Strategies for Orchard Irrigation in South-Western Germany under the Limitation of Meeting Instream Flow Requirements of the Used Stream

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Condensed abstract: In South-Western Germany, orchard-irrigation farming may endanger the ecological conditions of streams used for supplying irrigation water during hot and dry summers. A method is described for the quantification of the ecological requirements of a stream (using program CASiMiR) and the economic irrigation-needs of orchard-farmers (using FAO's CROPWAT). Scenarios have been created to quantitatively illustrate ranges of irrigation water deficits and ensuing yield losses. Mitigation measures such as water storage, increase of irrigation efficiencies (shift from sprinkler to drip irrigation), and irrigation deficit management have been briefly discussed.

Key words: orchard-irrigation farming, river-ecology, dry low-flow periods, irrigation-water deficit, South-Western Germany, CASiMiR, CROPWAT

1 FRUIT IRRIGATION AND LIMITED SURFACE WATER RESOURCES – THE SITUATION

1.1 Point of departure

Due to its favourable climatic and soil conditions, the region around the Lake Constance is a preferred area for growing apples, pears, hop and the like. While Germany has not been a classical irrigation country so far, fruit farmers of that region traditionally rely on sprinkler irrigation for frost protection and full water supply to the crops during the summer growing periods. Although, in principle, Germany is known to be endowed with abundant water resources, the hot and dry summers of 1997 and 2003 have triggered conflicts between fruit farmers wanting to tap their water from nearby streams and the authorities being responsible for maintaining acceptable ecological conditions in the used streams also during low flow periods: In one case, farmers applied for extended water rights and the authority in charge had problems to determine up to which low-flow threshold-value water tapping from the stream under consideration should be permitted without endangering the aquatic ecology. In an other case, low discharge-, or rather water stage-threshold values at a gauging station had been set – and prevented fruit farmers from tapping ***any*** irrigation water during the hot and dry summer months of 2003 (O-COMM 2003, 2005). However, the awareness of the problem was for both parties, fruit farmers and authorities whose concern are rivers and creeks, not yet strong enough to make them quickly seek viable, balanced solutions. But having in mind climate change with the tendency of rather worsening conditions, first advices have been requested recently.

1.2 The procedure adopted

Since, for this first study on limitations of irrigation water from streams in South-Western Germany, more precisely the Lake Constance region, no external financial means could be allocated (for reasons see above), the efforts spent had also to be adapted to this situation. Therefore, the focus has been on the elaboration of a general procedure to be followed when tackling such a real-life-problem and less on the acquisition of most accurate data for a specific site (OPATA 2004). Thus, the quantitative figures produced and presented here are meant to illustrate the procedure of *developing strategies for orchard irrigation under the limitation of meeting instream flow requirements of the used stream.*

2 THE SITE, THE ORCHARDS, LOCAL CLIMATE & THE SCHWARZACH-CREEK

2.1 Site and scenarios for orchards

The site which is to illustrate the problem of irrigation constraints due to ecological limitations of the used stream, is located in the Lake Constance region, close to the town of Ravensburg, see Figure 1. Ravensburg is crossed by the Schussen-river. For this investigation, orchard-farm areas have been selected in the vicinity of the Schwarzach, a tributary of river Schussen, see Figure 1 and 2.

Figure 1. Geographical location of Ravensburg and the Schwarzach.

The staple fruits grown are apples (approx. 80 %). As for the remaining 20 % it was assumed that pears are grown. As a matter of fact, the actual distribution of fruits grown is of minor importance since the k_c-factors that determine the crop-water demand of pears and apples are practically the same. A typical orchard of the region is shown in Figure 2. For the present study, an orchard area of 1,100 ha which is to be irrigated has been assumed.

Figure 2. A typical orchard in the Schwarzach region

2.2 Climatic conditions

For the climatic characterization of the selected location, weather data of the the Deutscher-Wetterdienst-station 10929 (Constance) were deemed to be sufficiently representative as the distance of the study area to this station is only 36 km. With respect to irrigation requirements in the region under consideration, precipitation and basic evapotranspiration ETo are of particular interest, see Table 1. The so called *effective rainfall* has been computed according to FAO-recommendations. It determines that portion of total rainfall which is assumed to be usable by crops. Climatic data such as temperatures, humidity, solar radiation etc. are implicitly comprised in the ETo evapotranspiration-values.

