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Optimum irrigation and pond operation to move away from exclusively rainfed agriculture: the Boru Dodota Spate Irrigation Scheme, Ethiopia

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Abstract Under rainfed agriculture without supplementary supply, crop failure due to erratic rainfall has become a common phenomenon in many regions of Ethiopia. Spate irrigation development with storage provision at the 5,000 ha Boru Dodota Spate Irrigation Scheme is one of the initiatives to move away from exclusively rain-dependent agriculture. This initiative has faced several challenges. Lack of design experience and failure to fully grasp the unpredictable nature of the spate flow caused the Boru Dodota Spate Irrigation Scheme to be implemented without considering the necessity of storage ponds. In addition, absence of a systematic approach to assist planners has resulted in non-optimal design of ponds' capacity and operation. The study, on which this article is based, aimed at optimum storage operation to irrigate the maximum possible area with the existing ponds' capacity and available water resource. During the study, the surface storage and irrigation scheme planning model was developed and used to analyze several pond operation scenarios in Boru Dodota Spate Irrigation Scheme. The main findings were as follows: (1) Supplementing the rainfall with the operation of the existing 19 ponds that enable weekly irrigation frequency results in irrigating at least 6,600 ha. (2) An increase in the number of ponds does not always guarantee an increase in the size of irrigated land because the water resources, the operation, and management are defining factors. (3) It is not economical to only rely on spate flow for irrigation as even with 200 ponds, a maximum of 1,250 ha could be irrigated.

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Introduction

The annual renewable fresh surface water and groundwater potential of Ethiopia are 122 billion m^3 and 2.6 billion m^3, respectively. This makes the average physically available water resources per person per year to be 1,575 m^3 (Awulachew et al. 2007). However, the water resource is not evenly distributed by season and location, and only 3 % of it remains in the country (UN World Water Assessment Programme 2006).

Rainfed agriculture is the main stay of the economy. It accounts for 90 % of the export, 85 % of employment, and 55 % of GDP (World Bank 2004). Due to inadequate water storage capacity to smooth and schedule the water delivery, the entire agricultural cycle is disrupted whenever the rain fails or simply comes too early or too late (World Bank 2006). The result is that recurring droughts leave poor farming families without food crops and cause periodic famines (International Fund for Agricultural Development (IFAD) 2008). Therefore, moving away from exclusively rain-dependent agriculture is a way to combat frequent crop failure.

In rainfed areas, the water management system, water harvesting, and river basin management can contribute to the required increase in food production (Schultz et al. 2005). As part of flood water management, the initiation and support for the spate irrigation development by government programs', farmers' and a limited number of civil society organizations of Ethiopia are encouraging. This development contributes toward a sustainable increase in food production and in eradicating poverty (Van Steenbergen et al. 2009). Spate irrigation is defined as a type of flood management practiced in arid and semiarid lowlands bordering highlands. In spate irrigation systems, floods that are generated by heavy rainfall in upper sub-basins can be diverted from normally dry wadis (ephemeral streams) and distributed using earthen, brushwood, or concrete structures to irrigate low-lying fields (Mehari et al. 2008). Spate irrigation in the context of Ethiopia could be defined as a method of applying supplementary and complementary irrigation to the midlands (1,000–1,700 m + MSL) and the low-lying lands (below 1,000 m + MSL), respectively, by diverting floods that are generated from the adjacent upper lands. The traditional spate irrigation is practised in the lowland areas of Ethiopia; however, the current intervention on improved spate irrigation systems are encountered more in the midlands and some in the lowlands (Van Steenbergen et al. 2010). The Boru Dodota Spate Irrigation Scheme, the focal study of the research on which this paper is based, is the first modern medium-scale spate irrigation scheme in the Oromia Regional State of Ethiopia and is situated in the midlands.

The Boru Dodota Spate Irrigation Scheme has considerable direct rainfall on its command area, 813 mm per year. Though the rainfall during the main rainfed cropping season “Mehir” (June to September) on average exceeds the evapotranspiration by 6 %, the area is known for frequent crop failure due to the rainfall delays during the flowering stage of the crop. This challenge led to the intervention of supplementing the rainfall with flood (spate) flow from the Boru sub-basins. The main goal of the intervention was realizing food self-sufficiency for a population of 30,073 (John 2008). The construction of the scheme that encompasses diversion, conveyance, storage, and distribution structures started in January 2007. The scheme became partially operational in 2007 on 300 ha and fully functional serving the total area (5,000 ha) by mid of 2010.

The Boru Dodota Spate Irrigation Scheme has not met its stated objective for several reasons, mainly the lack of experience to divert and manage the unpredictable floods within the field, and technical and institutional incapability to effectively utilize the available water resources. For effective water resources utilization, in addition to the diverted flood, the direct rainfall on the command area, which is substantial in amount but erratic in nature, needs to be considered. Furthermore, channeling the vigorous flood directly to the field needs to consider the existence of dry crops in the command area. Hence, sufficient storages to retain and regulate the flood flow become essential.

In Boru Dodota Spate Irrigation Scheme, the need for flood storage devices was not considered during the design phase. The significance of flood storage was understood after the start of the project implementation. Accordingly, the existing few ponds which have long been used by the community to harvest surface runoff from the micro sub-basin were upgraded and their shape and the size (almost equal size on average; each with live storage capacity of 6,400 m^3) were adopted for the construction of an additional one. The flood from the micro sub-basins enters into the conveyance canal through a hydraulically regulating crossing structure (Fig. 1) and the excess runoff above the canal capacity flows to the pond. Ponds also get their supply from the canal system. Starting with the upgrading the existing few ponds in 2008, the total numbers of ponds in 2010 has reached 19.

The rural agricultural extension office in the Dodota District disclosed that in 2008 and 2009, only 1,821 and 1,686 ha of land, respectively, were able to be supplemented with spate flow, although the infrastructure was ready to serve a command area of more than 4,000 ha. In 2010 when good rain and flood were observed, only 3,353 ha out of the developed 5,000 ha got spate flood. This raised the question whether supplementing the preplanned 5,000 ha is possible with the existing numbers/capacity of the ponds.

