Water Balancing at System and Field Scale – Two Approaches for Estimating Irrigation Inputs

Jens Raunsø Jensen[1] , *Doan Doan Tuan*[2] *and Dang The Phong*[3]

Introduction

Assessing the impact of wastewater irrigation on agricultural production and on soil and environmental quality requires *inter alia* robust estimates of nutrient and pollutant loading rates of the agricultural land at the time scales of irrigation events and crop seasons. The loading rate of a particular element for a specified period of time and spatially defined irrigation system is generally obtained as the time integral of the product of element concentration and irrigation delivery. However, the spatial and temporal variations of flows, concentrations, hydraulic conditions and soil and crop management in irrigation schemes often make it a very difficult and resource demanding task to establish area-wide representative estimates at a reasonable accuracy at the level of farmers' fields.

This study was undertaken to estimate the irrigation deliveries as an element of assessing nutrient and pollutant loading rates in wastewater irrigated rice lands in a case study area in the Red River Delta, Vietnam. Recognising the complexities indicated above, two water balance based approaches have been applied for estimating area-wide irrigation delivery to the rice fields: **S**, a scheme-level inflow-outflow method based on flow measurements over system boundaries; and **F**, a field scale water balance simulation method. Whereas the former (**S**) analyses the water balance over the scheme boundaries treating the interior scheme area as a blackbox, the latter (**F**) analyses the water balance of a hypothetical representative field within the scheme.

The objective of this paper is to briefly summarise the findings on irrigation deliveries and water balance components in the form of a comparative analysis of the two different approaches. Further details on the studies are presented in Tuan et al. (2006; S-model) and in Jensen (2005; F-model).

Methods

Case study site

The Quan Chuot case study site is located close to the city of Nam Dinh in the lower part of the Red River Delta (RRD). The climate is sub-tropical with a main rainy season from May to October, year round high humidity and low wind speeds, and relatively low global radiation and air temperature during Nov – Mar. The typical cropping pattern in the prevailing heavy textured alluvial soils is double cropping of wetland rice with a main Spring Crop (Feb-Jun) and a Summer Crop (Jul-Oct). This study addresses the situation of the rice spring crop (2003 and 2004) when water balances and nutrient and pollutant loads are mainly influenced by irrigation.

The Quan Chuot pumping station was constructed in 1974 for drainage of storm water from Nam Dinh city. Following water scarcity caused by poor irrigation management since land redistribution in 1985, the station supplies wastewater to the tail end of the KC0 irrigation canal for a total paddy

[1] Department of Agricultural Science, The Royal Veterinary and Agricultural University (KVL), Denmark. jrj@kvl.dk
[2] Center for Participatory Irrigation Management, Vietnam Institute for Water Resources Research (VIWRR), doantuan@hotmail.com
[3] Center for Irrigation & Water Supply Research

field area of about 38 ha. The sub-area of 24.2 ha considered in this study is delineated by residential areas and the national road No. 10 and consists of 4 paddy field areas of 3.5, 8.5, 8.5 and 3.7 ha (Fig.1). A field survey was carried out to clarify all water routes in and out of the study area, identifying 2 inflow (STA08A, STA02A) and 2 outflow (STA03A, STA06A) locations. However, the northern 3.7 ha area is occasionally served by a mobile pump and by gravity inflows from the main drain (blue line). Thus, the true area of the Quan Chuot sub-scheme considered is somewhat uncertain and may vary within say 20 to 25 ha. Furthermore, some uncertainty is associated with the presence of fishponds drawing water from field runoff (eg., one major pond in the 1.2 ha sub area in Fig. 1), and the check gate in the T division box between STA07 and STA08 may not always be operated appropriately during pumping.