A comparison of the values of Table 1 reveals that in average the amount of annual rainfall is higher than evapotranspiration, but that in one out of 2.6 years the situation is inversed. This is an indicator for temporal "aridity" during the growing season of these dry years, where irrigation is required for successful fruit-farming.

Table 1. Annual total and effective rainfall, basic evapotranspiration computed according to FAO-standards of the Deutsche WetterdienstClimate station 10929 (Constance) for a series of 13 years (OPATA 2004)

Year	Total Rainfall [mm/year]	Effective Rainfall [mm/year]	ETo [mm/year]
1991	716.1	608.9	715.23
1992	896.3	756.3	730.19
1993	859.8	711.7	707.54
1994	869.6	743.1	718.80
1995	1040.2	857.3	692.36
1996	825.0	696.3	693.01
1997	708.3	613.8	724.01
1998	773.0	664.0	717.57
1999	973.4	814.5	696.25
2000	771.9	668.3	735.14
2001	895.7	766.4	715.19
2002	1018.2	858.7	733.65
2003	626.5	561.5	814.19
Mean	844.3	741.3	720.36

2.3 The Schwarzach-creek

It goes without saying that the climatic trends are mirrored in the stream flow of the Schwarzach. As there were no discharge records for the creek Schwarzach available, the respective data of the Schussen had to be transformed by using the ratio of the catchment areas: $Q_{Schwarzach} = Q_{Schussen} \times A_{Schwarzach} / A_{Schussen}$, where $A_{Schwarzach} = 161\ km^2$ and $A_{Schussen} = 785\ km^2$ at the relevant gauging station. Figure 3 shows average annual mean Schwarzach-discharges for years corresponding to Table 1.

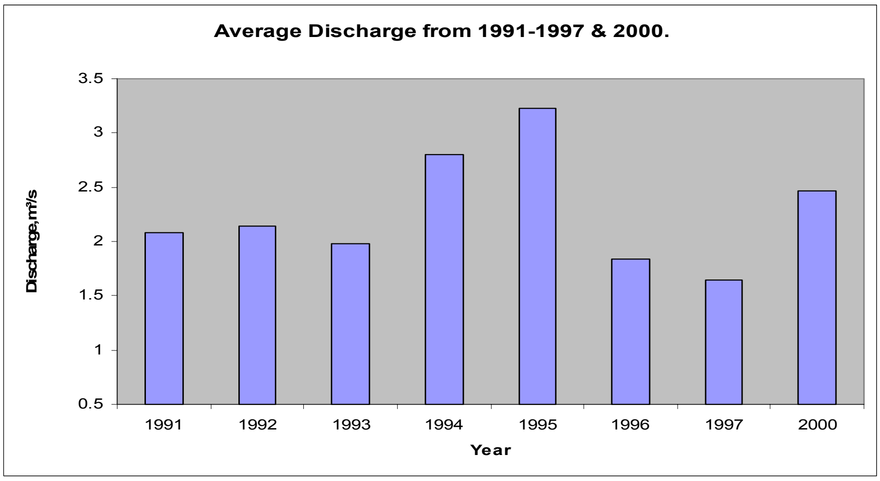


Figure 3. Average annual discharges of the Schwarzach derived from river Schussen for the years 1991-1997 and 2000 (OPATA 2004)

3 IRRIGATION-WATER REQUIREMENTS – THE DEMAND SIDE

Although the year 2003 was most critical in terms of high irrigation requirements, 1997 has been selected for this study since discharge records of the Schwarzach (respectively the Schussen) have not been available for 2003. 1997 was, however, also a dry year with comparably high and slightly more evapotranspiration than precipitation. Crop- and irrigation-water requirements for the Schwarzach-region have been computed with FAO's CROPWAT model which is based on the generally applicable Penman-Monteith approach (ALLEN et al. 1998). Although physiological properties of various crops could, principally, be considered directly in the Penman-Monteith formula, the traditionally way, still favoured by FAO and implemented in CROPWAT, has been followed: i.e. reference evaporation ETo for the optimally watered standard grass is computed and in a second step factors k_c are applied in order to consider specific crops. Unfortunately, these factors themselves may depend not only on the development stage of the respective crop but also on many other influencing parameters. Here, for apples and pears, $k_c(t)$ factors according to Table 2 have been considered.