A number of factors have made fixing the number, capacity, and operation of ponds sub-optimal with respect to irrigating the maximum possible area with the given infrastructures and dependable water resources. This includes the absence of a systematic approach to be adopted by the technicians who are active in the planning and operation of spate development works, variability of the floods, and the un-gauged nature of the floods. Therefore, the specific objectives of the study conducted in the Boru Dodota Spate Irrigation Scheme were as follows:

Fig. 1 Hydraulically regulating crossing structure where flood from micro sub-basin crosses the canal. The structure allows water from the micro sub-basin to join the flow in the canal; and regulates the carrying capacity of the canal not to be exceeded. The *arrow* indicates the flow direction in the conveyance canal

- to optimize operation of the ponds and irrigation scheduling so as to irrigate the maximum possible area in Boru Dodota spate irrigation scheme with the existing pond capacity;
- to learn the role of considering the complementary nature of the water resources (the direct rainfall and the flood) in determining the required number and capacity of ponds;
- to develop a spreadsheet program that can support the decision making for spate development works throughout Ethiopia and beyond by systematically optimizing the water resource, extent of land area, and operation of the storage ponds.

Materials and methods

The study area

The Boru Dodota Spate Irrigation Scheme is located at 8°11′N, 39°22′30″E in Arsi zone, Oromia Regional State, Ethiopia, 135 km from the capital Addis Ababa. This scheme is established to increase agricultural production to achieve food self-sufficiency at household level through supplementing the existing rainfed agriculture over 5,000 ha with spate irrigation (Aman 2007).

The rainfall in the command area lasts for 3 months, June to August, and may extend to a few days in September (John 2008). The command area experiences erratic events and sometimes remains dry almost all the year (Aman 2007). At Melkasa station, 12 km from the study area, based on the 40-year record, the average annual rainfall and potential evapotranspiration are 814 and 1,906 mm, respectively. In the sub-basin, where the flood originates, the rainfall is bimodal. The major rainy season "Kiremt" extends from June to September and the minor rainy season "Belg" usually begins in January–February and ends in April–May (John 2008). At Kulumsa station, located within the sub-basin, the 30-year mean annual rainfall and potential evapotranspiration are 859 and 1,458 mm, respectively.

The rainfall with the longer wet season in the highlands generates runoff that flows through Boru Wadi and local drains (Fig. 2). Boru Wadi starts at Chilalo Mountain (4,000 m + MSL) and reaches 1,840 m + MSL at the diversion weir (Aman 2007). Ogee Weir (1.5 m high and 8 m long) was designed for 100 m^3 s^{-1} peak flood (Aman 2007) to divert runoff from Boru Wadi at its left bank through the free rectangular intake (width 2 m and height 2.35 m) as supplement to the water supply for rainfed agriculture. The runoffs from the micro sub-basins enter the main canal through hydraulically regulated crossing structures (Fig. 1) that also ensure the main canal is not filled above its design capacity. As often happens in the ephemeral environments, neither the Boru Wadi nor the drain from the micro sub-basins have measured runoff data, except for water level measurements at the diversion since 2008. Site observation, information from people who have lived in the area, and rainfall-runoff modeling were used to understand the flood from the sub-basins. The size of the micro sub-basins is more than twice of the Boru sub-basin (Fig. 2). Discussions with farmers in the area and the rainfall-runoff modeling support the notion that the relative contribution of the flood amount from the Boru sub-basin and micro sub-basins to the scheme correlates well with the size of their corresponding watersheds.

The headwork has a manually operated under sluice gate to remove the sediment deposit in front of the free intake. The wider canal section in the main canal, just downstream of the intake, serves as sediment trap. The main canal was designed for 6 m^3 s^{-1}. If a higher discharge is diverted, or if water is not needed downstream, the rejection spillway on the main canal situated just downstream of the weir site is operated to return excess flow into the natural course of Boru Wadi. The system has a 17.4-km-long main canal which branches 2.5 km from the headwork. There are seven branch canals.

The Scheme is also equipped with 19 ponds unevenly distributed over the command area. Construction of ponds was not considered at design phase. However, their significance was later understood and the few ponds that had been used traditionally by the community for a long time were upgraded. Some new ponds were constructed bringing the total number of ponds to 19. All the storage ponds have trapezoidal frustum shape with 2.3 m depth, side slope 3:1 (vertical over horizontal), and bottom dimensions 48 by 43 m. The ponds have almost equal capacity: average live storage of 6,400 m^3 and dead storage of 50 cm deep below the ponds bottom outlet. The dead storage is meant for sediment accumulation. In fact, the sediment is absorbed in settling basin, canals, and division boxes minimizing its presence in ponds. There are 349 tertiary canals that take water from the ponds and supply canals to distribute water to the 5,000 ha command land (Oromia Water Works Design and Supervision Enterprise 2009). With the aim of fair water sharing among the farmers, these tertiary canals are ideal to operate the unevenly placed ponds in an integrated manner. Such an integrated operation is not, however, currently practised; each pond is restricted to only irrigate the area around it. These non-integrated pond operations could cause vehement conflicts as the farms located far from the ponds may rarely get a share of the stored water (Fig. 3).

This soil in the study area consists predominantly of silty clay loam (17.1 % sand, 39.9 % clay, and 43 % silt). The soil is characterized by an infiltration rate of

