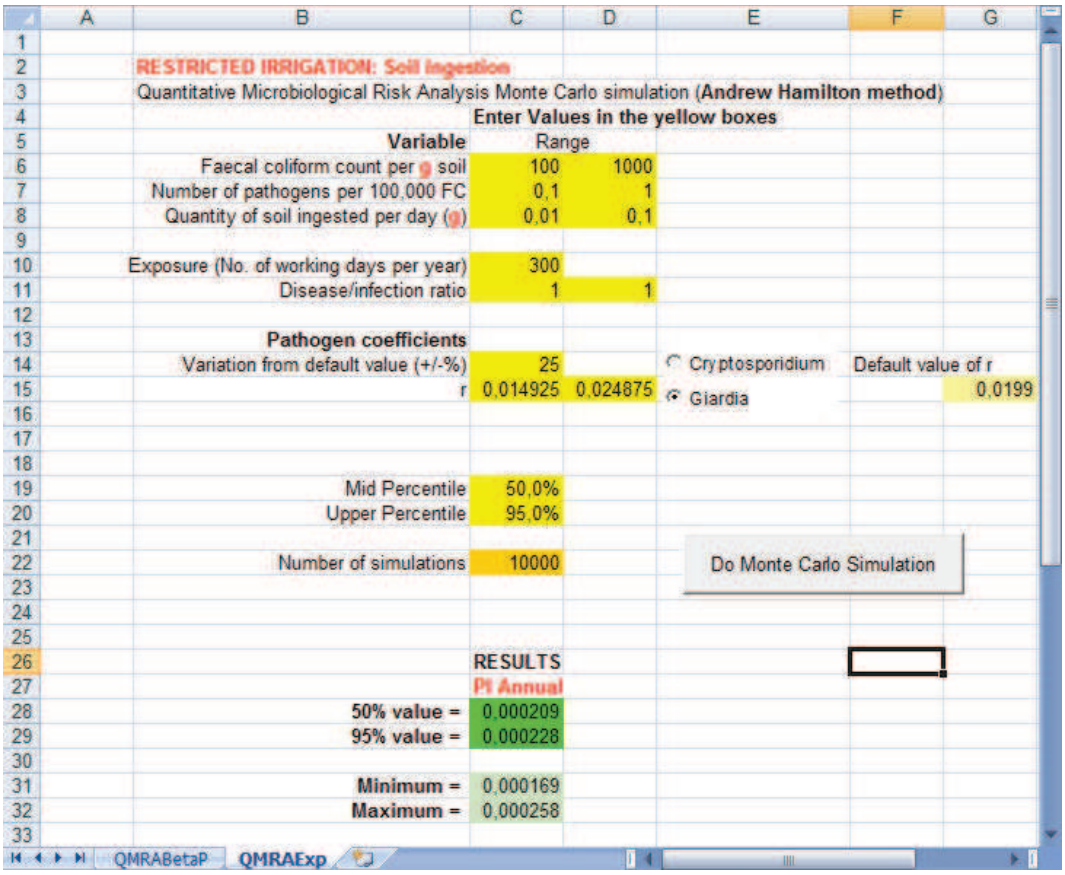
The key issue is therefore how to adapt the crop- and place-specific parameters for use in the DSS. An attempt to do this is for the prototype DSS for tomatoes and potatoes in Italy is shown in Table 3.33.

Exposure figures are transferred from the exposure model. As the exposure model calculates contamination on the tomatoes due to several irrigations and die-off from last irrigation to harvest, rather than assuming a certain amount of water on the tomatoes, the input will be in FC per 100 g fresh tomatoes and the amount of water on the tomatoes has to be given as 100 mm. For potatoes, the contamination comes in the form of a number of mg of soil. The amount of soil present on the potatoes will vary considerably depending on soil type and moisture content at harvest, but it is unrealistic to assume that the consumer will eat this. The rather low value of 10-15 mg has been assumed, probably entering the consumer through cross contamination or dirt on hands. The potatoes will be peeled and boiled and will, in themselves, never pose a pathogen risk. The same is more or less true for processing tomatoes. The risk assessment will be carried out for the processing tomatoes if eaten raw.

As the prototype DSS is tested on the Italian field site, consumption figures from Italy were included. Consumption figures will be place-specific and therefore changed if the model is used on other sites.

	A	B	C	D	E	F	G	H
1								
2		**UNRESTRICTED IRRIGATION: Lettuce ingestion**						
3		Quantitative Microbiological Risk Analysis Monte Carlo simulation (**Andrew Hamilton method**)						
4			**Enter Values in the yellow boxes**					
5		**Variable**	Range					
6		Faecal coliform count per 100 ml	1	10				
7		No.of pathogens per 100,000 FC	1	10				
8		Water on 100 g lettuce (ml)	10	15				
9		Quantity of lettuce consumed (g/day)	50	150				
10		Reduction factor (n log)	1	3	Factor	0.1	0.001	
11		Exposure (every n days)	2	2	Exposure (days/year)	182.5	182.5	
12		Disease/infection ratio	1	1				
13								
14		**Pathogen coefficients**						
15		Variation from default value (+/-%)	25		○ Rotavirus	Default values:		
16		N_50	4.6275	7.7125	○ Salmonella	N_50	6.17	
17		Alpha	0.18975	0.31625	○ Shigella	Alpha	0.253	
18								
19					○ Campylobacter			
20		Mid Percentile	50.0%		○ Vibrio cholerae			
21		Upper Percentile	95.0%					
22								
23		Number of simulations	1000		Do Monte Carlo Simulation			
24								
25								
26			**RESULTS**					
27			**PI Annual**					
28		**50% value =**	9.742E-05					
29		**95% value =**	0.0001214					
30								
31		**Minimum =**	6.365E-05					
32		**Maximum =**	0.0001465					
33								
34								

Figure 3.14: View of the risk calculation spreadsheet: QMRA-MC_UnrestrictedIrrigation_2, sheet 1 on which the calculations of risk to consumers is based. Pathogen parameters change as the different pathogens are selected.



	A	B	C	D	E	F	G
1							
2		RESTRICTED IRRIGATION: Soil Ingestion					
3		Quantitative Microbiological Risk Analysis Monte Carlo simulation (**Andrew Hamilton method**)					
4			**Enter Values in the yellow boxes**				
5		**Variable**	Range				
6		Faecal coliform count per g soil	100	1000			
7		Number of pathogens per 100,000 FC	0,1	1			
8		Quantity of soil ingested per day (g)	0,01	0,1			
9							
10		Exposure (No. of working days per year)	300				
11		Disease/infection ratio	1	1			
12							
13		**Pathogen coefficients**					
14		Variation from default value (+/-%)	25		○ Cryptosporidium	Default value of r	
15		r	0,014925	0,024875	◉ Giardia		0,0199
16							
17							
18							
19		Mid Percentile	50,0%				
20		Upper Percentile	95,0%				
21							
22		Number of simulations	10000		Do Monte Carlo Simulation		
23							
24							
25							
26			**RESULTS**				
27			**Pf Annual**				
28		**50% value =**	0,000209				
29		**95% value =**	0,000228				
30							
31		**Minimum =**	0,000169				
32		**Maximum =**	0,000258				
33							

QMRABetaP | QMRAExp

Figure 3.15: ***View of the risk calculation spreadsheet: QMRA-MC_UnrestrictedIrrigation_2, sheet 2, on which the calculations of risk to consumers is based. Pathogen parameters change as the different pathogens are selected.***

Table 3.33: Suggested changes in parameter values when applying the QMRA-MC_UnrestrictedIrrigation_2-spreadsheet in the SAFIR DSS prototype.