Table 2. Crop-factors k_c of apple- and pear trees. (ALLEN et al. 1998) used in this study.

kc: active ground cover, no frosts	0.8	0.8 to 1.2	1.2	0.85

Using the k_c-factors of Table 2 and the climatic information mentioned, CROPWAT computes annual distributions of ETo, cropwater requirements (CWR) and irrigation-water requirements (IWR) as shown in Figure 4. Here, IWR is equal to cropwater requirements minus precipitation and does not (yet) include an efficiency ratio for the used sprinkler-irrigation technology. Resulting figures for total and specific crop- and irrigation-water demands are displayed in Table 3.

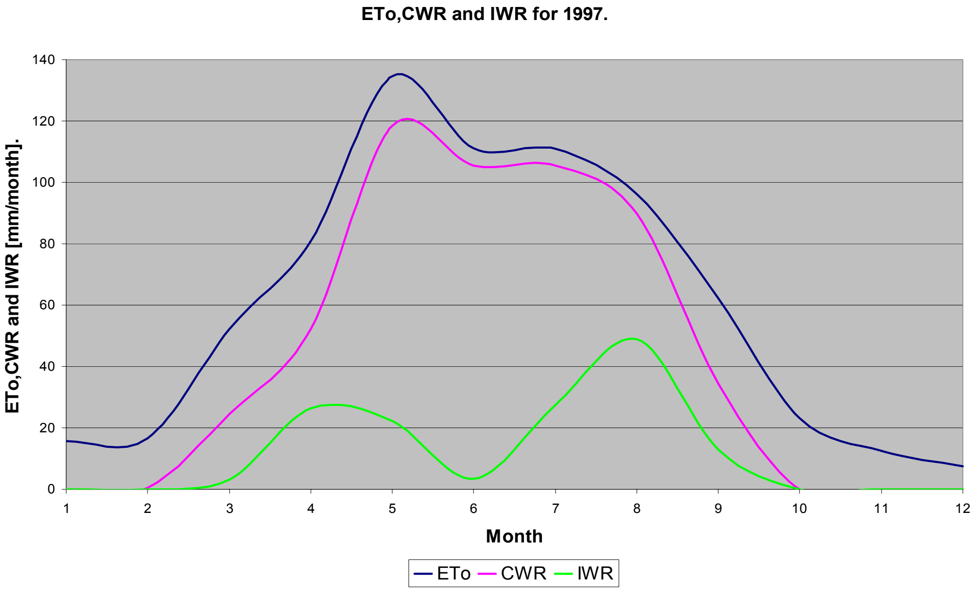


Figure 4. Graphs of the ETo, CWR and IWR for 1997, computed with CROPWAT using k_c from Table 2 (OPATA 2004)

Table 3. Irrigation-water of 1997 in various units for crop-factors k_c according to Table2; total and specific values for the critical month of August including $\eta_{irr} = 0.7$ for sprinkler irrigation

Annual spec. IWR_h	August spec. IWR_h	August spec. IWR_V	August spec. IWR_Q
[mm/year]	[mm/month]	[m^3/(day ha)]	[l/(s ha)]
160	70.37	22.7	0.26
167	70.37	22.7	0.26
327	104	33.3	0.38
349	104	33.6	0.39

