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Effects of irrigation performance on water balance: Krueng Baro Irrigation Scheme (Aceh-Indonesia) as a case study

Azmeri AZMERI[1) ABCDEF] ✉, Alfiansyah YULIANUR[2) AD], Uli ZAHRATI[3) BC], Imam FAUDLI[4) BC]

[1)] orcid.org/0000-0002-3552-036X; Universitas Syiah Kuala, Faculty of Engineering, Civil Engineering Department Jl. Tgk. Syeh Abdul Rauf No. 7, Darussalam – Banda Aceh 23111, Indonesia; e-mail: azmeri@unsyiah.ac.id
[2)] orcid.org/0000-0002-8679-1792; Universitas Syiah Kuala, Faculty of Engineering, Civil Engineering Department, Banda Aceh, Indonesia; e-mail: fian_7anur@yahoo.com
[3)] orcid.org/0000-0001-8665-8193; Office of River Region of Sumatra-I, Lueng Bata, Banda Aceh, Indonesia; e-mail: uli.zahrati@gmail.com
[4)] orcid.org/0000-0002-4944-3449; Hydrology and hydraulics consultant; e-mail: imamfaudli95@gmail.com

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Abstract

Krueng Baro Irrigation is focused on increasing the productivity of food crops in Pidie District, Aceh Province, Indonesia. However, due to the age of the irrigation infrastructure (more than 30 years) and its large networks, it is necessary to investigate the actual water conveyance efficiency. This study aimed to evaluate the conveyance efficiency of primary and secondary channels of the irrigation system, as well as to create a water balance model based on the actual water conveyance efficiency. The model by using Excel Solver with its objective function is to maximize the area of the irrigated land. Based on the optimization model of the water balance, the design condition can irrigate an area of 9,496 ha (paddy-I), 4,818 ha (paddy-II), and 11,950 ha (onion). The measurement results reported that the actual efficiency of Baro Kanan and Baro Kiri was 56% and 48% smaller compared to the efficiency of the designs (65%). The water loss was due to the damage to the channel lining and channel erosion resulting in the high sedimentation, leakage, and illegal water tapping. These lead to a decrease in the area of the irrigated land. Based on the optimization model of the actual water balance, the irrigated land was reduced to 7,876 ha (paddy I) and 3,997 ha (paddy-II) while it remained the same for onion. Therefore, to increase the efficiency, the regular maintenance and operations are required by fixing the damaged irrigation structure and channels, the maintenance of sedimentation, and the strict regulation of illegal water tapping.

Key words: *actual water conveyance efficiency, irrigation performance, the area of irrigated land, water balance*

INTRODUCTION

The increasing water demand for domestic, industrial, and agricultural needs is occasioned by the world requiring around 60% more food [FAO 2013]. In 2015, the rise is to feed 9.5 billion people [SINGH 2014]. This long-term problem requires resources sustainability, including water. Water is an essential resource for humans and is sometimes scarce and struggling to obtain, especially in arid regions [AZMERI *et al.* 2017].

The appropriate management and efficiency of the irrigation water use support the water resources sustainability [FASAKHODI *et al.* 2010] as the agricultural irrigation is the primary need for water resources, more than 80% and less than 60% in developing and developed countries respectively. Agricultural irrigation remains the most critical point in achieving food security [FAURES *et al.* 2007]. However, due to the decreasing water availability and the estimation results predicting that it will keep declining by half of its current state in 2025 [DIAO *et al.* 2008].

Water resources are getting scarce in many parts of the world and will be one of the most significant problems that must be addressed immediately [LITRICO, FROMION 2009]. The problem concerning the declining water resources is challenging due to the urbanization and climate change impacts [SINGH, PANDA 2012a]. This condition endangers irrigated agriculture in many regions [SCHOUPS *et al*. 2006]. The provision of irrigation is crucial to achieving food security [SINGH 2012; SINGH, PANDA 2012b, c]. Irrigation is natural engineering by extracting water from available sources, supplying water to the irrigated land having less water or previously none. Irrigated land contributes significantly to the agricultural outputs and food supply, and therefore it requires more efficient handling of the irrigation networks. It is essential especially for the arid and semi-arid land as water resources strengthen the economic development [FOLEY *et al*. 2005; KREBS *et al.* 1999; SINGH 2010; TILMAN *et al.* 2002; VAN DAM *et al.* 2006].