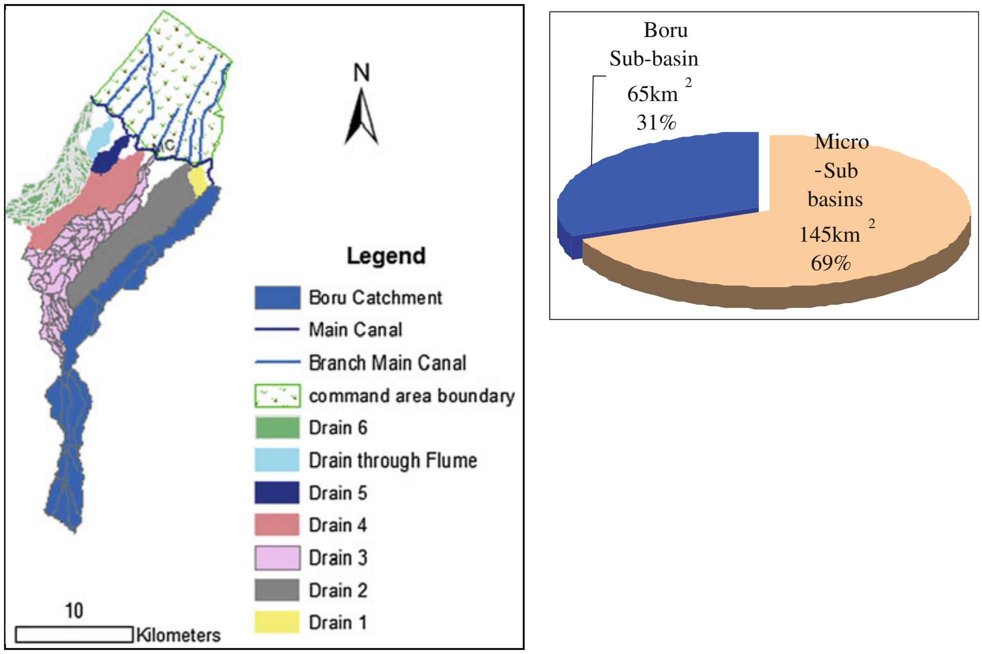

Fig. 2 Sub-basins supplying runoff to Boru Dodota Spate Irrigation Scheme

Fig. 3 Diversion Weir (*left*) and pond (6,400 m^3) (*right*) at Boru Dodota Spate Irrigation Scheme

33 mm day^{-1}, average bulk density in the top 0.60 m soil depth of 1.26 g cm^{-3} and a pH of 7.64 (John 2008). The soil moisture content is 372 and 185 mm m^{-1} at field capacity and permanent wilting point (De Laat 2002). The hydraulic conductivities corresponding to soil moisture level at permanent wilting point, field capacity, and saturation are 47×10^{-5}, 1.4, and 15 mm day^{-1}, respectively.

Wheat, barley, teff, maize, beans, and onions are the major crops grown in the command area. In 2009, wheat and barley covered 70 % of the land under spate irrigation. Most of the time, spate irrigation is needed during the entire wet season as rainfall is erratic. However, in a good season, supplementary irrigation is required only at the end of the wet season when the rain may stop during the flowering stage of the crops. The introduction of spate irrigation has led to an increase in yield when compared with the yield from rainfed agriculture. However, the yield increase is not satisfactory when it is compared with the maximum yield that can be obtained under optimum conditions (Table 1).

Surface storage and irrigation scheme planning (SSISP) model

The surface storage and irrigation scheme planning (SSISP) model has two sections: surface storage and an irrigation scheme water balance. The surface storage water balance considers the storage pond as control volume to evaluate the water balance and eventually determine the number, capacity, and operation of the pond. The scheme water balance is to determine the water deficit by simulating water fluxes in the root zone. Considering the storages and the scheme water balance separately helps to incorporate the irrigation (quantity and frequency) intervention, which is outflow from the storage water balance and inflow to the scheme water balance. Figure 4 portrays the schematization on how the SSISP spreadsheet program works.

In Fig. 4, θ is soil moisture content, ET_a/ET_m is actual/maximum evapotranspiration, ΔS is change in storage, E is

Table 1 Actual yield for 2009 on rainfed field versus Boru Dodota spate irrigated field

Crops	Rainfed (kg ha^{-1})[a]	At Boru Dodota spate irrigation (kg ha^{-1})[a]	High producing variety (kg ha^{-1})[b]
Wheat	80	350	4,000–6,000
Barley	100	270	–
Teff	109	160	2,200–2,800
Maize	85	60	6,000–8,000
Haricot bean	52	60	1,500–2,500

[a] Collected from the records of the Dodota 1-Sire district water office

[b] The yields for high-producing varieties adapted to arid and semi-arid areas under adequate water supply and high level of agricultural inputs under irrigated farming conditions, adapted from FAO-ID33 (De Laat 2002)

constant—its value to be defined based on the amount of water to be left to the downstream, ΔT is time step (in this case 1 day), P is rate of percolation/seepage from a pond, m is side slope of the pond, L and W are bottom length and width of trapezoidal frustum pond.

Part-1: surface storage water balance

Conceptual background The surface storage water balance is schematized to have runoff and rainfall as inflows and evaporation, percolation, and irrigation withdrawal as outflow components (Fig. 4). The model accepts daily runoff in m^3 day^{-1} and monthly or daily rainfall in mm. Then, the volume of rainfall to the ponds is computed by multiplying the rainfall depth by the top surface area of the storage ponds. The other components of the water balance are the losses in the form of evaporation and percolation, which depend among others on the shape of the storage and the amount of water within it. The water volume in the storage ponds varies in the simulation period and this results in fluctuations of the water surface area in contact with the atmosphere and the pond wetted area in contact with water which are used to compute the evaporation (Eq. 5) and percolation (Eq. 6) losses, respectively. In the SSISP spreadsheet program, the subsequent top water surface area and the wetted wall area are computed as described below. For length, L, and width, W, of the pond bottom and pond side slope, m, the volume (V) of water in the pond, the top surface area (A_T), and the wetted surface area (A_W) corresponding to the water depth (h) in the pond are computed as follows:

$$A_b = L * W \quad (1)$$

$$A_T = [W + 2 * m * h] * [L + 2 * m * h] \quad (2)$$

$$A_W = A_b + h[2 * W + 2 * L + 4 * m * h] * \sqrt{m^2 + 1} \quad (3)$$

$$V = 0.5 * h[A_b + A_T] \quad (4)$$

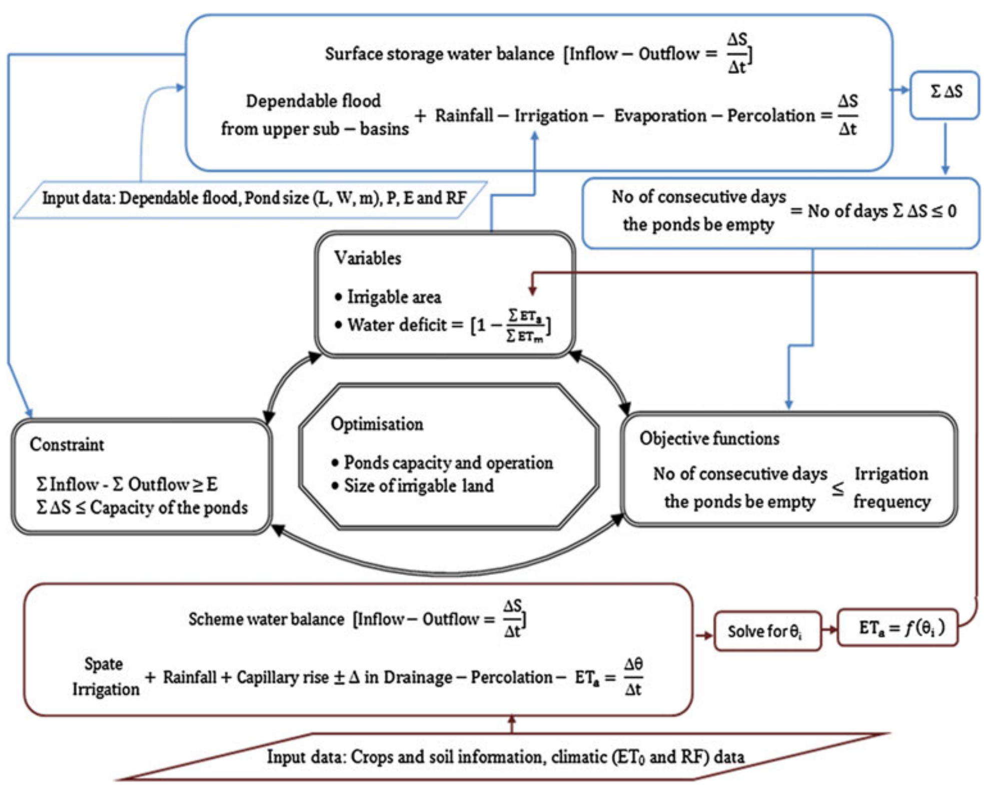

Fig. 4 Schematization of the surface storage and irrigation scheme planning (SSISP) spreadsheet program

$$E = E_o * \{[W + 2 * m * h] * [L + 2 * m * h]\} \quad (5)$$

$$D = \mathrm{DR} * \left\{A_b + h[2 * W + 2 * L + 4 * m * h] * \sqrt{m^2 + 1}\right\} \quad (6)$$

where L, W, and A_b are the pond bottom length, width, and the pond bottom area, respectively, m is the side slope of the pond, E is evaporation from the pond in m^3, E_0 is open water evaporation in m day^{-1}, D is deep percolation from the pond in m^3, and DR refers to deep percolation rate at m^3 day^{-1}.

After the live storage is depleted, the water below the bottom outlet (the dead storage) supports the water losses in the form of evaporation and percolation. To incorporate this component in the model, it is assumed that the evaporation and percolation will continue to occur from the surface area equal to the bottom area of the dead storage.

The irrigation water requirement is the other important component of the surface storage water balance. This flux depends on the crop types, climatic condition, and water losses while conveying water from the pond to the field and distributing it within the field. Irrigation scheduling in the model can be addressed in two ways. The first choice is to select irrigation intervals from the pre-defined intervals in the model (i.e., 7, 10, 14, or 21 days). The other option is user-defined; here, users can define the amount and timing of irrigation as per their interest. While selecting the interval, the model computes an irrigation depth equal to the crop water requirement for the interval and irrigates it at the beginning of the selected interval. In this case, if the computed irrigation requirement exceeds the soil moisture holding capacity, the model irrigates an amount that is only equal to the allowable moisture. For example, if an irrigation interval of 7 days is selected, then the irrigation water demand (IWD) to be applied every 7 days is computed as follows:

$$\mathrm{IWD}_7 = \bar{k}_c * \left(\sum_{i=1}^{1=7} \mathrm{ET}_0 - \sum_{i=1}^{7} \mathrm{eff.RF}\right) \quad (7)$$

$$\bar{k}_c = \frac{1}{7} * \sum_{i=1}^{i=7} \left(\frac{(k_{c\,I} a_I + k_{c\,II} a_{II} + k_{c\,III} a_{III} + k_{c\,n} a_n}{A}\right)_i \quad (8)$$

where IWD_7 is irrigation demand for 7 days in mm, k_c is weighted mean of crop coefficients, ET_0 is reference evapotranspiration in mm day^{-1}, eff.RF is effective rainfall in mm, i is number of days (1–7), I and a_I represent crop type and area covered by crop type I, whereas $A = \sum_{I=1}^{I=n} a_I$ is total area covered by all crops.

Then, the minimum amount of the computed irrigation demand or allowable moisture depth will be applied every week. Rainfall contribution is optional and it can be controlled by simply checking (considering rainfall) or un-checking (ignoring rainfall) the appropriate key in the main simulation window. Three methods: fixed percentage, dependable rain, and USDA soil conservation service methods (FAO 2008) were used to compute effective rainfall.

With the model, it is possible to operate one pond to supplement its own command area or manage a number of ponds in an integrated way. In the case of Boru Dodota Spate Irrigation Scheme, the model is arranged to manage the ponds in an integrated manner as the 19 ponds are unevenly distributed over 5,000 ha. The size of the flood storage ponds, their operation, and the size of the area to be supplemented with spate floods are optimized based on the dependable water resources by limiting the number of days that the ponds become empty to be less than the frequency of irrigation. The number of days that the ponds become empty is considered by counting the number of days that the cumulative change in storage is less than or equal to zero. The cumulative change in storage on each day cannot exceed the capacity of the ponds.

Part-2: irrigation scheme water balance

Conceptual background The continuous water balance equation is applied to the root zone of the irrigation scheme that receives spate irrigation and direct rainfall on the command area. The scheme water balance can be schematized to have inflows (spate irrigation, rainfall, capillary rise, and subsurface drainage) and outflows (actual evapotranspiration, surface drainage, percolation, and leaving sub-surface) components.