UNRESTRICTED IRRIGATION: Lettuce ingestion				Fresh Tomato ingestion	Potato ingestion/Processing tomato
Quantitative Microbiological Risk Analysis Monte Carlo simulation (**Andrew Hamilton method**)					
	Enter Values in the yellow boxes				
Variable	Range				
Faecal coliform count per 100 ml	1	10		From the exposure calculation, but in FC/100 g produce. Range over harvest dates.	From exposure calculation, in FC/100 mg soil, max and median amount in topsoil (0-25 cm) between 1st irrigation and harvest
No.of pathogens per 100,000 FC	1	10		Unchanged: Standard values are 1-10 rotavirus and campylobacter/10^{-5} FC and 0.1-1 Cryptosporidium/10^{-5}	Unchanged: Standard values are 1-10 rotavirus and campylobacter/10^{-5} FC and 0.1-1 Cryptosporidium/10^{-5}
Water on 100 g lettuce (ml)	10	15		The model input value is already in FC/100 g produce.The value is set to 100 ml to obtain the right value for further calculations	10-15 mg soil/100 g potato due to cross contamination or contaminated hands. 5-10 mg/soil/100 g processing tomato.
Quantity of lettuce consumed (g/day)	50	150		Data from WP5: 100-150 g/day every other day for Crete and Italy, Serbia every 3 days	WP5: 100 g/day every 3 days for Italy. Range: 100-150g/day For tomato, data for fresh tomatoes are used.
Reduction factor (n log)	1	3		Die-off between harvest and consumption(standard 10^{-2}-10^{-3} rotavirus and camphylobacter	Due to soil protective environment and moist dark storage conditions: lower range for die-off: 10^{0} and 10^{-1}
Exposure (every n days)	2	2		For Italy: every other day	For Italy, potato: every three days For Italy, p.tomato: every three days.
Disease/infection ratio	1	1		Standard values.	Standard values

*Data from Leoni et al. (1995) for Rome indicate 41 g fresh tomato/person/day and 54 g potato/person/day. For USA a comparative figure for intake of fresh tomatoes is 22 g/person/day (Willcox,et al., 2003).

Similarly, the risk to farmers using wastewater for irrigation is calculated. Figure 3.16 shows the first sheet of the spreadsheet used. As before, the upper part of the spreadsheet concerns local exposure and the second part the parameters of the pathogens. As before, the PI-Annual value should be below $1*10^{-3}$ to be acceptable.

	A	B	C	D	E	F	G
1							
2		**RESTRICTED IRRIGATION: Soil ingestion**					
3		Quantitative Microbiological Risk Analysis Monte Carlo simulation (**Andrew Hamilton method**)					
4			**Enter Values in the yellow boxes**				
5		**Variable**	Range				
6		Faecal coliform count per **g** soil	1.00E+02	1.00E+03			
7		Number of pathogens per 100,000 FC	0.1	1			
8		Quantity of soil ingested per day (**g**)	0.01	0.1			
9							
10		Exposure (No. of working days per year)	300				
11		Disease/infection ratio	1	1			
12							
13		**Pathogen coefficients**			○ Rotavirus		
14		Variation from default values (+/-%)	25		○ Campylobacter	Default values	
15		N_50	4.6275	7.7125	○ Vibrio cholerae	N_50	6.17
16		Alpha	0.18975	0.31625	○ Shigella	Alpha	0.253
17					○ Salmonella		
18							
19		Mid Percentile	50.0%				
20		Upper Percentile	95.0%				
21							
22		Number of simulations	10000		Do Monte Carlo Simulation		
23							
24							
25							
26			**RESULTS**				
27			**PI Annual**				
28		**50% value =**	0.032565				
29		**95% value =**	0.035773				
30							
31		**Minimum =**	0.026559				
32		**Maximum =**	0.039924				
33							

Figure 3.16: View of the risk calculation spreadsheet: QMRA-MC_RestrictedIrrigation_2, sheet 1 on which the calculations of risk to farmers is based. Pathogen parameters change as the different pathogens are selected.

In Table 3.34 suggested parameter values for the DSS-prototype are specified. Risk is differentiated between highly mechanised agriculture and labour intensive agriculture as described in WHO(2006). The main parameters to change are mg of soil ingested and the number of days exposed, which also depends on the period irrigation is carried out. For the Italian case, a value of 115 days is expected to be suitable.

The modified spreadsheets: QMRA-MC_UnrestrictedIrrigation_Tomatoes, QMRA-MC_UnrestrictedIrrigation_Potatoes and QMRA-MC_RestrictedIrrigation_Safir_workers are implemented in the DSS.

*Table 3.34: **Suggested changes in parameter values when applying the QMRA-MC_RestrictedIrrigation_2-spreadsheet in the SAFIR DSS prototype. Parameters are suggested for highly mechanised agriculture and for labour intensive agriculture.***

RESTRICTED IRRIGATION: Soil ingestion						
Quantitative Microbiological Risk Analysis Monte Carlo simulation (**Andrew Hamilton method**)						
	Enter Values in the yellow boxes			Risk assessment, highly mechanized agriculture, WHO (2006)	Risk assessment , labour intensive agriculture, WHO (2006)	Safir sites
Variable	Range					
Faecal coliform count per **g** soil	1.00E+02	1.00E+03				From model, specify range, topsoil
Number of pathogens per 100,000 FC	0.1	1		1-10 rotavirus and campylobacter/10^{-5} FC and 0.1-1 Cryptosporidium/10^{-5} FC	1-10 rotavirus and campylobacter/10^{-5} FC and 0.1-1 Cryptosporidium/10^{-5} FC	Unchanged:
Quantity of soil ingested per day (**g**)	0.01	0.1		1-10 mg/pers/day,	10-100 mg/pers/day	1-10 mg/pers/day,
Exposure (No. of working days per year)	300			100	300	105-125 days, site dependant
Disease/infection ratio	1	1		Standard value.	Standard value	Unchanged

3.8 Profit calculations in the DSS-model

3.8.1 Method of application

Profit calculations are carried out after the crop has been harvested. The calculation is simple and builds on the work carried out and data collected in WP6. In short, the value of the harvest is calculated as a product of the quantity produced and a (time-varying) price, and compared to the costs involved in irrigation and fertigation.

The inputs required are

- The area irrigated,
- Fixed costs and costs per m^3 related to each water source,
- Fixed costs and costs per kg N related to fertilizer and fertigation solution
- Price of the harvested crop, which is typically varying over time.

With respect to water sources, the fixed costs may be depreciation of equipment of different types; while the cost per m^3 could be a cost paid to the water authorities or be related to filters, energy or labour cost. The prices can be specified by the user, but some guide values from the test sites are included.

The amount of water used per source is calculated in the Water Source Administration Module.

As the main nutrient evaluated in the system is N, the cost of artificial fertilizer is evaluated in cost per kg N. It is possible to to include the cost of spreading the fertilizer. For fertigation, there may be a cost of establishment of the system that requires depreciation. In addition, there will be a cost per kg N applied.

The amount of N used is available from the Irrigation and Fertigation module.

Typically, the price of a crop depends on the quality of the crop. A fraction of the crop has to be allocated to each quality class as the model cannot calculate a fraction.

The data of the project does not allow a reliable prediction of crop quality and how dirty the crop is at harvest, so these factors cannot be taken into account in the assessment. Microbial contamination could, in principle, be included; if e.g. a washing process was to be included in order to sell the produce.

In reality, such an addition does not make much sense for the crops selected. Both processing tomatoes and potatoes are boiled, which means that microbial contamination is less important. The fresh tomatoes are situated above the ground and if irrigation ceases some days before harvest, the microbial risk is rather low.

The price does, however, vary over the season and this can be taken into account. Particularly the price of fresh tomatoes varies with availability. For processing tomatoes the farmer usually has a contract with a company with a fixed price. For potatoes it depends on the market if the variation is important or not (due to the fact that potatoes can be stored better than tomatoes).

It could be argued that if wastewater is used, the saved cost of P-fertilizer due to use of wastewater should be added to the earnings.

The spreadsheet used for the calculations are shown in Figure 3.17. Data on water and fertiliser use as well as of production is exported from the DSS-calculations, while prices are stored in separate tables. The yellow cells in the top column has to be filled out by the user.