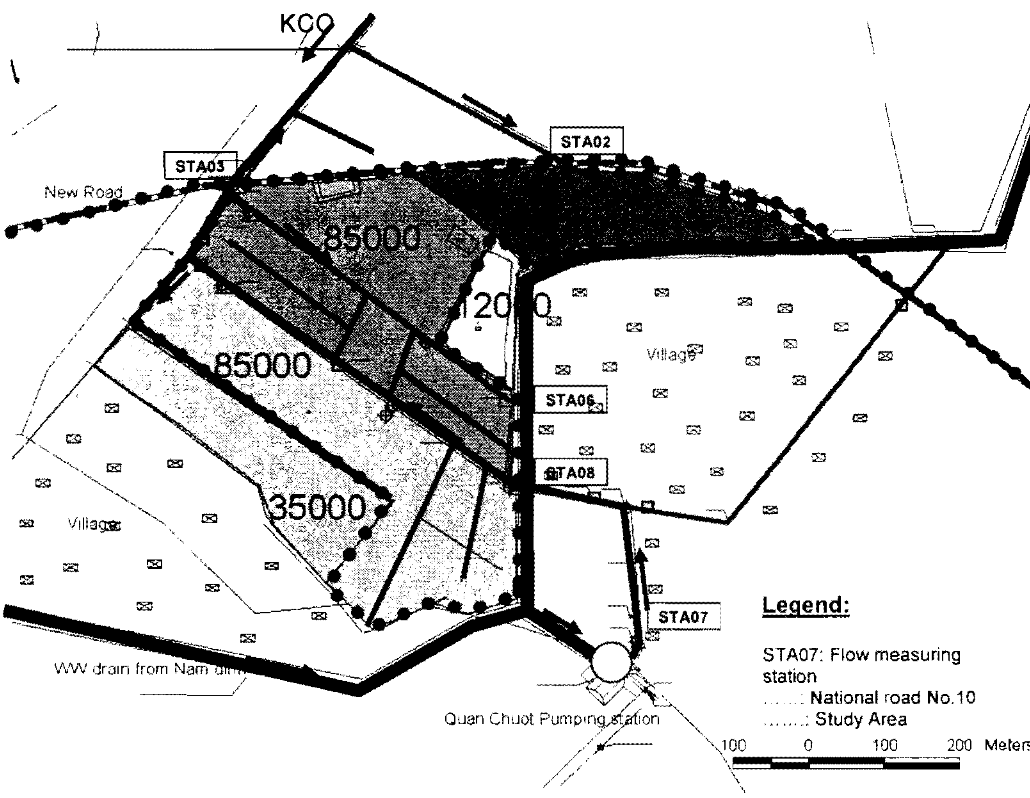

Fig. 1. Quan Chuot study area and water measurement locations (modified from Tuan et al., 2006).

Water balance concept

Conventionally, the water balance for a spatially and temporally defined domain – eg., field or scheme – may be written as:

$$\Delta S_D = Inflow - Outflow = (P+I)-(R+D+ET) \quad \text{(mm)} \qquad (1)$$

where the fluxes (mm per time period considered) are established across the boundary of the domain: P, rainfall; I, irrigation delivery; R, net surface runoff; D, net sub-surface drainage; and ET, evapotranspiration. For the assessment of irrigation related nutrient and pollutant loads of rice fields, the field level irrigation delivery (I_F) is of specific importance. Field level delivery is conventionally linked to the scheme irrigation delivery (I_S) via the conveyance and distribution efficiency (e_{CD}) representing net surface and subsurface losses in the canal and distribution network:

$$I_S = \frac{1}{e_{C,D}} I_F = I_{S,N} + I_{S,O} \qquad \text{(mm)} \qquad (2)$$

where $I_{S,N}$ is net irrigation delivery to the scheme and $I_{S,O}$ is irrigation outflow (mm). The e_{CD} is highly location specific and dependens on scale, scheme layout, land & water management and groundwater conditions, and there is no simple way of knowing this value *a priori* although indicative empirical estimates may be obtained from reference tables (eg., Doorenbos and Pruitt, 1977). It is important to note that the models described below estimate different variables: the S-model, $I_{S,N}$ and I_S ; and the F-model, I_F ; neither model estimates e_{CD} .

S: scheme-level inflow-outflow method using the concept of effective rainfall.

The physical and temporal domain considered is the surface water system of the 24.2 ha sub-scheme, from land preparation to 10 – 15 days before harvest using the following water balance:

$$\Delta S_S = I_{S,N} + P_{S,E} - \left(D_S + ET_S\right) \qquad \text{(mm)} \qquad (3)$$

where: ΔS_S , change in storage; $I_{S,N}$, net irrigation delivery to the scheme; $P_{S,E}$, effective rainfall here estimated from an empirical model for rice in "Vietnam" (Dastane, 1978) disregarding daily rainfall below and above 5 and 50 mm, respectively and using daily rainfall from the Nam Dinh City meteorological station; and D_S and ET_S are respectively "seepage & percolation" (i.e. sub-surface net outflows) and evapotranspiration, collectively termed "total water use" in the system. Surface runoff (R) is not explicitly accounted for in this model.