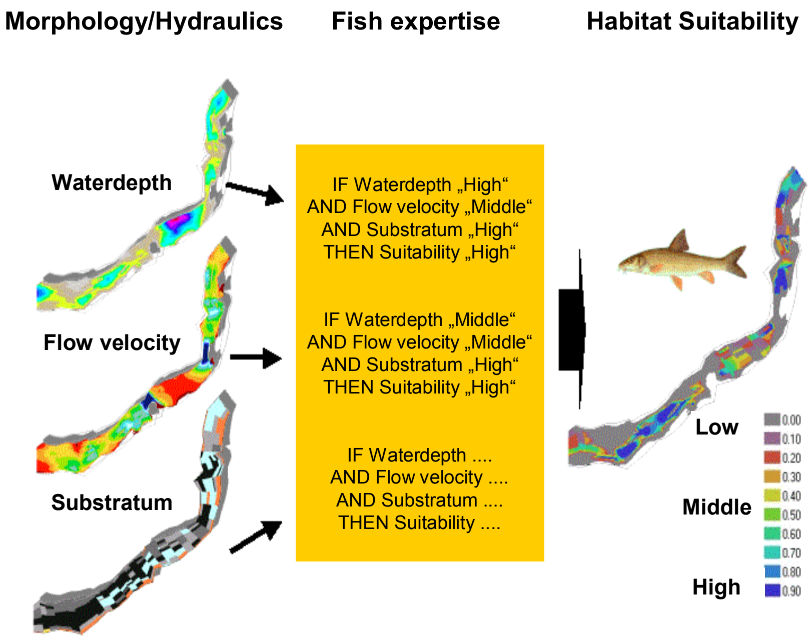
4 LIMITING LOW FLOW-THRESHOLD OF THE USED STREAM – THE SUPPLY SIDE

4.1 CASIMIR – tool for the assessment of ecological conditions in streams

The determination of a low flow threshold value for the creek Schwarzach up (down) to which irrigation-water withdrawal may be permitted without endangering the ecological functionality of the used stream has been carried out with the computer program CASIMIR (= Computer Aided Simulation Model for Instream Flow Requirements, JORDE 1997, SCHNEIDER 2001).

CASIMIR was originally destined for the prediction of minimum discharges required in diverted river sections of hydro power schemes in order to preserve or enable appropriate living conditions (habitat suitability) for aquatic organisms such as macroinvertebrates and fish. The interest for such investigations had arisen from the need to enact regulations of instream flow requirements in diverted river sections of hydro-power schemes. This imposes on the hydro-power owners economic losses due to less water for turbining. Therefore, the decreed values of minimum flow in diverted river sections that cannot be turbined had to be well grounded. Indeed, low-flow regulations based on ecologically oriented CASIMIR-results proved to be so transparent that they have been widely accepted by the concerned parties. In the mean-time, by further development, CASIMR turned into a tool which, apart from hydro-schemes, can be applied for the prediction of ecological conditions in any river sections where the consequences of human impact - be it structural changes of the river bed or alterations of the discharge patterns – have to be assessed.

Input data of CASIMIR are information about the stream geometry (cross sections, longitudinal slope etc.), bed substrate, cover facilities for aquatic organisms (for hiding and resting), biological/ecological preferences (concerning flow velocity distributions, water depths, substrate, cover) of endemic benthos and/or fish. Program-internally, preferences of aquatic organisms with respect to their living space, i.e. the investigated river stretch, can be provided either in the form of preference functions or fuzzy rule sets, see Figure 5. Based on these input data and hydraulic calculations, indicators for habitat suitabilities (SI, HHS) and *Weighted Usable Areas* (WUA) for species specific to the area and type of stream are derived as output by CASIMIR. The objects of investigations are river-channel stretches which can, according to the long-standing experience of the investigators, be qualified as being ‘representative’ for longer river-channel sections.



IF Waterdepth „High“
AND Flow velocity „Middle“
AND Substratum „High“
THEN Suitability „High“

IF Waterdepth „Middle“
AND Flow velocity „Middle“
AND Substratum „High“
THEN Suitability „High“

IF Waterdepth ....
AND Flow velocity ....
AND Substratum ....
THEN Suitability ....

Figure 5. Input and output of CASIMIR for the assessment of habitat suitabilities for fish (EISNER et al. 2004)

4.2 Evaluation of ecologically acceptable low-flow thresholds of the Schwarzach-creek using CASIMIR

CASIMIR-simulations have been carried out for the Schwarzach-creek in order to determine ecologically grounded low-flow thresholds as the minimum values up to which withdrawal of irrigation water from the Schwarzach can be allowed.

The focused creek-section (about 18 km) has a longitudinal slope of 6.8 ‰. The average width of the Schwarzach is about 6.5 m and the mean depth during low flow periods is around 10 cm. For a period of 78 years (up to the year 2000) discharges of the month August showed the following characteristics (derived from gauging station at river Schussen): Mean monthly overall discharge was 578 l/s, mean lowest discharge was 294 l/s and the mean highest discharge was 2157 l/s. The Schwarzach is not heavily channeled and has some close-to-nature features, see Figure 6. All kinds of vegetation can be found along it. There are some rocks piled up along certain sections of the creek, while sand and gravel banks as well as dead wood can be found elsewhere. The substratum differs from section to section as well as the cover and shading.