Costs and earnings

Site	Italy	Irr type	Drip_surface	Strategy	FI or PrD* PRD	crop	potato
Filters, source 1							
Filters, source 2	GF	HMR	UV				

* if DI, write FI as investment costs are identical. Differences in water use are accounted for automatically

Investment costs						
Pumps, pipes etc.					2071.00	€/ha
Running costs			price			
labour	48	h/ha	7.5	€/hour		€/ha
Water use	from sim.					
- source 1	580	m3/ha	0.02	€/m3	11.60	€/ha
- source 2	500	m3/ha	0.01	€/m3	5.00	€/ha
Energy use	896.4	kWh/ha	0.12	€/kWh	107.57	€/ha
(calc. From water s1)	0.83	kWh/m3				
(calc. From water s2)	0.83	kWh/m3				
Filter costs, source 1						
- filter 1	580	m3/ha		€/m3		€/ha
- filter 2	580	m3/ha		€/m3		€/ha
- filter 3	580	m3/ha		€/m3		€/ha
Filter costs, source 2						
- filter 1	500	m3/ha	0.0075	€/m3	3.75	€/ha
- filter 2	500	m3/ha	0.06	€/m3	30	€/ha
- filter 3	500	m3/ha	0.01	€/m3	5	€/ha
Fertilizer cost						
- labour, tractor	1	No.of passes	3	€/ha	3.00	€/ha
- fertilizer	40	kg N/ha	0.7	€/kg N	28.00	€/ha
- fertigation solution	100	kg N/ha	0.7	€/kg N	70.00	€/ha
Total, running costs					263.92	€/ha

Total costs					**2334.92**	€/ha
Production						
- class I	5000	kg/ha	0.16	€/kg	800.00	€/ha
- class II	20000	kg/ha	0.24	€/kg	4800.00	€/ha
- class III		kg/ha		€/kg		€/ha
Premium					0.00	
Total earnings					5600.00	
Profit					3265.08	

Figure 3.17 Overview of the farm profit calculation in the prototype management model.

3.8.2 Farm unit costs

All farm unit cost information has been received from WP6 or WP1. The tables created and used to back up the cost calculation are shown below.

Investment costs, pump, pipes etc.

€/ha		CAU Tomato	CAAS Potato	Serbia Potato	Italy Tomato	Italy Potato	Crete Tomato
Drip, surface	FI	532	836	2125	1404	1404	613
Drip, surface	PRD	1032	1236	3173	2071	2071	920
Drip, subsurface	FI	532	836	2125	1404	1404	613
Drip, subsurface	PRD	1032	1236	3173	2071	2071	920
Sprinkler						150	
Furrow							

Labour, hours

hours		CAU Tomato	CAAS Potato	Serbia Potato	Italy Tomato	Italy Potato	Crete Tomato
Drip, surface	FI	16	50	18	10	10	10
Drip, surface	PRD	21	65	32	48	48	48
Drip, subsurface	FI	16	50	18	10	10	10
Drip, subsurface	PRD	21	65	32	48	48	48
Sprinkler							
Furrow							

Labour, price

€/hour		CAU	CAAS	Serbia	Italy	Crete	
labour cost		0.6	0.6	1.5	7.5	5	

Water source cost

€/ha		CAU	CAAS	Serbia	Italy	Crete	
source 1		0.02	0.01	0	0.02	0.1	
source 2		0.01	0.005	0	0.01	0.05	assumed

Energy consumption /m3 of water

€/m3	CAU	CAAS	Serbia	Italy	Crete	
source 1	0.29	0.12	0.3	0.83	0.34	
source 2	0.29	0.12	0.3	0.83	0.34	

Electricity, cost/kWh

€/kWh	CAU	CAAS	Serbia	Italy	Crete
electricity cost	0.08	0.05	0.12	0.12	0.12

Filters, cost

€/m3	CAU	CAAS	Serbia	Italy	Crete	
gravel filter	0.0075	0.0075	0.0075	0.0075	0.0075	GF
heavy metal dev.	0.06	0.06	0.06	0.06	0.06	HMR
UV	0.01	0.01	0.01	0.01	0.01	UV
MBR	0.33	0.33	0.33	0.33		MBR

Cost of spreading fertilizer by tractor

€/ha	CAU	CAAS	Serbia	Italy	Crete	
tractor+labour cost	1	1	2	3	4	assumed

Cost of fertilizer

€/kg N	CAU	CAAS	Serbia	Italy	Crete	
"solid fertilizer"	0.3	0.3	0.8	0.7	0.7	assumed
fertigation solution	0.3	0.3	0.8	0.7	0.7	assumed
						Except for Italy

Crop prices

€/kg	CAU	CAAS	Serbia	Italy	Crete
potato					
grade 1				0.16	
grade 2				0.24	
grade 3				0.24	
tomato, proc					
grade 1				0.9687	
grade 2				0.8097	
grade 3					
premium/ha				1400	
tomato, fresh					
grade 1				2.65	
grade 2					
grade 3					

3.9 User Guide, taking into Account that it is a Prototype.

Running the prototype management model has a number of pre-requisites that includes:

1. Installation of Mike Zero
2. Installation of Daisy
3. Installation of the SAFIR DSS

These steps are described in the following sections.

3.9.1 Install Mike Zero

The SAFIR DDS takes advantage of a several existing software protocols from DHI's off the self products. In order to setup SAFIR DSS it is therefore required to download and install a demo version of Mike SHE version 2009 available from the link below:

http://www.dhigroup.com/Software/Download/MIKEByDHI2009.aspx

Figure 3.18 Sceendump of the Mike SHE download page

From the link there is access to Mike SHE download and installation guide. Having downloaded Mike SHE 2009 it is ready to install, in the installation process, choose demo version and the default set-up settings, consult the installation guide.

3.9.2 Install Daisy

SAFIR DSS also require an installation of Daisy version 4.73 in order to work. Daisy is accessible for download from the Daisy homepage on the link below:

http://code.google.com/p/daisy-model/

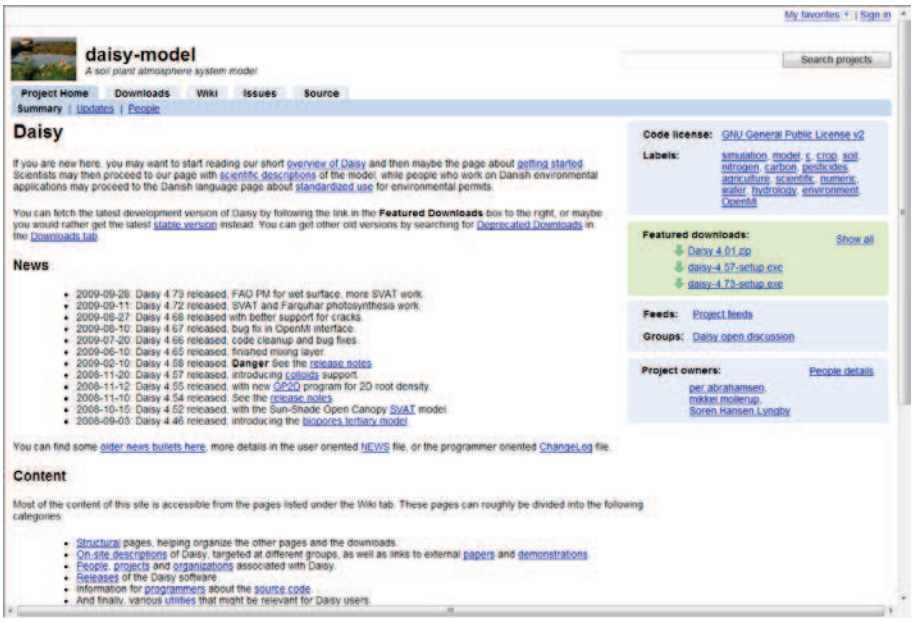


Figure 3.19 Screendump of the Daisy homepage from where Daisy is available for download.

Daisy must be installed into the default path i.e. c:\program files\

3.9.3 SAFIR DSS installation

As mentioned above a pre-requisite for installing SAFIR DSS is that Mike SHE 2009 (Demo) and Daisy version 4.73 is installed.