Indonesia has approximately 148 million hectares of potential dry land [DWIRATNA *et al.* 2018]. The dry land for agricultural cultivation lies in Sumatra, Java, Kalimantan, Bali, Nusa Tenggara, Sulawesi, Maluku and Papua [NURPILIHAN, DWIRATNA 2015; NURPILIHAN *et al.* 2015]. The development of dryland agriculture faces several obstacles [NURPILIHAN *et al.* 2015a], especially, the dependence of rainfall for water supply and the long dry season. The dryland agriculture is more vulnerable to water shortage. Thus, additional water supply through irrigation is needed to overcome this issue. Irrigation is vital for the agricultural productivity and growth and plays an essential role as a unit consisting of various components, such as providing, distributing, and managing water to increase the agricultural production [KERCHEVA, POPOVA 2010]. Therefore, the availability of resources for irrigation management is paramount to suffice the irrigation water needs in the cultivation process. The climate change causes a shift in the start of planting season around one to two weeks [DWIRATNA, NURPILIHAN 2016].

Currently, more than 80% of available water resources in the world are used to meet irrigation needs [BHALAGE *et al*. 2015]. The figures have a significant impact on water resources. To date, a large amount of water is lost in most irrigation networks due to the inefficient control, although some irrigation networks use concrete layers on the inner surface of open channels [LITRICO, FROMION 2009]. This type of channels is designed to save water significantly. Although this lining technique needs substantial capital investment, the efficiency level of the irrigation is low. In Indonesia, the lining technique is mostly applied to primary irrigation channels. However, the average efficiency of irrigation water use remains poor [DWIRATNA *et al.* 2018].

Knowledge concerning the system efficiency is important and useful for both examining the feasibility of a system before installation and evaluating post-construction performance. Each system has an inherent performance capacity, and many efficiency terms can be used to describe the system performance. Although a single definition describing the irrigation efficiency comparing all systems is desirable, it is hard to establish one definition to include physical, economic, and biological evaluations. Thus, many expressions are developed to express various aspects of efficiency [IRMAK *et al.* 2011].

The performance of the irrigation scheme will be obtained through the evaluation of the water conveyance efficiency applied to each segment of the irrigation channels or pipelines. The efficiency level is usually higher in the pipeline due to the less evaporation and seepage. The minimal water loss in a closed/pressurized conveyance system leads to 100% of the distribution efficiency [IRMAK *et al.* 2011]. Also, lined channels will have higher efficiency due to the less seepage compared to single channels. Most of the irrigation water in Indonesia is distributed by open channels [DWIRATNA *et al.* 2018]. This paper discussed the effect of physical efficiency of a surface irrigation system on water balance in the Krueng Baro irrigation system.

The irrigation scheme contributes to the water distribution for agriculture. In the scheme of Krueng Baro irrigation, the irrigation channels are lined by concrete to save water. However, the study conducted by MEIJER *et al.* [2006] reported that concrete layers could prevent 95% of seepage loss from public channels. The value is somewhat optimistic as some previous literature report lower rates. The seepage reduction using the hard surface layer ranges from 60–80%. Even though coating materials may have low seepage rates, the possibility of cracks or connections not being correctly connected can lead to considerable seepage loss. Consequently, the coating can reduce the seepage loss by only 60% even in a favourable condition.

The expectations to enhance agricultural yields depend on the development of irrigation schemes in the areas with insufficient rainfall and weather variability being a major obstacle. In the Krueng Baro irrigation system, unpredictable weather patterns will increase the risk of farmers depending on the irrigation system. It is complicated to assess the risk level because it does not only rely on the location of the irrigation system but also the temperature fluctuation, the soil parameters (such as texture, fertility) and other weather uncertainties. A water allocation model is required considering some of these aspects [BOBOJONOV *et al.* 2016].

According to GEBRIYE *et al.* [2011], an irrigation scheduling method is based on three approaches, namely the plant monitoring, soil monitoring, and the water balance technique. The purpose and type of the irrigation system determine the irrigation scheduling method to use. It is necessary to analyse both extremes of the water deficiency and surplus considering the increasing variability of water supply in agriculture in the past decade. The water balance analysis is required to measure the supply, loss, and consumption of water to maximize the rice production in the irrigated land. Optimizing the hydrological condition is a major challenge in the water saving technology by determining the optimum amount of water supply to the fields [ARIF *et al.* 2012]. The water balance indicates the water availability for a year by calculating the factors influencing the water availability (input and output) for the water deficiency and surplus months [CAHYONO *et al.* 2016]. The water balance model is highly beneficial to manage from the first circumstance of the irrigation to the end of planting [VANINO *et al*. 2015]. Several computerized simulation models for plants water needs require to be developed. This approach is to discover the broad application of the irrigation and rainfed agriculture planning and management.