Uniform distribution of the moisture content (θ) in the root zone with depth (z) or $\mathrm{d}\theta/\mathrm{d}z = 0$ is assumed. In addition, the percolation rate at the lower boundary is treated to be equal to the hydraulic conductivity in the root zone (Mehari et al. 2008). The running scheme water balance is used to compute the actual evapotranspiration flux and then to compare it with the maximum evapotranspiration to eventually determine the water deficit. The relationship between the irrigation scheme water balance and surface storage water balance in the SSISP spreadsheet program is depicted in Fig. 4.

The spreadsheet program quantifies the vertical flux (capillary rise, percolation). The vertical flux is considered as a positive or negative value, depending on the net flux is downward or upward. To quantify the percolation, the one-dimensional vertical steady flow equation (Eq. 8) (Darcy's law) was simplified after assuming uniform distribution of the moisture content (θ) with depth (z) as follows:

$$q_z = -k\left(\frac{\mathrm{d}h}{\mathrm{d}z} + 1\right) \quad (9)$$

where q_Z is soil water flux density (positive upward) in cm day^{-1}, k is hydraulic conductivity in cm day^{-1}, h is soil water pressure head in cm, and z refers to vertical coordinate in cm, taken positively upward.

The assumption $d\theta/dz = 0$, which may be valid after a long infiltration time, implies that dh/dz be equal to zero. Then, Eq. 8 reduces to $q_z = -k$, implying a percolation rate at the lower boundary of the root zone equal to the hydraulic conductivity in the root zone (Mehari et al. 2008). Eventually, the relationship between the hydraulic conductivity k (cm day^{-1}) and the moisture content θ helps to compute the hydraulic conductivity that was assumed to represent the deep percolation for the corresponding known moisture content in the root zone. If the moisture content exceeds soil saturation, a deep percolation value corresponding to the maximum hydraulic conductivity at soil saturation is adopted. The spreadsheet program incorporates data from De Laat (2002) for four soil types, namely silty clay loam (soil type of the Boru Dodota command area), silty loam, loam, and silty clay. In addition, a user defining window is prepared where users can define the relationship of the hydraulic conductivity with moisture content k (θ) of their soil.

Irrigation and rainfall are inflow components. Irrigation is applied as it is described under "Part I: the surface storage water balance." Irrigation takes its water resource from the storage ponds. However, this water encounters losses before it is used by the crops. These losses are accounted through efficiency terms:

- *Conveyance efficiency* is the proportion of water that reaches the field inlet with respect to the amount withdrawn from the storage ponds or diverted from the stream;
- *Field application efficiency* is the proportion of water that is used by the crops with respect to the amount at the field inlet.

For planning purposes, the conveyance and field application efficiencies are estimated by considering the expected situation of the scheme and earlier experiences. However, during the operational phase, these efficiencies could be measured and used to simulate the scheme.

Surface runoff is the outflow from the scheme root zone water balance. Soil and crop types, rainfall intensity, irrigation depth, operation, and management in the scheme all affect the surface runoff. In the SSISP spreadsheet program, the surface runoff leaving the scheme was considered proportional to the amount of irrigation and rainfall depths. The ratio of measured surface runoff to the applied amount of irrigation and rainfall depths can be used as a proportional value to be entered into the model. The user can also select zero as surface runoff, if water does not leave as surface runoff from the scheme or if the user accounts the surface runoff as loss within the definition of field application efficiency.

The model considers the net subsurface drainage (subsurface inflow minus subsurface outflow) from the scheme to be zero considering the command area to be flat.

The other important terms in the scheme water balance are the actual evapotranspiration and soil moisture change in the root zone. The actual evapotranspiration depends on the characteristics of the crop, soil type, climatic condition, soil water pressure, and the hydraulic conductivity in the root zone. The available moisture in the root zone is the moisture content between field capacity and wilting point. Crops can consume their potential or maximum evapotranspiration (ET_m) only for a fraction p of the total available moisture called the readily available moisture in the soil. The factor p depends on the types of crops and their potential evaporative demand. For more than one crop in the scheme, the weighted average potential evapotranspiration is considered based on the proportion of the area under each crop. Actual evapotranspiration depends among others on the soil moisture content. Within the range of readily available soil moisture, actual evapotranspiration is equal to the potential evapotranspiration. This value decreases linearly from ET_m to zero corresponding to the soil moisture at the lower limit of the readily available soil moisture and at the wilting point, respectively. Writing the above in the form of equations: if θ_t is a soil moisture content at time t, then the actual evapotranspiration can be quantified as follows: (De Laat 2002)

$$\theta_t \geq \text{FC} - \text{RAM}, \quad \Rightarrow \text{ET}_a = \text{ET}_m \tag{10}$$

$$\text{FC} - \text{RAM} \geq \theta_t \geq \text{WP} \quad \Rightarrow \text{ET}_a = \frac{(\theta_t - \text{WP})}{\text{AM} * (1 - P)} * \text{ET}_m \tag{11}$$

$$\theta_t < \text{WP} \quad \Rightarrow \text{ET}_a = 0 \tag{12}$$

where θ_t is soil moisture content in the root zone at time t in mm, FC and WP are soil moisture content in the root zone at field capacity and wilting points in mm, respectively, AM and RAM are available moisture (AM = FC − WP) and readily available moisture (RAM = p*AM) in mm, and p stands for depletion factor.

The running scheme water balance in the model is initiated with initial soil moisture to start the simulation, and the corresponding actual evapotranspiration is computed based on this initial value. Then, the soil moisture for the next time step is computed from the scheme water balance. In general, the actual evapotranspiration at $t + 1$, ETa_{t+1}, is computed from the soil moisture at the earlier time step, θ_t. The soil moisture for the next time step, $t + 1$, is computed from the water balance equation as below.

$$\theta_{t+1} = \theta_t + [I_{t+1} + \mathrm{RF}_{t+1} - (\mathrm{FD} + D + \mathrm{ET}a)_{t+1}] * \Delta t \quad (13)$$

where θ_t and θ_{t+1} refer to soil moisture content in the root zone at time t and $t + 1$, respectively, in mm, I is irrigation in mm, RF is rainfall in mm, FD is surface runoff in mm, D is deep percolation in mm, ET_a is actual evapotranspiration in mm, and Δt is time step in day.