The prototype SAFIR DSS is downloadable from the menu tab “Results” on the SAFIR homepage, choose “Advanced DSS”. The downloaded SAFIR DSS is a zipped file named “SAFIRDSS.zip” which must be saved to c:\SAFIR\ and unzipped here.

The unzipped file contains:

1. File: DHI.Safir.Installer.msi

2. File: Safir.exe
3. Folder: Daisy files
4. Folder: Potato – Fertigation RDI - Example

Install the SAFIR DSS by running the "DHI.Safir.Installer.msi" file. Subsequently, copy the *.dai files from the folder "Daisy Files" to the folder c:\program files\Daisy473\lib and then the SAFIR DSS system is installed and ready to use.

3.9.4 Understanding the prototype management model file structure

When the user wants to create a new scenario, the user must copy a previous scenario folder and modify it. The folder e.g. "Potato – subdrip fertigation FI – Example" is copied through Window Explorer and then renamed and subsequently, are parameters in the database or time series files modified in order to test the wanted parameterisation.

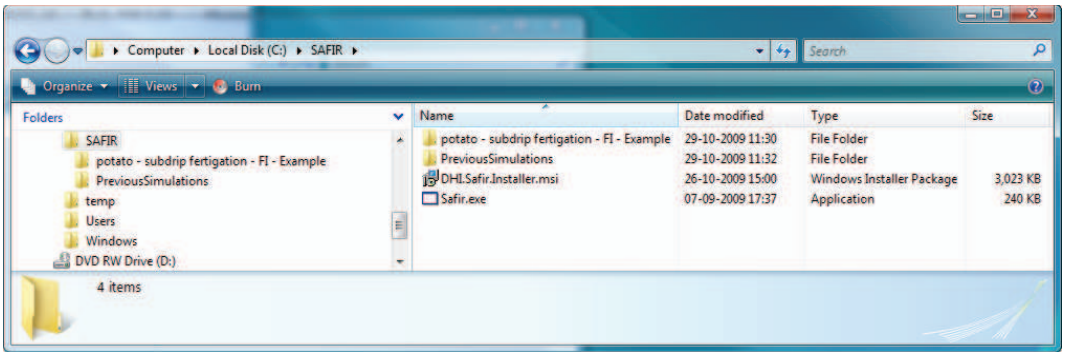


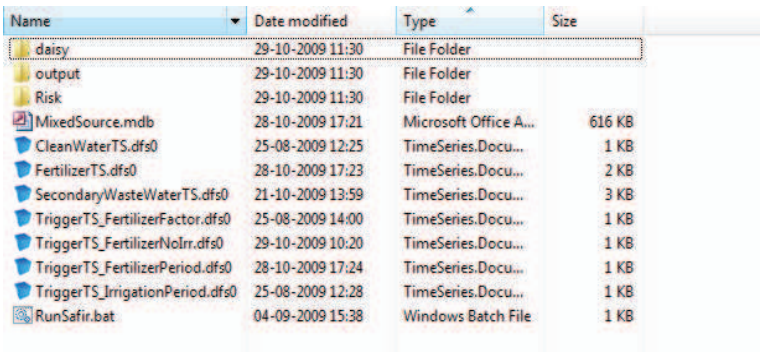
Figure 3.20 The SAFIR root directory including an example,

To execute the prototype management model the user executes the "safir.exe" stored in the root of the SAFIR folder, whereby the dialog in Figure 3.21appear. The user then clicks the folder button and points to the scenario folder in which the wanted scenario is defined and then clicks the "Start simulation" button. The management model can also be executed without use of the user interface and instead via a bat-file "RunSafir.bat" stored in the root of a scenario folder.

Depending on CPU and pc configuration a simulation will on most standard pc's last around 3-5 minutes, not much longer than a normal Daisy simulation. When the simulation has finished the result presentation Excel spreadsheet can be accessed by clicking the "Result Presentation" button or by clicking the plot.xls in the subfolder "Output" c.f. Figure 3.22.

Figure 3.21 The execution dialog of the prototype management model

Going into the root folder of a scenario folder it contains three folders and nine files that allow the user to specify settings for the prototype management model. The files include an Access database called “MixedSource.mdb”, which hold settings for a number of variables linked to the water administration. Changing settings in the database require that Microsoft Access is installed on the computer.



Name	Date modified	Type	Size
daisy	29-10-2009 11:30	File Folder	
output	29-10-2009 11:30	File Folder	
Risk	29-10-2009 11:30	File Folder	
MixedSource.mdb	28-10-2009 17:21	Microsoft Office A...	616 KB
CleanWaterTS.dfs0	25-08-2009 12:25	TimeSeries.Docu...	1 KB
FertilizerTS.dfs0	28-10-2009 17:23	TimeSeries.Docu...	2 KB
SecondaryWasteWaterTS.dfs0	21-10-2009 13:59	TimeSeries.Docu...	3 KB
TriggerTS_FertilizerFactor.dfs0	25-08-2009 14:00	TimeSeries.Docu...	1 KB
TriggerTS_FertilizerNoIrr.dfs0	29-10-2009 10:20	TimeSeries.Docu...	1 KB
TriggerTS_FertilizerPeriod.dfs0	28-10-2009 17:24	TimeSeries.Docu...	1 KB
TriggerTS_IrrigationPeriod.dfs0	25-08-2009 12:28	TimeSeries.Docu...	1 KB
RunSafir.bat	04-09-2009 15:38	Windows Batch File	1 KB

Figure 3.22 Files in the root directory of a scenario folder in the prototype management model.

In addition to the database the user can adjust a number of settings related to the irrigation and fertigation strategy via*.dfs0 files.

1. **CleanWaterTS.dfs0** – Specifies the flow [m^3/s] from the clean water source.
2. **FertilizerTS.dfs0** - Specifies the flow of the fertigation source [m^3/s] and the concentration [mg/l] of its constituents including the NO_3 and NH_4 and other constituents.
3. **SecondaryWasteWaterTS.dfs0** – Specifies the flow [m^3/s] of secondary waste water and the concentration [mg/l] of its constituents

4. **TriggerTS_FertilizerPeriod.dfs0** Specifies the period (days) in which the fertilizer demand is estimated
5. **TriggerFertilizerFactor.dfs0** - Specifies an extra amount [kg] of fertilizer given at each fertilizer application
6. **TriggerTS_FertilizerNoIrr.dfs0** - Specifies the amount of fertilizer deficit [kg/ha] that the DSS accumulate, before fertilization starts without irrigation. (If irrigation is initiated before, fertilizer is also applied)
7. **TriggerTS_IrrigationPeriod.dfs0** - Specifies the minimum period [days] between two consecutive irrigations

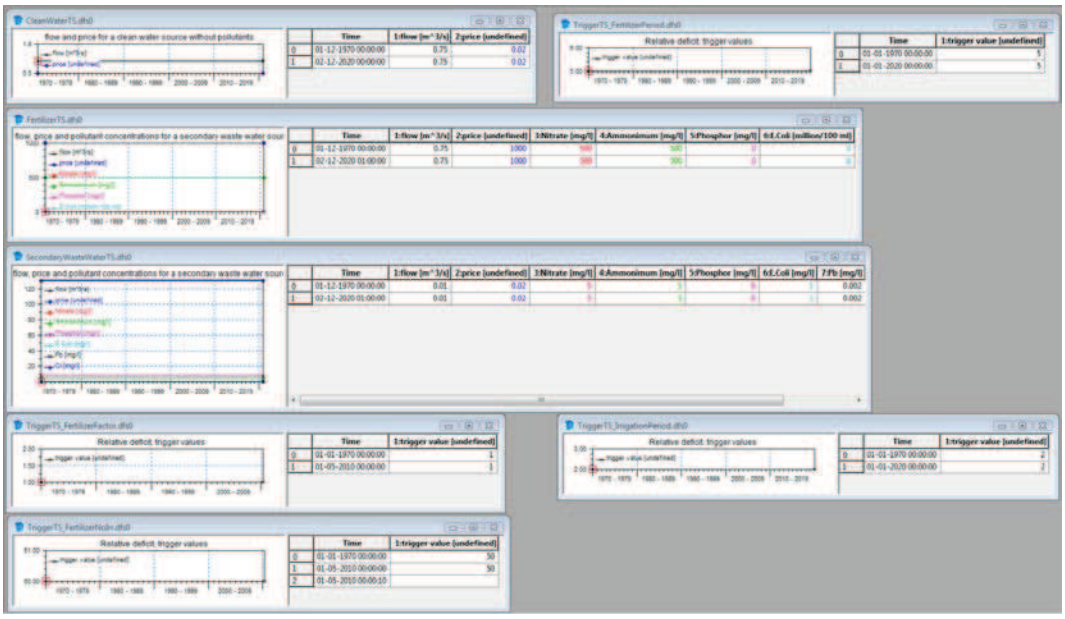


Figure 3.23 Overview of the items in the dfs0 files that allows the user to give input to the protytype DSS.