PURPOSE OF STUDY

The Krueng Baro irrigation scheme was established in 1984. The primary and secondary channels are 156.24 km. The channels are estimated to experience a degradation function of flowing water considering the age of more than 30 years and the length of the channel. Therefore, a study aiming to evaluate the conveyance efficiency of primary and secondary channels and determine the water balance based on the actual efficiency level of the Krueng Baro irrigation system needs to be conducted. Krueng Baro irrigation system must be adequately managed to achieve balanced water supplies throughout the year of planting considering its important role. The change in irrigation efficiency leads to the need of conducting a water balance approach [HARSOYO 2011] to provide information on the real area that can be served. The study was performed employing the field observation for the channel efficiency value, while the rainfall, plant water needs and water balance analyses were carried out using the optimization techniques. This study contributes to the existing literature by (a) observing the actual efficiency value of the channels and comparing it with the initial design efficiency, and (b) applying the actual efficiency value to the water allocation optimization model. Thus, the actual efficiency value obtained will adjust the water allocation and the area of the land that can be irrigated in real terms.

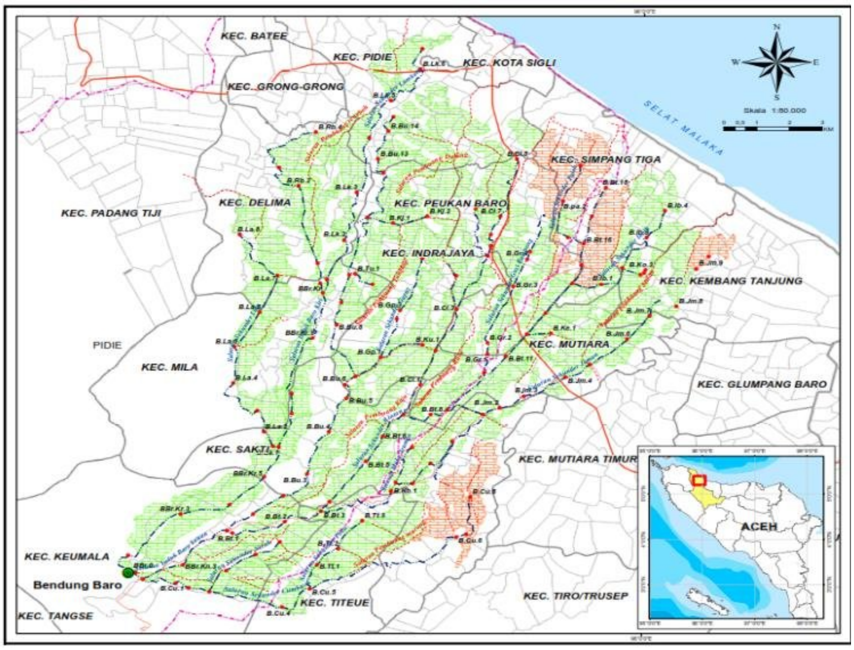

Fig. 1. Krueng Baro irrigation scheme; source: Balai Wilayah… [2017]