The S-model relies on a few sample surface flow measurements across system boundaries, to establish the net irrigation water delivery to the scheme over the period considered accordingly:

$$I_{S,N} = I_S - I_{S,O} = \frac{1}{10 A_S} \sum_{j=1}^{n} \left(Q_{n,avg}\, t_{p,j}\right)_j \qquad \text{(mm)} \qquad (4)$$

where I_S and $I_{S,O}$ are irrigation delivery and outflow, respectively (mm); $Q_{n,avg}$, the average net inflow (i.e. inflow – outflow) during pumping (m^3/h); $t_{p,j}$, pumping time (h) during j-th irrigation; n, number of irrigations; and A_S , scheme area considered (24.2 ha). The "total water use" ($D_S + ET_S$) over the crop season may then be estimated from eq.(3) by assuming that ΔS_S equals the estimated $I_{S,N}$ during the land preparation period.

The average net inflow during pumping was found to be 462 m^3/h, using canal cross section surveys and flow measurements during 4 irrigation events (Table 1). Flows were measured at the pumping station's discharge basin (STA07A) and at the inlets (STA08A, STA02A) and outlets (STA03A, STA06A) of the study area. Normally, 2 pumping units with a theoretical discharge of 1000 m^3/h per unit were operated during irrigations. However, flow measurements at STA07 showed that the real discharge of a pump unit was 860 m^3/h corresponding to an effective pump coefficient of 0.86 (actual/theoretical discharge).

Table 1. Flows in the main canal and over the study area (m^3/h).

Date	Qin at STA07 (m^3/h)	Qin at STA08 (m^3/h)	Conv. loss (m^3/h)	Qin at STA02 (m^3/h)	Qout at STA03 (m^3/h)	Qout at STA06 (m^3/h)	Qin-Qout (m^3/h)
6-Jun-03	1825	1219	606	0	414	10	795
7-Jun-03	1787	1325	462	9	466	10	858
22-Mar-04	1553	1167	386	0	85	0	1082
6-Apr-04	1714	1102	612	0	102	0	1000
Average	1720	1203	517				934
1 pump unit	860	602					462

The delivered discharge at the outlet of the discharge basin (STA07) varied from 1553 to 1825 m^3/h, likely associated with variations in water availability and electricity supply etc. The average discharge was 1720 m^3/h (860 m^3/h per unit) whereas the average inflow to the study area at STA08 was 1203 m^3/h or 602 m^3/h per unit, suggesting a high conveyance loss of 30 % over this short canal section (canal overtopping ?). The water balance for the study area averaged 462 m^3/h per pump unit, with a coefficient of variation of 14 %. Then, irrigation inputs were estimated for Spring Crops 2003 and 2004 by combining the estimated average net inflow per pump unit (462 m^3/h) with information on pumping hours from the pumping station record. For the land preparation period, values of 172 mm and 246 mm were applied for spring 2003 and 2004, respectively. The limited observations suggest that the inflow / outflow relationship could be considerably different among events and/or between summer (wet) and spring (dry) irrigations. Apparently, 34 % and 8 % of the gross irrigation delivered to the scheme was "lost" in direct outflows on the summer and spring sample dates, respectively. The rough average of about 20 % may be considered operational losses. Furthermore, the average net inflow could be higher in spring irrigation (10 % on the sample dates).

F: field-level daily simulation with calibration of the sub-surface drainage rate

In the field-level water balance model as applied here, the sub-surface is considered saturated throughout. The average irrigation delivery to rice fields (I_F) is estimated from local irrigation criteria combined with a daily field water balance simulation model, calculating the daily average water level in the rice fields (h) from differences in inputs and outputs during day i :

$$\Delta S_F \;=\; \Delta_i h \;=\; I_{F,i} + P_{F,i} - R_{F,i} - D_{F,i} - ET_{F,i} \qquad \text{(mm)} \qquad (5)$$

The model is executed from transplanting to maturity as a sub-model within a rice crop modelling complex. Daily values of climatic variables are obtained from an on-site automatic weather station, supplemented by calibrated data from the official meteorological station in Nam Dinh City. The *ET* is calculated from the FAO Penmann-Monteith model (Allen et al., 1998) with the crop coefficient ranging from 1.1 to 1.3 depending on growth stage. Runoff occurs when $h > 10$ cm (eg., when $P_{F,I} >$ 50 mm/d on top of 5 cm field water depth) while final field drainage - included in the R_F term - takes place during the last week before maturity. The daily sub-surface drainage (i.e., $D_{F,i}$; net field "seepage & percolation") is calculated assuming a constant rate (D_0) under flooded conditions and a value of zero during days of $h = 0$ including the period after final field drainage. The D_0 is considered the only unknown parameter of eq.(5) and therefore estimated from a model calibration minimising the variance between observed (pumping record) and simulated irrigation dates.