The Daisy folder contains the setup file for Daisy with the extension *.dai. The setup file includes settings for a range of parameters. For setting up Daisy the user is referred to the Daisy home page, where tutorials and reference manual are available c.f. http://code.google.com/p/daisy-model/, but in short, the Daisy setup file includes information on a range of settings such as:.

1. References to external input files,
2. OpenMI settings for corresponding with the SAFIR IFM.
3. Description of heavy metals and E. Coli,
4. Description of the soil column and its horizons
5. The lower boundary condition for the soil column

6. Description of the crop
7. Crop management that doesn't include irrigation or fertilization
8. Simulation period
9. Specification of the required output from the Daisy model

The remaining files in the Daisy folder are system files, that aren't intended for user manipulation.

The last folder named "Risk" include the spreadsheets in which the Daisy calculated soil content of E.Coli is assessed for risk towards farm workers and consumers.

3.9.5 Analyzing results from the management model

Having executed a simulation in the prototype management model, the user opens the Excel spreadsheet "Plot.xls", which includes functionality to read and present the main results.

The Excel Spreadsheet "Plot.xls" is located in the path "..\SAFIR\ScenarioName\output". When opening, remember enabling macros. The user then goes to the sheet "ResultsProcessing" where the Excel Spreadsheet then reads all the necessary raw data from into dedicated sheets and then subsequently calls the microbial risk assessment spreadsheets located in the subfolder named "risk". The main results are extracted to the sheet "Main Results" The "Plot.xls" contains an overview of the main results and a number of sheet containing the most important raw data. The Plot.xls contains the following sheets:

1. ResultProcessing
2. Main Results
3. Plot
4. AccPlot
5. FarmEconomy
6. UnitCost
7. Settings
8. HeavyMetalThresholds
9. Daisy Output
10. Safir Output
11. Processed Data
12. CleanWater
13. SWW
14. SandFilter
15. MixedWater
16. Harvest
17. Crop Production
18. Field Water
19. Field Nitrogen
20. PRD Left
21. PRD right
22. Soil E.Coli
23. Soil Pb

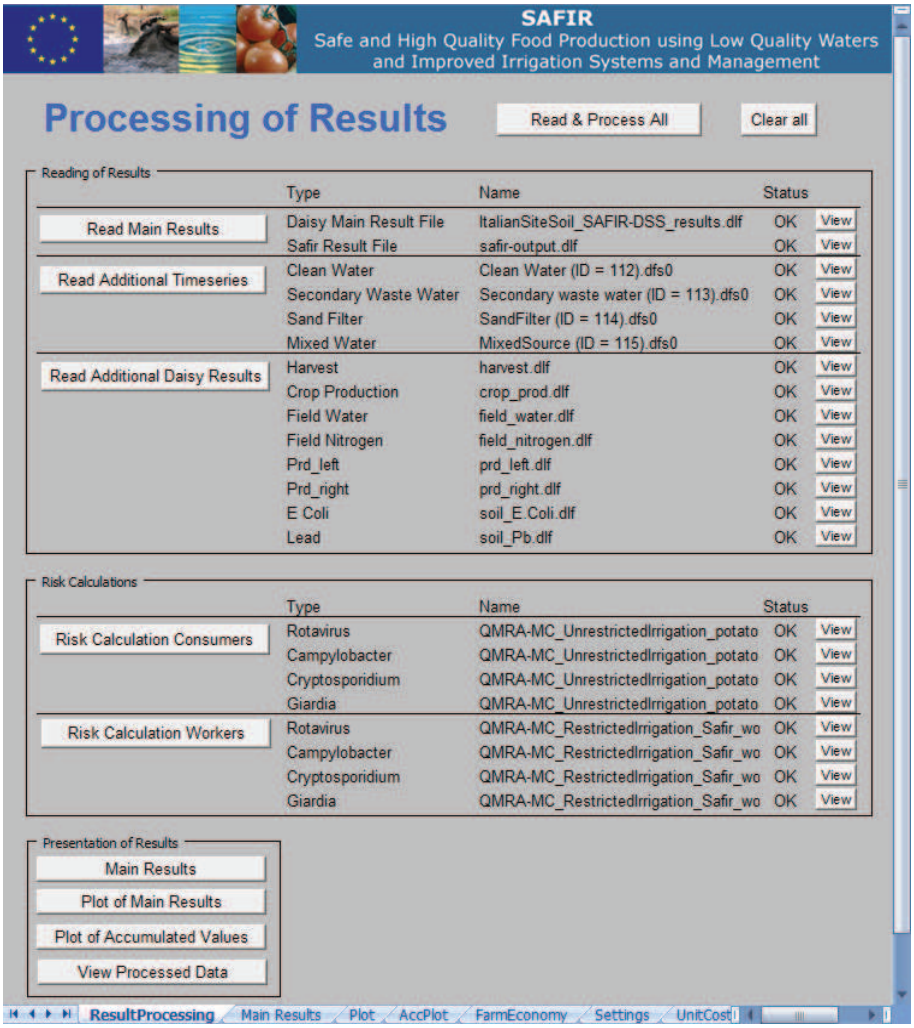


Figure 3.24 Result extraction sheet in the Excel spreadsheet distributed with the prototype management model for viewing simulation output

The workflow in viewing results from a new scenario run is as follows: Access the Result processing sheet and then push the “Clear all” button. Secondly the user can choose to Read and process all results or read them in smaller groups.via the buttons on the left side in Figure 3.24. After import and processing of results has occurred the user may view the main results and plot sheets or go into some of the raw data for in depth analysis.

3.10 Example of Use and Results

This section shows an example of using the prototype management model. The example is based on the potato crop calibrated in WP4, at the Italian field trial site CER, comprising a silty clay soil with a shallow groundwater table using the weather

data for the season 2007. The crop is sown in the middle of March 2007 and all applications of nitrogen and water are handled through the prototype management model.

In the example the available water sources are a clean water source from groundwater and a source of secondary waste water SWW, which is led through a gravel filter. The supply of water in the example is not constrained. The farmer has in this case a drip irrigation system for subsurface irrigation and fertigation.

Figure 3.25 shows the parameterization of the clean and secondary waste water source in the example. Also the parameter of the irrigation fertigation module is defined; it specifies the time period for which the fertilizer demand is estimated (2 days in the example). Furthermore it is specified that a 3 kg/ha deficit that must accumulate in the crop before fertilization starts without irrigation (if irrigation is applied) and that the minimum period between two consecutive irrigations is 2 days.