Figure 6. Typical section of creek Schwarzach´s bed

The fish species of the Schwarzach-creek are Brown trout *(Salmo trutta)* and bullhead *(Cottus gobio)* in their life stages '*spawning, juvenile, fry and adult'*. By means of CASIMIR simulation-runs, habitat suitabilities in selected representative river sections are found for these fish-species under varying discharge conditions. The habitat suitabilities are quantified by WUA- and HHS-functions. The *Weighted Usable Area WUA* is defined (SCHNEIDER & JORDE 2002) according to

$$\text{WUA [m}^2\text{]} = \sum_{i=1}^{n} A_i . SI_i = f(Q) \quad \text{[m}^2\text{]}$$

where

WUA	Weighted Usable Area expressed in [m²] for the investigated representative section of a river bed
A_i	Area of cell i in investigated river section = function(aquatic and morphological properties)
SI_i	Suitability index of cell i = function(fish preferences for flow velocities, water depth, substratum, etc.)

The *Hydraulic Habitat Suitability* (HHS) is equal to WUA divided by the total wetted area:

$$HHS = \frac{1}{A_{Total}} \sum_{i=1}^{n} A_i . SI_i = \text{f(Q)} \quad [-]$$

The dimensionless HHS-indicator ranges from 0 to 1. Higher values of WUA and HHS show a better habitat quality for specific life stage of fish species. An Example of visualized results are displayed in Figure 7. The overall results of CASIMIR simulation-runs for the Schwarzach-creek are summarized in Table 4.

According to experience by field investigations, stream discharges that guarantee a certain minimum of weighted usable areas (WUA) and overall habitat suitability indices $HHS \geq 0.7$ are appropriate to ensure sustainable, general ecological functionality of the considered river section. For the present case of the Schwarzach-creek, the minimum discharges pertaining to minimum WUAs are listed in column 2 of Table 4. By scrutinizing the last two columns of Table 4 it can be deduced that a minimum flow of 250 l/s (includes all life stages of both fish-species) ought to be conceived as a low-flow threshold value in order to maintain sustainable acceptable ecological conditions in the Schwarzach-creek. However, at least for short periods (a few hours of a day) an absolute minimum flow of 170 l/s seems to be tolerable, since only adult fish would be affected by low flows in the range from 250 to 170 l/s. It can be assumed that they would be able to temporally use escape-habitats. Below the absolute low-flow threshold value of 170 l/s the ecological functionality of the Schwarzach would be endangered.

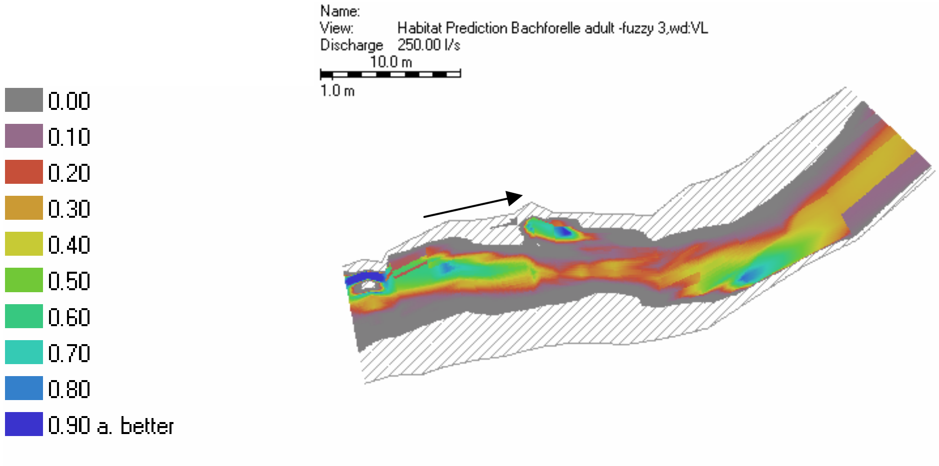


Figure 7. Brown Trout, adult-habitat suitability at Q = 250 l/s

Table 4. Results of minimum flow analysis with CASIMIR for representative sections of the Schwarzach-creek