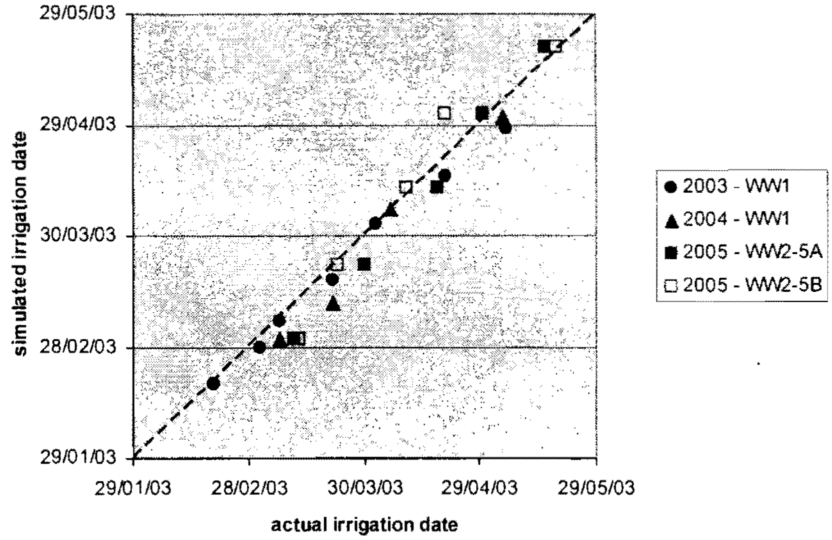

Fig.2. Calibration of field water balance model.
(WW1 and WW2, Hong Long and Cong Hoa schemes, respectively; Jensen, 2005).

The irrigation criteria adopted were established from interviews with farmers and irrigation managers and summarised as target field water depth as a function of crop development stage. Thus, irrigation takes place when $h \sim 0$ with a target field water depth increasing during crop development from 30 to 60 mm and with a final irrigation at flowering targeting 70 mm field water depth. Rainfall in May is generally sufficient for sustaining the rice crop without irrigation. The results of the model calibration for 2003 and 2004 are summarised in Fig. 2 along with additional simulations for a similar study at the neighbouring Cong Hoa scheme. The model apparently calibrated well and a partial sensitivity analysis supports the estimates of D_0.

Results and Discussion

The key parameters and model estimates are presented in Table 2 below. The results from the two models can not be directly or easily compared because of differences in: (i) model concept, estimating physically different variables; (ii) data, drawing on partly different sources; and (iii) calculation period.

Table 2. Water balance variables from the two models, Scheme and Field.
(LP, land preparation; the period of calculation used for $I_{S,N}$ after LP is taken from F-model; ref. text).

Water balance item	2003				2004			
	Scheme (S)		Field (F)		Scheme (S)		Field (F)	
	mm	mm/d	mm	mm/d	mm	mm/d	mm	mm/d
Period of calculation	07 Feb–07 Jun		15 Feb– 07 Jun		15 Jan–27 May		26 Feb – 21Jun	
Δt (day)	120		113		132		117	
P ($P_{S,E}$ and P_F)	91	0.8	276	2.4	215	1.6	514	4.4
$\Sigma(P_{F,i} < 5\ mm)$	33	-	-	-	50	-	-	-
ET_F	-	-	356	3.2	-	-	347	3.0
LP: $I_{S,N}$, I_F=200	162	-	200	-	246	-	200	-
after LP: $I_{S,N}$, I_F	463	4.1	351	3.1	398	3.4	189	1.6
total: $I_{S,N}$, I_F	625	-	551	-	644	-	389	-
$e_D = I_F/I_{S,N}$ (after LP)	0.76	-	-	-	0.48	-	-	-
$e_{CD} = I_F/1.25 I_{S,N}$ (after LP)	0.61	-	-	-	-	-	-	-
$D + ET$	554	4.6	525	4.6	613	4.6	541	4.6
D_S ($ET_S = ET_F$ over Δt), D_F	170	1.4	169	1.5	217	1.6	194	1.7
D_0	-	-	-	1.9	-	-	-	1.8
R_F	-	-	122	-	-	-	202	-
$P_F - R_F$	-	-	154	-	-	-	312	-
($I_{S,N} + P_{S,E}$), ($I_F + P_F - R_F$)	716	6.0	705	6.2	859	6.5	701	6.0
ΔS	-	-	- 20	-	-	-	- 40	-

Calculation period: The differences in calculation periods weaken the comparison. However, all actual irrigation events are covered by both models and estimates of irrigation delivery are not influenced.