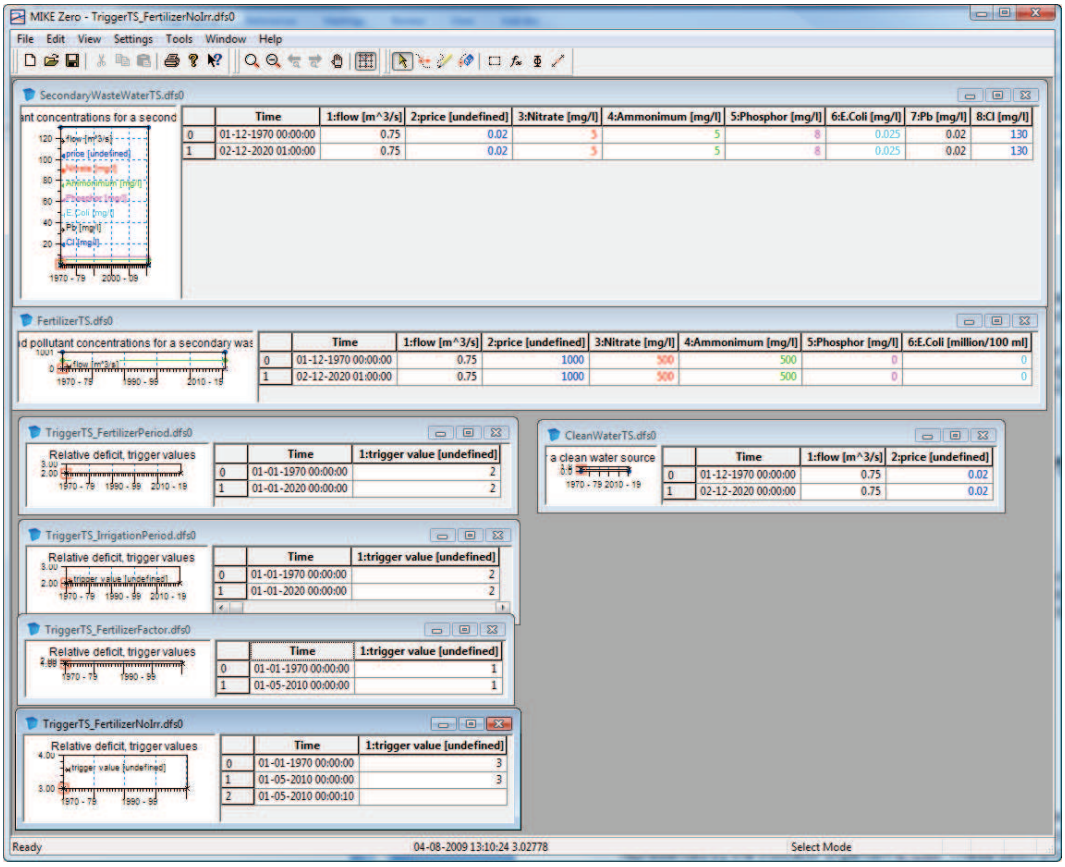


Figure 3.25 Parameterization of the water sources and irrigation fertigation module in the example

Having run the scenario and extracted the results using the “ResultProcessing” sheet in “Plot.xls” the main results are available from the “Main Result” sheet c.f. Figure 3.26. Here an overview is presented that shows accumulated amounts of applied fertilizer and nutrients applied through usage of secondary waste water. The overview also contains the total water use, crop yield (DM) and production economy.

In the example, the dry matter yield is high, resembling potential production, as it is only determined by the incoming radiation as no environmental stresses (nitrogen or water) occur, due to the prototype management model control of irrigation and fertigation.

In order to estimate the production economy, the user have to specify location, irrigation type, irrigation strategy and the crop type on the “Farm Economy” sheet. In the example the unit cost specified reflect the Italian field test site, using sub-surface drip lines and a regulated deficit irrigation strategy in potatoes.

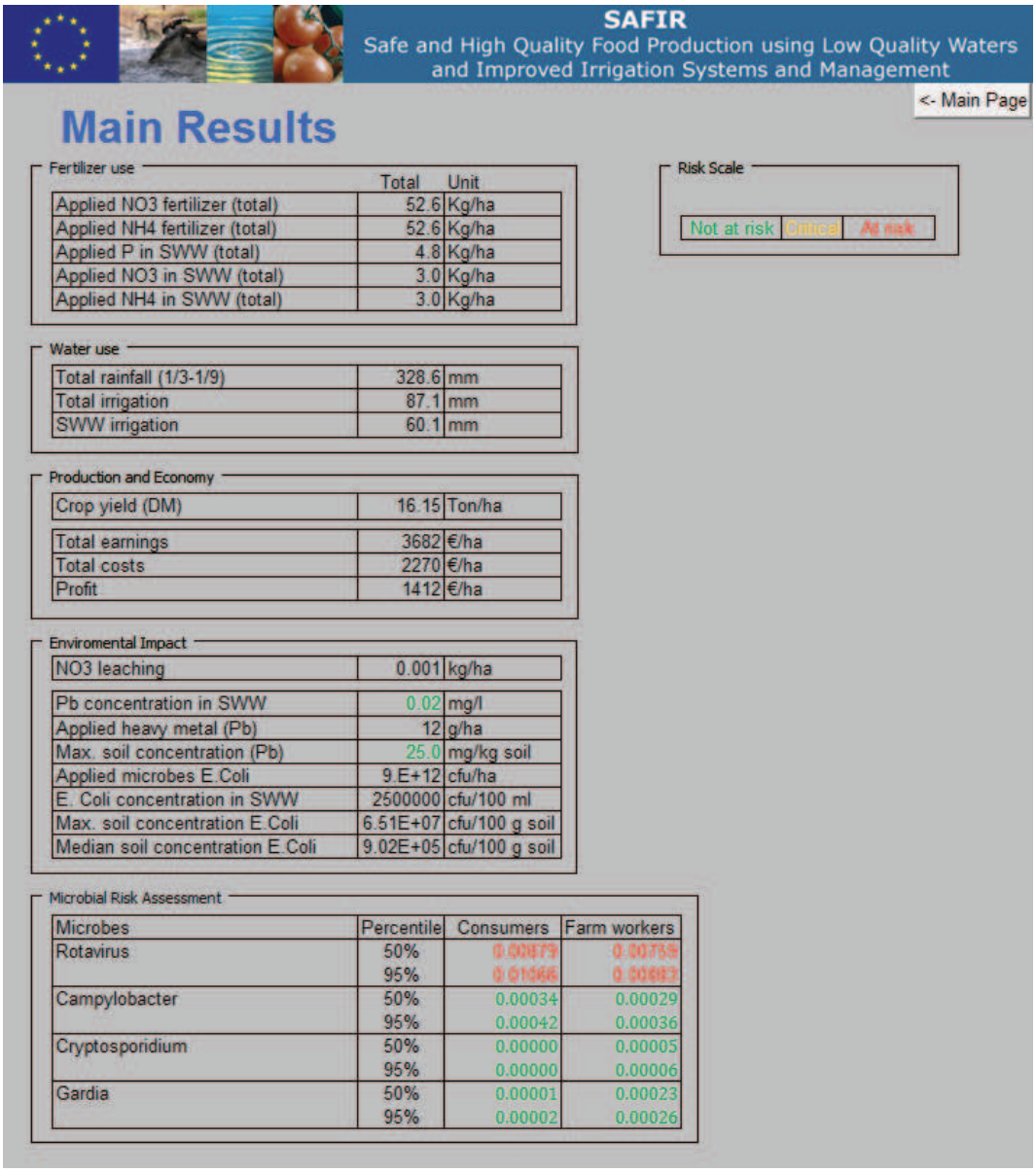


Figure 3.26 Main results from the prototype management model

Furthermore, a range of different indicators is presented, evaluating the scenarios environmental impact, including the nitrate leaching during the growth season and

Pb concentration in the waste water and in soil, which are related to thresholds for prolonged use and acute risk limits in waste water and maximum tolerable concentrations in soil.

In the example the nitrogen leaching out of the root zone is close to zero reflecting a very efficient crop uptake. The Pb concentrations in the secondary waste water and in the in soil are both evaluated within the category “not at risk”, taking into account the soil background concentration.

The microbial risk assessment is presented with traffic light colouring of the actual value i.e. highlighted green, orange or red depending on the estimated risk c.f. Figure 3.26.