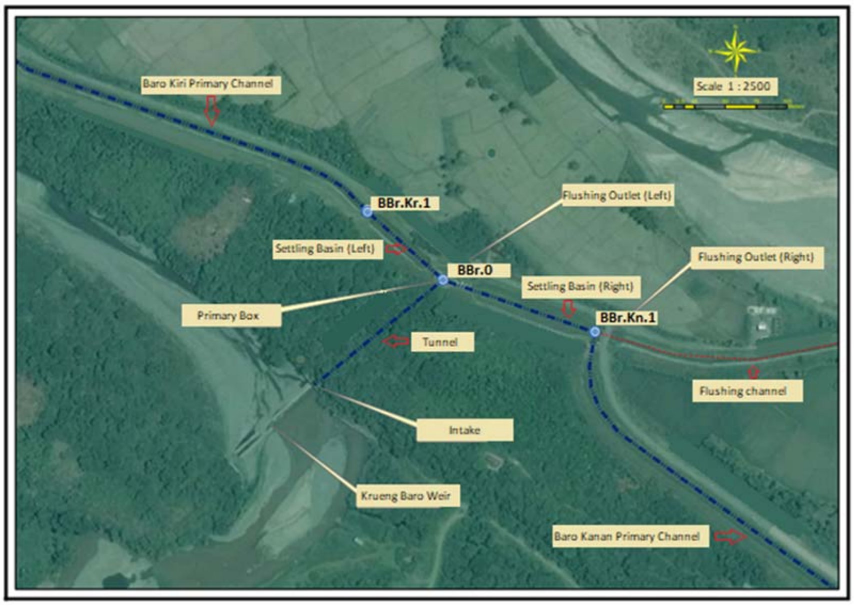

Fig. 2. Keumala weir – the Krueng Baro River; source: own elaboration

THE STUDY AREA

The study was conducted in the Krueng Baro irrigation scheme in the Krueng Baro River, Pidie District, Aceh Province, Indonesia (Fig. 1). Keumala weir as the water source in the Krueng Baro irrigation scheme is presented in Fig. 2. This irrigation scheme focuses on increasing the food crops productivity in Aceh Province.

METHODS

The water source in the Krueng Baro irrigation scheme is dammed to obtain the high energy to reach the rice fields. However, sometimes the amount of water run from Keumala weir does not reach the rice fields due to the conditions of the conveyance facilities, the open channels. Usually, water conveyance efficiency is a concern for the irrigation scheme supplying water to a group of farmers using an open channel system [ALAM *et al.* 2002].

This research involved several stages presented as follow.

A. Site investigation

The Krueng Baro irrigation scheme irrigates two rice fields, the right and left areas of Krueng Baro irrigation covering 8,920 ha and 3,030 ha respectively. The total area of rice fields is 11,950 ha. The total of the primary and secondary channels are 156.24 km, consisting of 17,397 km primary and 138,847 km secondary channels. This research started from the Baro Kanan primary and Baro Kanan secondary channels, followed by the Baro Kiri primary and the Baro Kiri secondary channels.

B. Field measurements

The field measurements were conducted by employing the following stages:
- surveying the morphological conditions of the irrigation channels in the study area;
- measuring the channel section namely the width of the channel base and the water surface;
- measuring the water levels along the irrigation channels;
- measuring the speed along the vertical part of the irrigation channels;
- measuring the discharge running through the irrigation channels.

C. Analysis of the actual efficiency results

Many conveyance systems experience the transmission loss, meaning that the water delivered to the paddy fields is less than the water diverted from the source. The water loss in the conveyance systems involves the channel seepage, the overtopping (operational or accident), the evaporation loss from the channels, and the pipeline leakage. Water conveyance efficiency is defined as the ratio of the irrigation water reaching the fields and the water diverting from its source [FAIRWEATHER *et al.* 2012], as stated in the following formula:

$$Ec = (Vf/Vt)\ 100 \tag{1}$$

Where: Ec = water conveyance efficiency (%); Vf = water delivered to the field (m^3); and Vt = water diverted from a source (m^3).

The range of application efficiencies for surface irrigation systems is as follow [IRMAK *et al.* 2011]:
- furrow (conventional) 45–65%,
- basin (with or without furrow) 60–75%,
- basin (paddy) 40–60%,
- precision level basin 65–80%.

The water conveyance efficiency for primary, secondary and tertiary channels in Indonesia is presented in Table 1.

Table 1. The range of design efficiencies for primary, secondary and tertiary channels in Indonesia

Channel type	Design efficiency range (%)
Primary	75–80
Secondary	85–90
Tertiary	75–80

Source: Kriteria Perencanaan [2013].

D. Irrigation management on the surface farming system by water balance analysis

The irrigation water requirements and irrigation scheduling are determined based on the analysis of plant water balance in a certain interval of water supply. The analysis of water balance is undertaken to establish the surplus and deficit condition in the rice fields. It is beneficial in choosing the appropriate planting schedule for the irrigation water supply. When the rainwater is deficient, the irrigation supplies the water. In Indonesia, the water regularly provided at 15-days interval was generally accepted. According to DWIRATNA and NURPILIHAN [2016], the calculation of water balance consists of six main components including the rain, the potential evapotranspiration, the actual evapotranspiration, the groundwater availability and the surface runoff (surplus and deficit). The cropping pattern in the study area was paddy–paddy–onion.