Rainfall and Evapotranspiration: There are examples of major discrepancies in daily rainfall between the two stations, emphasising the need to use location specific rainfall when possible. Furthermore, rainfall estimates differ because of different calculation periods, Thus, in 2004, rainfall (P_F) of 45 mm and 185 mm occurring respectively before 26 Feb and after 27 May are included in the F model causing a major difference in the rainfall input data. Furthermore, the 5 mm lower limit of the $P_{S,E}$ model should ideally be zero. Thus, accumulated daily rainfalls < 5 mm totals 33 and 50 mm during the S-model calculation periods, adding further to the discrepancy between rainfall estimates. However, this has no direct impact on differences in estimates of irrigation deliveries but will have contributed to differences in estimates on "water use" ($D+ET$) calculated partly by difference in the water balance equations. The estimate of ET during the field crop period (ET_F) is considered fairly accurate as the ET_F is calculated from an international standard model with appropriate local calibrations and data.

Irrigation delivery: The main objective of both models was to estimate the hydraulic loading rate of the rice field area, i.e. conceptually the field irrigation delivery I_F.

Net irrigation delivery during land preparation (LP) estimated by the S-model was on average 213 mm which if correct implies some overestimation by the F-model of the field level application during LP. However, this difference between the models' estimates would appear to be of minor importance.

The estimates of field irrigation delivery I_F by the F-model and the net scheme irrigation delivery $I_{S,N}$ by the S-model may be compared by calculating the ratio $I_F / I_{S,N}$ (e_D, Table 2). This ratio should ideally reflect the internal distribution efficiency of the scheme, i.e. the fraction of net scheme delivery which is lost internally between scheme and field inlets associated with channel storage, evaporation and deep percolation effects. This internal distribution efficiency is generally expected to be in the order of say 0.8 – 0.9 for a scheme of this type. However, taking only the field crop period (i.e., after land preparation), the calculated efficiency was 0.76 in 2003 and only 0.48 in 2004. This indicates some inconsistency in the irrigation estimates of either or both models, i.e. an overestimation of $I_{S,N}$ and/or an underestimation of I_F, especially in 2004. Thus, while relatively the model estimates appear reasonable in 2003, the very low efficiency in 2004 must be taken as an indication of a major error in either or both models. Tentatively, if accepting the S-model estimate and assuming conservatively an internal efficiency of 0.9, the field irrigation delivery in 2003 after land preparation would equal 417 mm implying a relative underestimation of I_F by the F-model of about 16 %. Similarly, if the I_F estimate of the F-model is accepted, the S-model would have overestimated the $I_{S,N}$ by 19 %.

The uncertainty in irrigation estimates associated with data errors is difficult to establish for the F-model. In case of the S-model, the uncertainty of the $I_{S,N}$ associated with measurement errors may be estimated from the limited data to be 17 % , considering only errors in $Q_{n,avg}$ and A_S of 14% and 10%, respectively (ref. Table 1 and eq.(4)). Thus, in 2003, the irrigation estimates of the two models are effectively within the same range when considering basic measurement errors, whereas the discrepancy in 2004 remains unresolved. In 2004, unusual heavy rains occurred at flowering – when the final and often heavy irrigation is normally applied. This may have caused the irrigation system and management to function non-ideally and at variance with some of the assumptions of the models (eg., irrigation target depth in F, average net inflow and $P_{S,E}$ in S, event-based runoff rather than continuous runoff, etc).

The apparent conveyance and distribution efficiency (e_{CD} , eq.(2)) may tentatively be estimated for 2003, when the time periods are nearly similar, assuming that I_S equals 1.25 $I_{S,N}$ (20 % lost as through flows on average, Table 1). A value of 61 % is found which – if correct – is rather poor and may reflect a combination of the variance between the model estimates discussed above and a low level of water management.