Microbial risk is assessed in relation to farmers and consumers for four microbes (rotavirus, Camplylobacter, Cryptosporidium and Gardia) based on estimates of the amounts of E.Coli (indicator organism) in the applied waste water and the soil. The specific calculations for each type of microbe can be viewed in detail by clicking the respective “View” buttons on the “ResultsProcessing” sheet these will give access to the individual Excel calculations as shown in Figure 3.14 to Figure 3.16. If needed, settings in the risk calculations can be modified and the results extracted to the “Main Results” sheet.

Figure 3.27 shows some of the main time series results, including the crop development stage (A) and the rainfall and applied irrigation (B) during the crop growth season. In plot C is shown the relative soil moisture content in relation to the development stage dependent soil moisture limits, that vary according to irrigation strategy and soil hydraulic properties. Plot D show the root zone content of ammonium and nitrate and the fertilizer applications requested by the IFM module. In Plot E, is shown the resulting nitrogen status of the crop, which in this example is maintained just above the critical crop content, which minimizes excess fertilization and risk of post-harvest leaching.

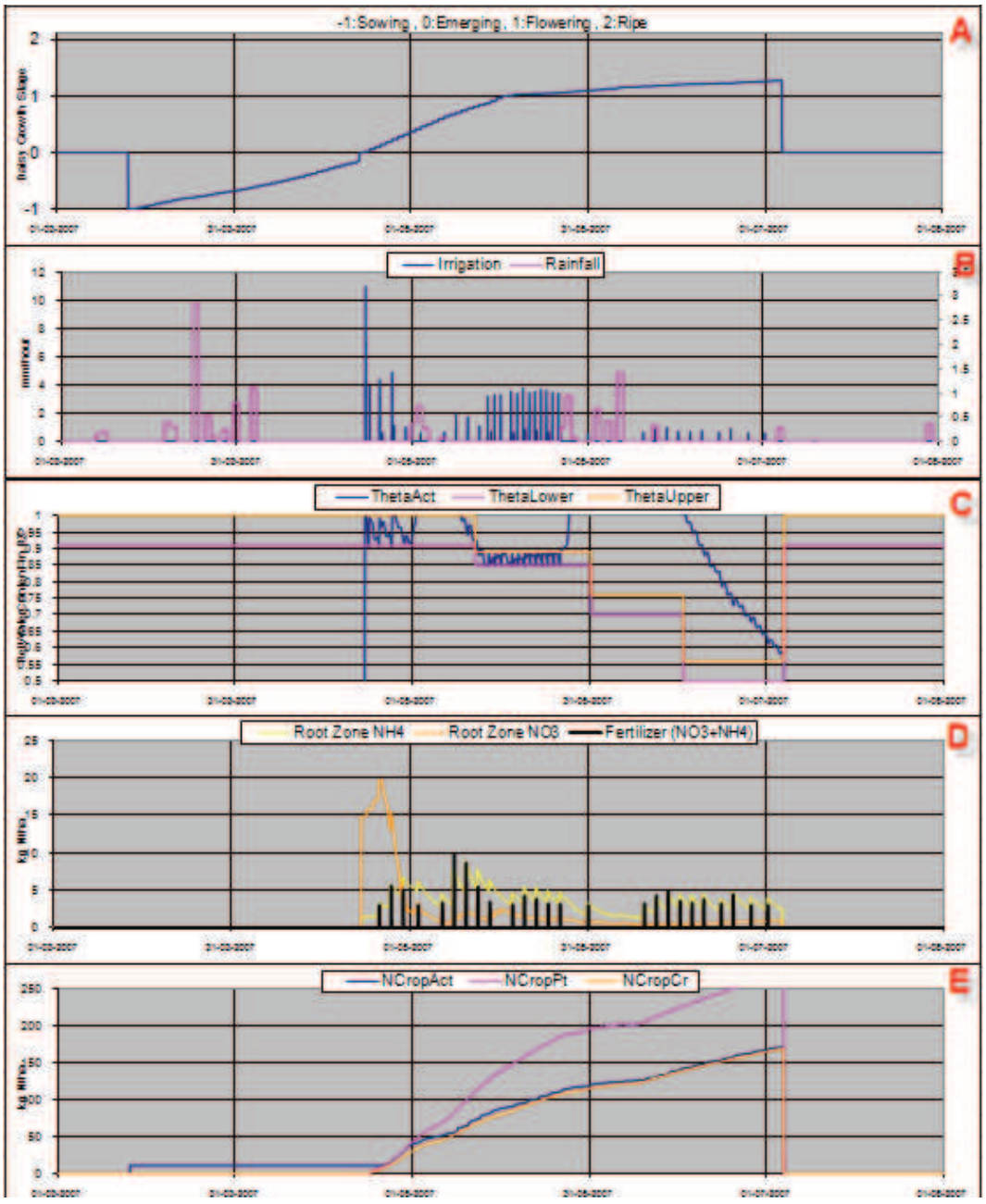


Figure 3.27 Time series plots from the prototype management model showing A) crop development stage, B) precipitation and applied irrigation, C) relative soil moisture content, D) nitrogen level in the root zone and E) nitrogen content in the crop

Figure 3.28 shows two additional environmental parameters Pb leaching (F) and the concentration of E.Coli in the top soil layer (G). In the latter plot the die off after each application with secondary waste water is seen. These concentrations are used for microbial risk assessment.

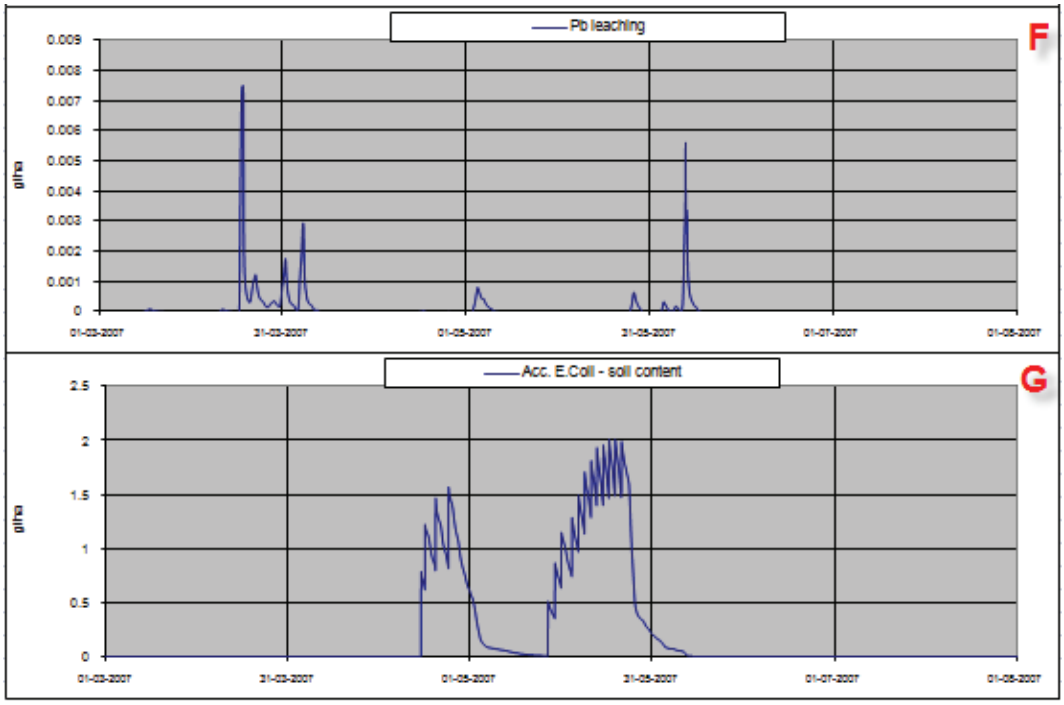


Figure 3.28 Additional time series from the management model showing F) Pb leaching from the top soil layer (0-25 cm) and G) concentration of E.Coli in the top soil layer.

In Figure 3.29 is the accumulated amounts of used fertilizer and water are plotted giving the user an overview of the consumption of resources and their distribution in time. Using the unit cost from the FarmEconomy sheet the accumulated cost on water, fertiliser, clean and waste water is calculated and also presented in plots for the user.