Water deficit application

Deficit application is said to take place when there is not enough moisture in the root zone to support the crops' potential evapotranspiration demand. When irrigating with an amount less than the crop, water requirement once could save water to bring more lands under deficit irrigation. In the SSISP spreadsheet program, the water deficit section is optional as an irrigation development can be planned with or without deficit application. This section helps the user to assess the extent to which the crop water requirement is satisfied with the planned ponds operation and irrigation application. The water deficit for the crop period is computed using Eq. (14).

$$\text{Water deficit} = 1 - \frac{\sum_{t=1}^{B} (\overline{\mathrm{ET}}_a)_t}{\sum_{t=1}^{B} (\overline{\mathrm{ET}}_m)_t} \quad (14)$$

$$(\overline{\mathrm{ET}}_a)_t = \left(\frac{a_1 * (\mathrm{ET}_a)_1 + a_2 * (\mathrm{ET}_a)_2 + a_n * (\mathrm{ET}_a)_n}{A} \right)_t \quad (15)$$

$$(\overline{\mathrm{ET}}_m)_t = \left(\frac{Kc_1 * a_1 + Kc_2 * a_2 + Kc_n * a_n}{A} \right)_t * (\mathrm{ET}_o)_t \quad (16)$$

where A is area, B is the period from earliest plantation to the last harvesting time in day, ET_a and $\mathrm{ET}m$ are actual and potential evapotranspiration, respectively, in mm day^{-1}, n is number of crop types in the scheme, and kc_1 and kc_2 refer to crop coefficient corresponding to *crop-1* and *crop-2* that cover area a_1 and a_2 of the total area (A), respectively.

Two options are provided in the SSISP spreadsheet program to simulate and practice water deficit. The first one is through the user-defined scheduling method by adjusting the irrigation timing and irrigation depths until the intended water deficit is gained. The second option is through reducing the application of the full irrigation requirements using the key on the main simulation page. Using this key, the irrigation supply can be adjusted from 0 to 100 % of the total requirement until the targeted water deficit is obtained. In both options, water is saved by reducing the amount of irrigation water. However, water could also be saved through improving the operation and management practice, which can only be incorporated through adjusting the efficiency components.

Operation of the SSISP spreadsheet program

The macro in the Excel program gives the SSISP model an interactive user-interface where keys assist the user to select among options, update data, and navigate between different data entry and simulation windows. The data could be entered either manually or by selection from dropdown alternatives. In addition, the model is equipped with graphical representations of water level fluctuation in the pond, the root zone soil moisture fluctuation, and water deficit display in the cropping period to enable the user visualize inputs and operation results. The model structure allows updating or modification of a database containing values of the site-specific user-defined constants. This makes the model interactive, simple to use and to support decision making in the fast track water developmental works that is currently ongoing in Ethiopia.

Obtaining all the input data with finer time step is difficult. For this particular study, all the other water balance components except for the dependable runoff can be estimated on a daily basis. Hence, a daily time step is adopted to run the water balances. The daily time step helps to quantify the effect of water balance fluxes on the storage at a daily base and eventually helps to compare it with the irrigation interval that is measure in days.

The following input data, which can be obtained relatively easily either through direct measurement or from secondary sources, are expected from the user:

- Dimensions for the trapezoidal frustum-shaped pond: bottom length and width, maximum depth of live storage and side slope of the pond walls;
- Percolation (in mm m^{-2} day^{-1}) through the wetted surface area of the pond;
- Initializing values for the irrigable area (ha), the number of ponds, the amount of water in the pond (m^3), and the initial moisture content in the soil (mm). These terms are treated as variable during optimization unless their value is known beforehand. For example, the initial amount of water in the pond can be zero, and the initial moisture content of the soil can be the moisture content at field capacity or wilting point or a measured value.
- Daily or monthly runoff and climatic data (rainfall and potential evapotranspiration). The user can select from three methods for estimating effective rainfall: (1) fixed percentage, (2) dependable rain, and (3) US Department of Agriculture, Soil Conservation Service (SCS) method. The user can consider or omit the rainfall contribution in a simulation by simply checking or un-checking the rainfall key;

- The crop coefficients (*Kc*), the rooting depth, and duration of the stage (days) are needed for each growth stage of a given crop. The planting date (day/month) and area (%) covered by each crop should also be defined;
- *Soil data* including the Boru Dodota soil, four soil types are built in the model. The soil characteristics (the volumetric water content (−) and hydraulic conductivity (cm day^{-1}) of these soils were adopted from the literature (De Laat 2002). Hence, the user can select one of these soils or enter their own soil data.
- Irrigation scheduling, irrigation efficiency, deficit irrigation, and leaching practice in the model: Irrigation scheduling in the model can be addressed in two alternatives. The first choice is through selecting irrigation intervals from the pre-defined intervals in the model (i.e., 7, 10, 14, or 21 days) that are able to supply an irrigation depth equal to the crop water requirement for the selected interval. The other option is through user-defined windows where it is possible to apply one's own scheduling (depth and interval). Irrigation water efficiency (conveyance efficiency and field application efficiency) and the field drainage are also required from the user. As the irrigation efficiencies are also dependent on the management and operation aspect, it is difficult to estimate the irrigation efficiencies when using the SSISP for planning. However, when using the SSISP model for operational purpose, the actual loss can be measured from site and incorporated. In the main simulation window, it is possible to control the amount of irrigation to be applied using a key. This key helps to practice the deficit water application by adjusting the irrigation amount to be applied from 0 to 100 % of the crop water requirement. However, by increasing the percentage value above 100 %, it is also possible to practice irrigation with leaching.