Seepage & Percolation and "Water use": The estimated average daily "water use" rate ($D+ET$) at scheme and field levels are remarkably similar in both years (4.6 mm/d), but they are theoretically different and calculated for different time periods. Assuming (reasonably) that the average daily ET is similar for scheme and field level, D_S is slightly less than D_F as generally expected from the scale effect on the D term. However, considering also daily rainfall less than 5 mm as effective, D_S becomes higher than D_F contrary to theoretical expectations. The seasonal average D_F is within the range of general expectation of say 1 – 5 mm/d for a rice field in a lowland rice alluvial clay soil area (eg., Truong and Bouman, 2003). It may be speculated that the "true" D_F and D_S are overestimated by the models, as slow surface outflows from open field bunds and ditches after irrigations would be included in the D-terms as estimated in the models. Rather, such flows should in principle have been accounted for as surface runoff.

Surface runoff: Surface runoff is in both models only attributed to rainfall events: in the S-model by using the empirical effective rainfall sub-model disregarding "actual" field water levels; and in the F-model by assuming field runoff only when 10 cm field water level is exceeded. However, as mentioned above, slow surface runoff between irrigations have likely taken place, also during land preparation. Thus, most likely, both water balance models may have underestimated the surface runoff term (R) and consequently overestimated the D terms as mentioned above. In principle, this would not have influenced the I_F estimate of the F-model but it may have contributed to an overestimation of the $I_{S,N}$ of the S-model if sizeable surface runoff following irrigations was not accounted for in the outflow measurements.

Conclusion and Perspectives

Although the studies were not designed to rigorously test the validity of either model or to facilitate a rigorous comparison of the two models, the results indicate that the F-model may have underestimated and/or the S-model overestimated irrigation deliveries and "water use" ($D+ET$) at their respective scales. However, a simple measurement error analysis suggest that, in 2003 the apparent difference between the S-model's net irrigation delivery, when conservatively corrected for distribution losses, and the F-model's field irrigation delivery may *inter alia* be explained by basic measurement errors of 17 % in the net irrigation delivery estimate. In 2004, the models' estimates seem to be at major variance but unusually high rainfalls may have contributed to this discrepancy. On balance, and since the S-model can not in itself provide estimates of the field irrigation delivery without additional assumptions on the distribution efficiency, it is tentatively concluded that the I_F estimate of the F-model and the $I_{S,N}$ estimate of the S-model are both valid though somewhat uncertain estimates of the seasonal hydraulic loading rate with wastewater of respectively the rice fields and of the overall scheme area.

The study highlights the fundamental problem of estimating area-wide and seasonal average irrigation and water balance components and the need to combine both system and field level analysis when estimating irrigation deliveries and water balance components in irrigation schemes. Furthermore: location specific rainfall data is a must; field water levels should be monitored for validating the field model; and the scheme-level model require inflow-outflow measurements and scheme boundary inspections during all irrigation events for accurately estimating seasonal net irrigation delivery. The separation of the D and R terms, conceptually and by estimation, needs to be improved especially in hydrologically open schemes. Thus, the R-term may need to be included in the scheme water balance equation and to be considered a continuous process in the field water balance model.

The uncertainty of nutrient and pollutant loading rates at field level estimated from irrigation deliveries is obviously considerable, combining estimation errors in irrigation deliveries and in element concentrations. Thus, the field-level seasonal nutrient and pollutant loading rates could easily be associated with uncertainties in excess of say 25 % on average and with a considerable field-to-field variability. Resource demanding field work would be required to reduce this uncertainty substantially.

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References

1. Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome.
2. Dastane, N.G. (1978). Effective rainfall in irrigated agriculture. FAO Irrigation and Drainage Paper No. 25. FAO, Rome.
3. Doorenbos, J. and Pruitt, W.O. (1977). Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper No. 24 (revised). FAO, Rome.
4. Jensen, Jens Raunsø (2005). Climate, water balance, irrigation, and nutrient loads. Technical Report of the Project wastewater Reuse in Agriculture in Vietnam – A Case study on wastewater irrigated rice at Nam Dinh, Red River Delta, Vietnam. The Royal Veterinary and Agricultural University (KVL), Copenhagen, Denmark.
5. Tuan, Doan Doan, Raschid, Liqa and Priyantha, Jayakody (2006). Waste water management and impact of water use on farm households – a case study in Nam Dinh City. Project report, VIWRR/IWMI.
6. Tuong, T.P. and Bouman, B.A.M. (2003). Rice production in water-scarce environments. p 53-67 In Kijne, Barker and Molden (eds.) water productivity in agriculture: limits and opportunities for improvement. CAB International.