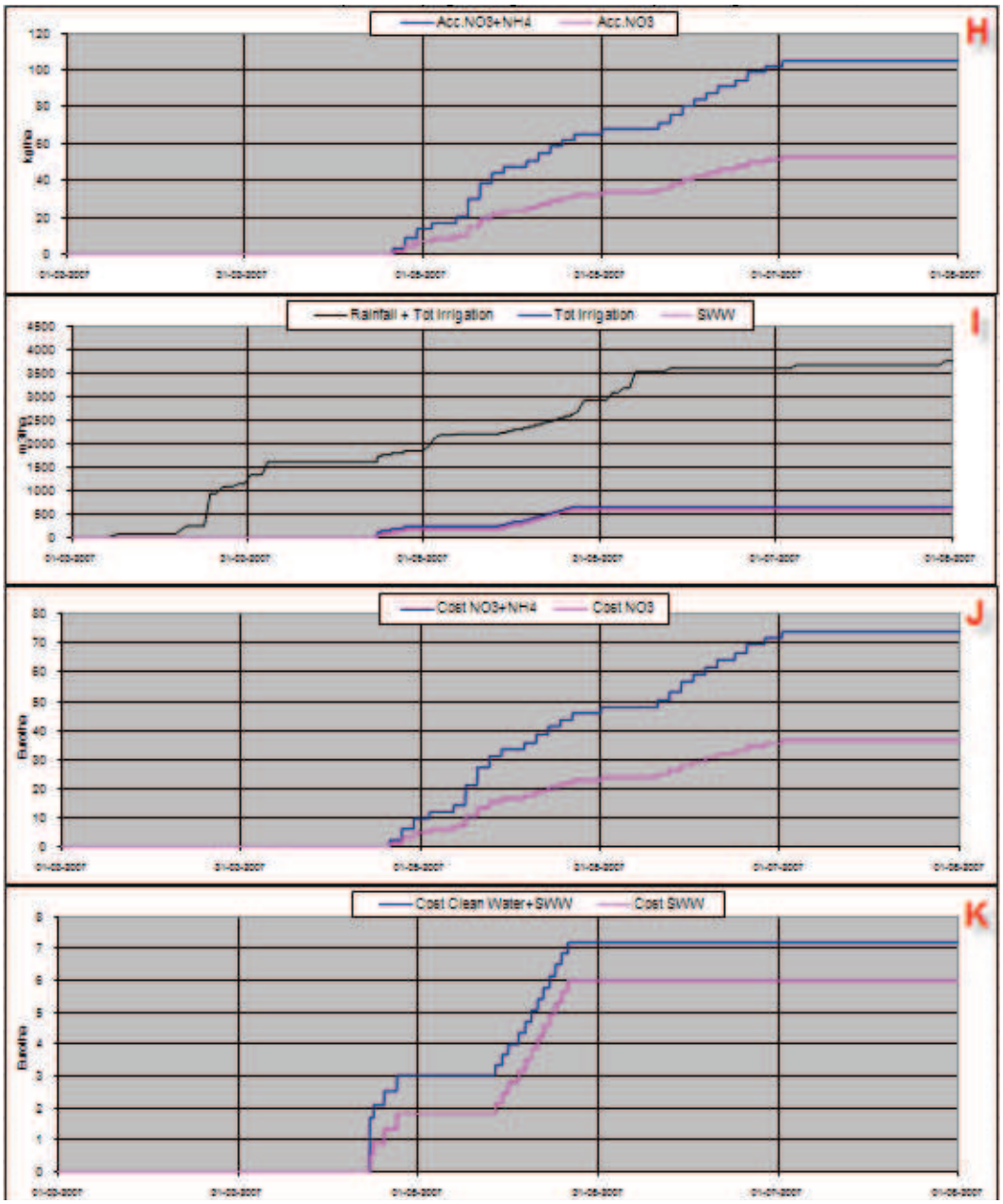


Figure 3.29 Accumulated plots in the prototype management model showing H) accumulated amounts of NH4 and NO3 I) accumulated

3.11 Possible Developments of the System

There are several options for expanding the capabilities of the prototype management model. On obvious choice of future development could be to implement more crops. In particular vegetable crops would be interesting to include as they often are irrigated due to quite high crop water requirements and also often eaten raw or without much preparation by consumers.

Ideally, the management model should also comprise a larger database of heavy metals and their soil behaviour that would allow assessment of the majority heavy metals that can be found in waste water. What heavy metals to include in the management model can, however, vary according to local conditions such as e.g. specific types of industry discharges can pose special problems that farmers and consumers should be aware of.

Similarly, modelling of additional types of microbes rather than relying on E.coli as an indicator organism could be relevant. One example could be to implement parasites, as they in many places in the world poses substantial risk to human health and welfare caused by using different types of waste water for irrigation purposes. DHI is presently involved in a recently started Ph.D (autumn 2009). study looking at issues linked to human diseases caused by parasites originating from irrigation water. Vira , which are subject to sorption rather than filtration, are another possibility.

Farmers will often have more than one field growing more than one crop, which in situations where the water resources is limited, force the farmer to prioritize how to allocate water and fertilizer in between different crops and fields. Fertilizer and water demands often develop differently due to different sensitivity in crops during their respective growth stages. Fields may also comprise different soil types with varying water holding properties or groundwater conditions. Also fields may be distributed in space and may thereby not receive equal amounts of precipitation. All these mentioned factors and more, contribute to farm heterogeneity. Developing the management model so it systematically can handle, optimize and assess management across multiple fields could comprise a promising expansion improving farmer decision support.

Water is in many parts of the world a resource that is handled and managed on a catchment scale, through local water authorities' administration. Not uncommonly this type of management involves the application of numerical surface and groundwater models, typically used for assessments of the available water resources and its usage, but not often are water quality, environmental and health issues considered. In particular, in areas where the water resources are scarce, it can be foreseen that an increasing pressure will be put on authorities to save high quality water for domestic purposes and increase usage of lower quality water e.g. different types of wastewater in the agricultural food production. Shifts in this direction will directly feed a demand for assessing the health risk to consumers and farm workers within the boundaries of water authorities' administration, in this light and in cases where existing surface and groundwater models exist it would be an option to expand the assessments to also include the concepts of the management model in order to also assess environmental aspects and health risk issues linked to the usage of lower quality water for food production on a larger catchment scale.

In addition, the prototype management model could be developed into an on-line system, where the model is updated daily with actual rainfall and irrigation/fertigation actions and five-day weather forecasts. As the Daisy model is able to hot-start from a saved result-file, there is no serious technical problem in doing so. However, development of a shell that keeps track of model runs, result files and weather forecasts is rather expensive and requires local interest and agreement with a

relevant supplier of forecast data. In this case, the basic field and crop-information would be prepared in advance and a computer-literate farmer would be able to update management information and evaluate a daily forecast.

4 REALISTIC TARGET GROUPS AND USE OF THE SYSTEM

The simple DSS is very simple to use and can be used by educated farmers or farmers' consultants to create an overview of different irrigation and fertilization strategies with and without the use of wastewater.

The prototype management model is not easily handled by farmers or consultants at this stage. There are too many different parameters to keep track of. A necessity for running the DSS is a Daisy model for the soil and crop to be modelled. Parameterised Daisy colums were created for some of the sites used in the Safir project, and can, of course, be developed for other sites. The system has been parameterised with respect to the filters tested in the Safir project. These can be used also with other soil/crop conditions, and if the performance of other filters are known, they can be included in the Access database.

The considerations for microbial contamination are general and would be applicable also under other conditions. The heavy metal simulation is possible; however, as parameters were developed only for the Crete site and only for Pb, thus generalisation is difficult. If, however, a Freundlich isotherm can be established for a given heavy metal and a given soil type, it is possible to parameterise the prototype management model to take this into account.

Presently, the management model must be considered a research system that can be applied for a location with some assistance for setting up the system. Afterwards and with training, it could be run by agricultural consultants.

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