The water allocation in this study employed an optimization model for irrigation management. This model involves the objective function, the water balance for the irrigation system and the crop water production. This model also incorporates the physical constraints on the area of the irrigated land, namely the maximum of the irrigated land and the proportional area of irrigation land of the Baro Kanan and Baro Kiri. The constraint concerning the pattern of the water allocation was imposed to maintain the Keumala weir capacity to ensure the reliability of the irrigation water supply.

The objective function in the model represents the total area of irrigated land presented in the following formula:

$$Z = \sum_{i=1}^{n=3} (A_{Baro\ Kanan} + A_{Baro\ Kiri})_i \tag{2}$$

Where: A = the area of irrigated land, i = the total area of irrigated land, and n = three kinds of cropping pattern developed in the area, namely: paddy–paddy–onion.

The constraints function in the optimization model is presented as follow.
1) the availability of dependable discharge for irrigation water needs:

$$\sum_{j=1}^{k=24} (Q_{dependable_j} - Q_{irrigate_j}) \geq 0 \tag{3}$$

2) the total area of irrigated land:

$$A_{Baro\ Kanan} \leq 8920 \text{ ha and } A_{Baro\ Kiri} \leq 3030 \text{ ha} \tag{4}$$

3) the proportional comparison of the area of the Baro Kanan and Baro Kiri irrigated land:

$$\frac{A_{\mathrm{Baro\ Kanan}_i}}{A_{\mathrm{Baro\ Kiri}_i}} = \frac{8920 \text{ ha}}{3030 \text{ ha}} \tag{5}$$

Where: $Q_{dependable}$ ($m^3 \cdot s^{-1}$); $Q_{irrigate}$ ($m^3 \cdot s^{-1}$); j = the irrigation period of the irrigation land (15 days) and k = 24 for a year of irrigation.

The water requirement in the rice fields was calculated using the water balance with the difference of water input and output in the irrigated rice fields:

$$NFR = ETc + p - Re + WLR \tag{6}$$

Where: NFR = net field requirement ($mm \cdot day^{-1}$); ETc = consumptive use ($mm \cdot day^{-1}$), p = percolation ($mm \cdot day^{-1}$), Re = effective rainfall ($mm \cdot day^{-1}$), WLR = water layer replacement ($mm \cdot day^{-1}$).

The water for land saturation included the water needed for land preparation, 250 and 200 mm for paddy I and II respectively, added a change of the water layer in the rice fields by 50 mm, making the total of 300 and 250 mm for rainy and dry season paddy respectively. The water layer replacement was 50 mm during the period of land preparation.

The water balance analysis employing the Penman–Monteith method was conducted using the value of crop evapotranspiration (*ETc*) to calculate the actual evapotranspiration using the potential evapotranspiration (*ETp*). The *ETp* can be obtained from several different calculation methods. However, FAO recommended the *ETp* calculations using the Penman–Monteith method as the best estimation of evapotranspiration. The plant evapotranspiration value was calculated using the following formula [DWIRATNA *et al.* 2018]:

$$ETc = ETp \cdot Kc \tag{7}$$

Where: ETp = the potential evapotranspiration (mm·day^{-1}); ETc = the crop evapotranspiration (mm·day^{-1}); and Kc = the crop coefficient values according to the selected cropping pattern. In this study, the chosen cropping pattern is paddy–paddy–onion.

The examples of *ETc*, *ETp* and *Kc* calculation for paddy-I are presented in Table 2.

Table 2. The calculation of *ETc*, *ETp* and *Kc* for paddy-I

Period	Potential evapotranspiration *ETp* (mm·day^{-1})	Crop coefficient *Kc*	Crop evapotranspiration *ETc* (mm·day^{-1})
October II	4.802	LP	–
November I	4.888	LP	–
November II	4.888	LP	–
December I	4.814	1.083	5.216
December II	4.814	1.067	5.135
January I	4.906	1.017	4.987
January II	4.906	0.667	3.270
February I	5.312	0.317	1.682

Explanations: LP = land preparation.
Source: own study.

RESULTS AND DISCUSSION

THE MORPHOLOGY CONDITION SURVEY OF THE IRRIGATION CHANNELS AND STRUCTURE

The 156.24 km was hydrographically surveyed in this study using General Positioning Systems (GPS) and current meter. The condition of the structure, the channels, the morphology of primary and secondary channels in Baro Kanan and Baro Kiri are identified in Photo 1 and 2.