Fish type and life-stage	Min. Flow pertaining WUA [l/s]	Min. Flow pertaining HHS > 0.7 [l/s]
Brown Trout-Adult	200	250
Brown Trout-Fry	-	60
Brown Trout-juvenile	170	100
Brown Trout-spawning	110	130
Bullhead-Adult	220	250
Bullhead-Fry	80	180
Bullhead-juvenile	100	100
Bullhead-spawning	170	250

5 IRRIGATION WATER SHORTAGES IN DRY PERIODS AND THEIR CONSEQUENCES

In order to get a quantitative idea of irrigation water shortages during the month of August under varying conditions, two scenarios have been conceived:

- Scenario I: Climate and discharge conditions represented by data of August 1997,
- Scenario II: Extreme low flow conditions generated by multiplying the daily discharges of August 1997 by the ratio $Q_{\text{lowestAug75years}} / Q_{\text{lowest,Aug 1997}}$

Figure 8 and 9 display the natural low flows of the Schwarzach without irrigation-withdrawal at the tapping point for 1997 (***Q**_Schwarz_tap*) and for an extreme dry August (*extreme low Q_Schwarz*), the virtually remaining Schwarzach-flow (*Q_Schwarz_residual*), the ecologically required minimum flow of the Schwarzach *(min Q_Schwarz_oeko*) and the irrigation-water deficit (*Q_irr_deficit*) for the case that irrigation water is withdrawn only up to the limit of the ecologically required minimum flow of the Schwarzach. The remaining Schwarzach-flow has been marked 'virtual' since in scenario II (extremely dry August) the flows would be smaller than zero. The graphs of Figure 8 and 9 reveal that irrigation-deficits will be encountered in both scenarios.

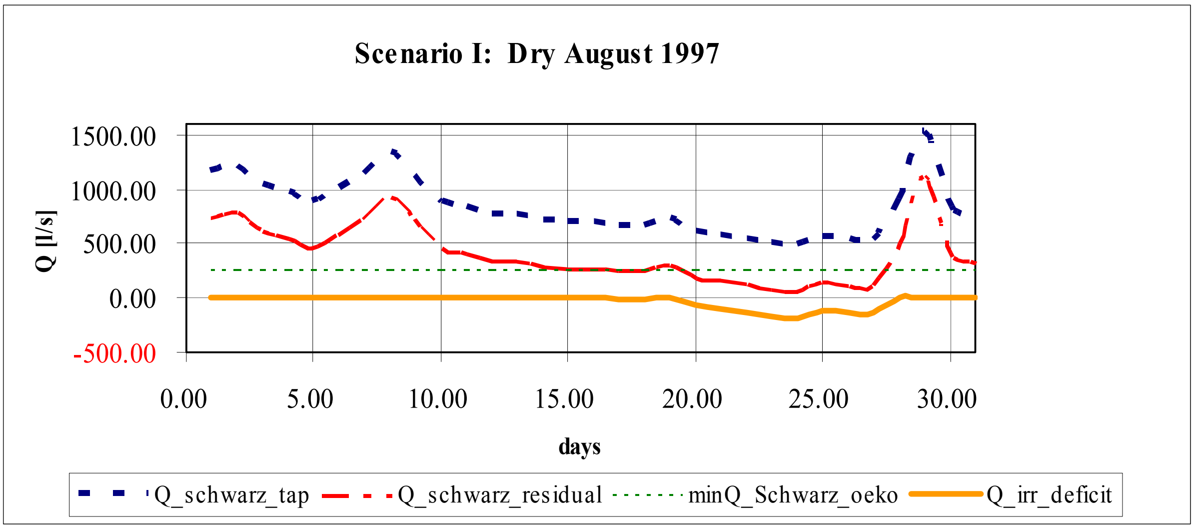


Figure 8. Creek- and irrigation-flow scenario I (dry August 1997) for 1100 ha of orchard land and k_c for apples and pears according to Table 2