Optimization

Optimization is done using the Excel solver on the simulation window. First, the irrigation scheduling needs to be adjusted either for full irrigation or until the planned water deficit is attained, and then optimization is made to fix the capacity and operation of the storage and irrigation land size based on the set irrigation scheduling. The objective, constraints, and variables need to be defined while optimizing with the Excel solver; for instance, the objective could be: The number of days when the pond is allowed to be empty should not exceed the maximum tolerable irrigation interval. Constraints refer to water resources and capacity of the surface storage. Cumulative change in storage (i.e., cumulative inflow minus cumulative outflow) cannot exceed the capacity of the surface storage. The variable, the irrigable area, cannot exceed the maximum available potential irrigable area.

Applying the SSIP model to the study area

To optimize operation of the pond and irrigation frequencies with the goal to maximize the use of dependable water resources to irrigate the maximum irrigable area with the existing pond capacity, the following irrigation application scenarios were tested: flood irrigation with a depth equal to 100 and 50 % of the crop water requirement with an application frequency of 7, 14, and 21 days. These scenarios were compared with and without contribution to the direct rainfall.

The input data for the SSISP spreadsheet program are shown below.

Crop data Crop types and the proportion of the area covered by each crop at the Dodota District are defined taking into account the crops' cover that are currently on the ground and the crops that were suggested in the design document of the Boru Dodota Spate Irrigation scheme. Table 2 summarizes the adopted crops and their information.

The rooting depth is the depth up to which the crops can absorb the soil water. The rooting depths differ for different crop types and stages of the crops. They can be limited by the depth of the soil profile. Hence, the minimum crop depth or depth of the soil profile is adopted. In this case, the crop root depth was adopted.

Climatic data (Rainfall and Evapotranspiration) Rainfall and evapotranspiration data were used from the nearest station (Melkasa at 12 km from the command area). The data were screened by tabular comparison of monthly (minimum, maximum, total) and time series plotting (through stacked-column graphs for daily rainfall data) to check for suspicious (e.g., extreme high) values and then missing data were filled. Statistical tests were done to check the stationary and homogeneity of rainfall data time series. The spearman's rank test for the absence of trend, *F* test for stability of variance, and *T* test for stability of mean were used. Eventually, the variance and mean were found to be stable and there was no trend detected.

Computation of irrigation water requirement using the average monthly rainfall data on the command area showed that the rainfall is enough to grow crops without yield reduction; however, this is not true as there is frequent crop failure every year. This is believed to happen due to rainfall being substantial in amount but erratic in occurrence. Hence, it is decided to reduce the dependency on the direct rainfall contribution, and rainfall at 80 % probability of exceedance was adopted for the analysis.

Table 2 Summary of crops and their information

Crops	Stage duration (days)				% of area coverage	Planting date	Source for K_c and duration
	I	II	III	IV			
1. Wheat							
Duration	30	30	40	30	41	5-June	FAO[a]
K_c	0.3		1.15	0.3			FAO
2. Barley							
Length	20	30	40	30	28.5	5-June	John (2008)
K_c	0.3		1.15	0.25			John (2008)
3. Teff							
Duration	30	30	40	30	18	5-July	Aman (2007)
K_c	1.1		1.1	0.55			John (2008)
4. Maize							
Duration	25	40	45	30	7.5	5-June	John (2008)
K_c	0.4		1.1	0.8			John (2008)
5. H. Bean							
Duration	20	30	25	15	5	10-June	Aman (2007)
K_c	0.4		1.15	0.35			FAO

[a] FAO Irrigation and drainage Paper No. 56, Guidelines for computation of crop water requirements (Allen et al. 1998)

Runoff data The scarce water resource in ephemeral rivers is often aggravated by climatic variability and uneven distribution of rainfall over the basin resulting in unpredictable flood both in time and in volume. In ephemeral rivers, it is very difficult to get measured run-off data that can help to trace back the trend of historical hydrographs and to adopt for water development works. Hence, the abundant measured climatic data (rainfall and evaporation) over the last 15 years from Kulumsa station (7.28′48″N, 39.32′24″E and 2,450 m + MSL) 15 km from the sub-basin were used to generate runoff from the sub-basins using rainfall-runoff modeling, NAM model (De Laat 2007), and 80 % dependable flood flow is adopted as runoff supply.

The NAM model is a so-called deterministic, conceptual, lumped type with moderate input data requirements precipitation, potential evapotranspiration, and air temperature if snow melt and snow accumulation processes are modeled. NAM model represents a drainage basin by a cascade of stores, which conceptualizes the rainfall-runoff process by three different and mutually interrelated storages: snow storage, surface storage, and lower or root zone storage. Being a lumped model, NAM treats the catchment as one unit, and hence, average value of parameters and variables represents the entire catchment.

Due to scarcity of measured data, 2-year flow data, which were too small, were used to calibrate and validate the model.

Soil data Soil type of the Boru Dodota Spate Irrigation Scheme, silty clay loam soil type, was used.

Irrigation was applied according to the scenarios, that is, irrigation depth of 100 and 50 % of the crop water requirement with the application frequencies of every 7, 14, and 21 days.

At the start of the simulation, the ponds were considered empty and the soil was considered to have a moisture content of 32 mm. The 32 mm is 6 mm more than the wilting point of silty clay loam soil as farmers usually grow their crops after one or more rainfall events.

Water management in the conveyance canal and in the agricultural field can affect irrigation efficiency. Here, conveyance efficiency and field application efficiency of 60 and 50 %, respectively, were assumed. Negligible or 0 % surface runoff was assigned, assuming water will not leave the field as surface runoff. The groundwater table was found to be deep enough to neglect capillary rise. However, deep percolation at the lower boundary of the root zone is considered equal to the hydraulic conductivity that depends on the moisture content in the soil. The net inflow or outflow subsurface drainage from almost flat command area is assumed negligible. This is because the inflow and outflow subsurface drainage is equal. If the net inflow or outflow is different from zero, then this quantity is distributed over the command area and the scheme water balance can be computed.

Optimization was made for the existing number of ponds. As the dimensions of the ponds were needed for the SSISP program, typical dimensions of the existing ponds were adopted. The pond should not be empty longer than the most frequent irrigation interval (in this case 7 days).

Hence, the maximum number of days the pond was allowed to be dry was fixed at 6 days.

Finally, by using the SSISP model, the size of the area, which can be brought under irrigation for different pond numbers (pond capacity), was compared.

Results and discussion

The SSISP model was applied to the study area for the defined irrigation schedule scenarios and the existing pond capacity. The results are presented in Tables 3 and 4.

From Tables 3 and 4, the following could be inferred:

- If spate flow is the only source of irrigation, even at a 50 % water deficit irrigation, only 46 % of the total 5,000 ha command area can be irrigated with the maximum capacity of the existing 19 ponds;
- When the irrigation interval drops from 21 to 7 days, the irrigated area increases by one to two-thirds;
- Both 7- and 14-day irrigation intervals ensure that the whole command area (5,000 ha) can be irrigated with the existing pond capacity if the spate flow is conjunctively used with direct rainfall on the command area. However, a weekly irrigation interval is preferred to ensure that almost all floods are harvested. Although based on the historical data, it can be inferred that floods usually occur on a 2-week or longer intervals, discussion with farmers, revealed that there have been some years when a number of subsequent floods have occurred on a weekly basis.

The SSISP model was also used to simulate the correlation between different number of ponds and the corresponding size of irrigated areas (Figs. 5, 6).

On the basis of Figs. 5 and 6, the following deductions can be made:

- An increase in the number of ponds does not always result in an increase in the size of the land under irrigation. This is mainly because the spate flow resource is limited and cannot support the extended size of land under irrigation. Several ponds would simply remain empty;
- The use of the spate flow as the only source of irrigation is uneconomical. Under this condition, a maximum of 1,250 ha or about a quarter of the total command area will be irrigated with 200 ponds in operation.

From the above results, it can be further inferred that:

- The farmers in Boru Dodota could be food self-sufficient only if optimum conjunctive use of the spate flow and direct rainfall is realized.
- This optimum conjunctive use could be obtained by operating the existing 19 ponds in such a way that they are emptied preferably every week and at most on a biweekly basis so that the available flood water resources could be optimally harvested.

Conclusions and recommendations

The study conducted in Borru Dodota Spate Irrigation Scheme, on which this article is based, has established that optimum operation of the existing 19 ponds is imperative for effective conjunctive use of the spate flow and rainfall, and for maximizing the irrigated area. Simulations using the SSISP model developed during the course of the study have revealed that 7- and 14-day irrigation intervals guarantee irrigation of the whole command area of the Scheme (5,000 ha). However, given the high unpredictability of the spate flow in frequency, duration, and amount, the 7-day interval is recommended to enhance the likelihood that the next spate flow is fully harvested. The model has also shown that an increase in the number of ponds does not always correlate with an increase in size of the irrigated area since the available water resources, the operation, and management play a significant role. The model further illustrated that relying only on spate flow for irrigation is not economical as even with 200 ponds, the maximum irrigated area is just 1,250 ha.

These model analyses are based on the assumption that the 19 ponds, which are unevenly distributed within the command area, are utilized in an integrated manner. Currently, each pond is being operated in isolation to only irrigate the area in its immediate vicinity. It is advisable to

Table 3 Summary of the surface storage and irrigation scheme planning model's output, based on 80 % dependable flood irrigation without considering rainfall contribution

Irrigation scheduling	Water deficit (%)			Irrigable area (ha)		
	Irrigation intervals (days)			Irrigation intervals (days)		
	7	14	21	7	14	21
100 % of the CWR	0	0	0	1,150	573	428
50 % of the CWR	8	5.9	4.7	2,310	1,150	856

Table 4 Summary of the surface storage and irrigation scheme planning model's output, based on 80 % dependable flood and rainfall with 80 % probability of exceedance

Irrigation scheduling	Irrigable area (ha)		
	Every 7 days	Every 14 days	Every 21 days
100 % of the crop water requirement	6,600	5,280	4,470
50 % of the crop water requirement	13,200	10,600	8,940

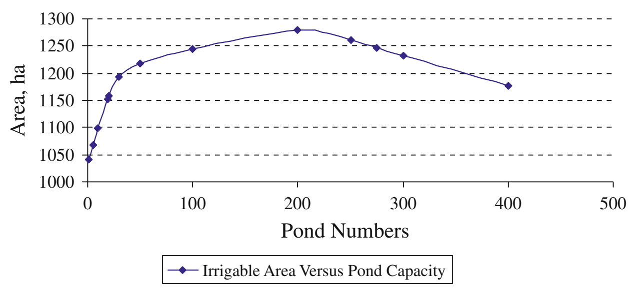

Fig. 5 Irrigable area versus pond numbers considering only runoff supply from the upper land (excluding the direct rainfall over the command area)

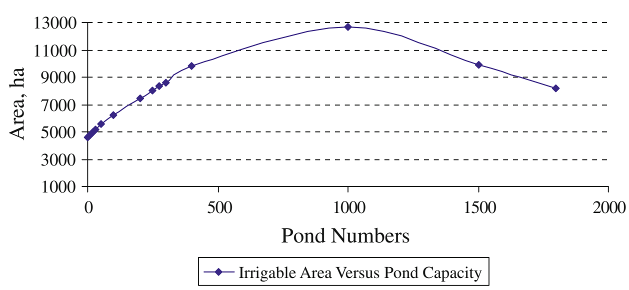

Fig. 6 Irrigable area versus pond numbers considering runoff supply from the *upper land* and direct rain fall over the command area

stop such disintegrated operation as it has already created disparity in water sharing and conflicts among the farmers.

The SSISP model is a simple spreadsheet model with an easily understandable user-interface, concepts, and computational procedures. It combines well-known and proven procedures, and equations for computing continual surface storage and irrigation scheme water balances, crop water requirement, effective rainfall, and dependable flow analysis. Its simplicity and reliance on very limited easily accessible crop, soil, runoff, irrigation scheduling and climatic data, while delivery reliable results, has earned the model acceptance among the top technical experts at the Oromia Water Resources Bureau (OWRB). Further awareness creation is required to ensure adoption of the model by the wider community of irrigation designers, managers, and practitioners.

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