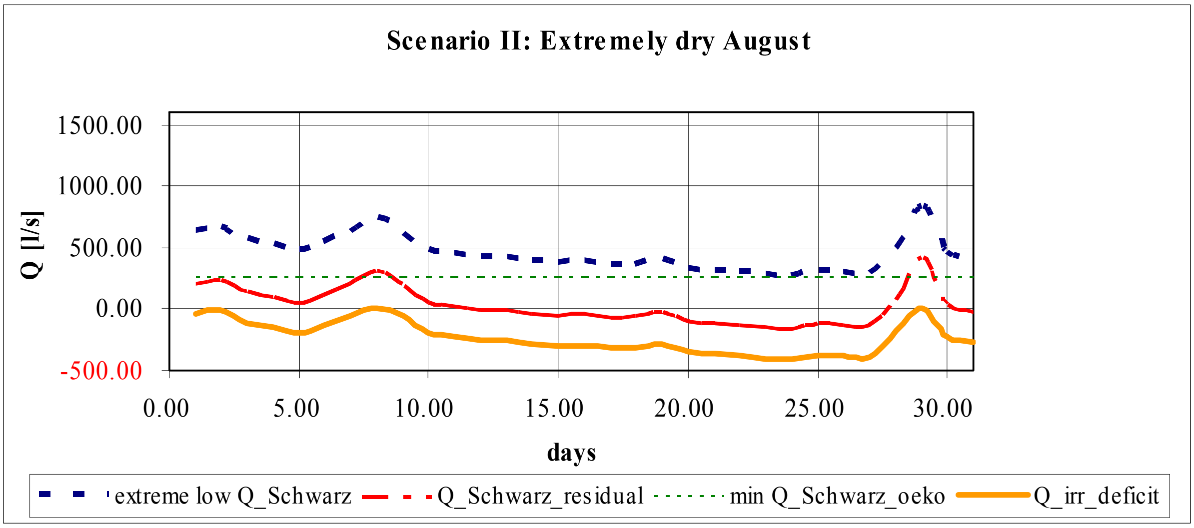


Figure 9. Creek- and irrigation-flow scenario II (extremely dry August) for 1100 ha of orchard land and k_c for apples and pears according to Table 2

In order to estimate reduced yields $pY_{reduced\_Irr}$ [%] due to shortage of irrigation water, the approach recommended by FAO has been used (ALLEN et al. 1998, SMITH et al. 2000)

$$pY_{reduced\_Irr}[\%] = \left[1 - k_y \cdot \left(1 - \frac{ET_{reduced\_Irr}}{ET_{full\_Irr}}\right)\right] \cdot 100$$

where k_y [-] is the yield reduction factor. The expressions $ET_{reduced\_Irr}$ for reduced and ET_{full_Irr} for full irrigation water supply can - for the considered area and time period - be measured in various units such as mm, m³, l/s or the like. According to FAO experience, k_y depends on the type of crop and varies with the growing stages. Recommended values range from 0.5 to 1.0. A value $k_y = 1$ means that yield reductions are proportional to irrigation water shortages. In principle the response of crops to water shortage is rather complex. Therefore the derived figures of reduced yields can give just an idea of the tendencies.

Table 5 lists the main results of irrigation water shortages and their consequences on drought scenarios under the conditions that irrigation water withdrawals do not affect ecologically required minimum flows in river Schwarzach.

Depending on the climatic conditions, and the assumed response of orchard trees to water stress (k_y), reduced yields range from 95 to 46 % of the yields which could be achieved with fully irrigated orchards. The specific yield (40 t/ha) assumed here is based on local experience (O-COMM 2003,2005).

Table 5. Compilation of data used in this study and results with respect to irrigation water shortages and their effects on yields of the under-irrigated areas due to ecologically grounded restrictions of water withdrawal from the used river.

Irrigation water shortages and consequences for sprinkler irrigation						
Total irrigated orchard area	[ha]			1100		
Specific yield of apples & pears	[t/ha]			40		
Total yield of fully irrig. orchard area	[t]			44000		
		Scenario I: Dry August 1997			Scen. II: Extreme dry Aug.	
ET_Full_Irr (vol. of required irrig. Wat.)	[m3]			1149034		
ET_Deficit_Irr (Lacking Vol. of irrig. wat.)	[m3]	-92792			-621123	
Yield reduction factors ky	[-]	ky: low reduction	ky: high reduction		ky: low reduction	ky: high reduction
		0.65	1.00		0.65	1.00
Specific reduced (actual) yield	[%]	94.75	91.92		64.86	45.94
Reduced yield for total orchard area	[t]	41690.35	40446.69		28539.95	20215.31
Yield deficit per m3 of Irrigation Water	[t/m3]	0.02	0.04		0.02	0.04

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Perspectives of mitigation measures

Although the deficit values presented above are based on figures that cannot claim to achieve a high degree of accuracy, general tendencies impacting orchard irrigation farming in South-western Germany have been revealed. It is, however, most likely that due to increased awareness of environmental problems associated with ecologically inappropriate low discharges in streams and due to future climatic changes, the situation of irrigation water shortages might even get worse. Therefore, mitigation-measures have to be identified. Some options are discussed below:

- **Improvement of irrigation efficiency:** Based on in-situ measurements of soil moisture in the root zone of the orchard trees, irrigation water could be allocated more precisely. Another issue could be to replace sprinkler irrigation by drip irrigation. Due to better uniformity of water distribution in the soil and – in particular in the case of orchards - the reduction of soil volume to be moistened, considerable water savings could be achieved. In the framework of the present study, an improvement of the irrigation-efficiency by 10 percent as compared to sprinkler irrigation (i. e. from 70 to 80 percent) and a reduction of the wetted area by one third (uniquely the soil around the trees needs to be watered) has been assumed. Under these circumstances, only 670,000 m^3 instead of 1,150,000 m^3, see Table 5, were required. Thus, the reduced yields would range between 99.9 and 65 % only (as compared to 95 to 45 % with sprinkler irrigation). However, a big problem with drip irrigation reportedly is the rather high content of lime-particles in the streams of the region. Without proper treatment of the tapped river water, clogging of the drip emitters unavoidably is a negative consequence (O-COMM 2003, 2005).

- **Management of irrigation water deficits:** As GOODWIN & BOLAND (2000) suggest in their paper on *Scheduling deficit irrigation of fruit trees for optimizing water use efficiency,* water stress induced by under-irrigation may even have positive effects on yields of fruit trees (among them European pears grown in Australia). The reason is that water stress during the right period prevents the development of too an abundant canopy which in turn may have positive effects on the development of the fruits. Although controlled deficit irrigation seems to be quite appealing, it has to be clarified whether the method can be successfully applied in the study area, since the farmers are already using dwarf-trees with low potential for the development of shoots and leaves and the appropriate period for under-irrigation may not readily coincide with low flow conditions of the used stream.

- **Storing water**: For a typical case such as it has been studied here, irrigation water volumes of up to 1 Million m^3 could be useful for irrigation needs. Such small reservoirs could also help to mitigate the ecological problem of natural low flow. These goals could be combined with purposes of flood protection and recreation, the latter if the water quality is appropriate. A disadvantage of reservoir-solutions is - as usual – incurring costs. The 20, respectively 40 kg of apples and pears which could be produced by one m^3 of irrigation water additionally provided (see Table 5) may not be sufficient to economically justify such a measure. Another negative aspect is that it is often not desirable, again for ecological reasons, to have reservoirs erected in a freely flowing stream.

6.2 Future investigations

Preparing for the challenges of drought periods which might be experienced more frequently in forthcoming years than today, encompasses the following steps for the development of locally applicable orchard irrigation strategies:

- Adaptation of the used computation methods such as CASIMIR and CROPWAT to on-site conditions by calibrating parameters of river hydrology and ecology (e.g. flow records,) and irrigation (e.g. k_c, k_y)
- Inclusion of measured and computed soil water balance figures into considerations of irrigation under conditions of limited water supply
- Collection of reliable agricultural basic data such as specific yields, irrigated areas, present irrigation scheduling, local crop characteristics
- Systematic statistical evaluation of climate and discharge data in order to classify the frequency of problematic drought periods for farmers as well as for the used stream
- Assessment of economical feasibility of possible mitigation measures
- Practicable & affordable measures for the elimination of lime and other particles that are susceptible to clog drip irrigation emitters

It is intended that – on the basis of the above investigations - the procedure pointed out here will contribute to working out sustainable irrigation strategies for the advantageous coexistence of both, sound ecological conditions in the used streams and economic feasibility of orchard irrigation farming in South-Western Germany, also under uncertain future, probably worsening, climatic conditions.

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