Photo 1. The condition of the structure, the primary channels of Baro Kanan (phot. *A. Azmeri*)

Photo 2. The condition of the structure, the primary channels of Baro Kiri (phot. *A. Azmeri*)

In Photo 2 the landslide and damage of the protection in the downstream waterfall.

In Photo 1 the sediments of soil and the weeds on the edge of the stone masonry lining channels.

HYDRAULIC MEASUREMENTS

The hydraulic characteristics measured the velocity of distribution and discharge passing along the cross section at the beginning and the end of each irrigation channel. The diagram of determining the sample points for each channel segment is provided in Figure 3.

Table 3 shows that the conveyance efficiency in the Baro Kanan primary channel was 86.8%. Thus, the water loss in the Baro Kanan primary channel was 3.2% of the design condition efficiency for the primary channel of 90%. The same measurement and analysis of conveyance method were used for the Baro Kanan secondary channel. The efficiency was 80.9% indicating that water loss along

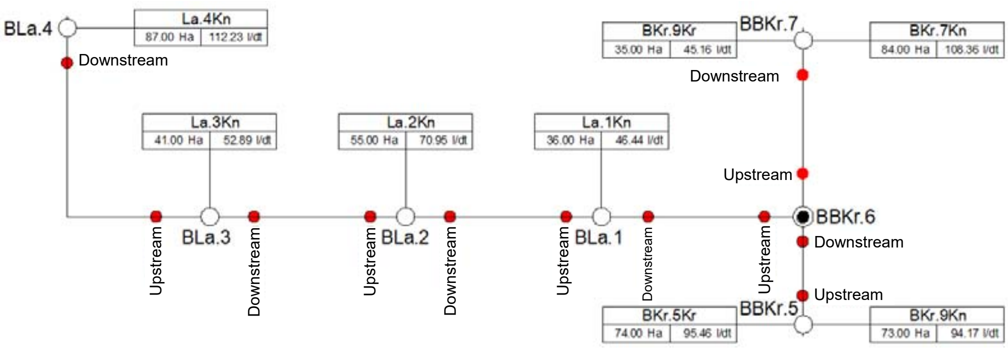

Fig. 3. Scheme of determining the sample points for each channel segment; source: own study

Table 3. The actual and design efficiency for study reaching the cross sections (Baro Kanan primary channel)

Channel code	Hydraulic characteristics									
	water diverted from a source (upstream)				water delivered to field (downstream)				water conveyance efficiency (%)	condition
	water depth (m)	cross section area (m^2)	mean velocity ($m \cdot s^{-1}$)	discharge ($m^3 \cdot s^{-1}$)	water depth (m)	cross section area (m^2)	mean velocity ($m \cdot s^{-1}$)	discharge ($m^3 \cdot s^{-1}$)		
BBrkn 1-BBkrn 2	1.42	12.61	0.55	6.98	1.72	15.28	0.40	6.08	87.0	soil channel
BBrkn 2-BBkrn 3	0.70	4.58	0.75	3.44	0.46	4.14	0.72	2.98	86.7	stone masonry channel
BBrkn 3-BBkrn 4	0.79	5.95	0.49	2.94	0.48	3.79	0.67	2.54	86.6	stone masonry channel
	Mean of the actual water conveyance efficiency								**86.8**	
	Design water conveyance efficiency								**90.0**	

Explanations: BBrkn = Baro Kanan primary channel.
Source: own study.

Table 4. The actual and design efficiency for study reach cross sections (Baro Kiri primary channel)

Channel code	Hydraulic characteristics									
	water diverted from a source (upstream)				water delivered to field (downstream)				water conveyance efficiency (%)	condition
	water depth (m)	cross section area (m^2)	mean velocity ($m \cdot s^{-1}$)	discharge ($m^3 \cdot s^{-1}$)	water depth (m)	cross section area (m^2)	mean velocity ($m \cdot s^{-1}$)	discharge ($m^3 \cdot s^{-1}$)		
BBrkr 1-BBrkr 2	1.27	9.18	0.41	3.78	1.15	6.75	0.50	3.36	88.8	stone masonry channel
BBrkr 2-BBrkr 3	1.19	6.39	0.52	3.35	0.83	3.27	0.72	2.35	70.3	soil channel
BBrkr 3-BBrkr 4	1.12	6.25	0.37	2.33	0.79	4.81	0.33	1.57	67.4	soil channel
BBrkr 4-BBrkr 5	0.58	2.88	0.53	1.53	0.38	1.58	0.46	0.72	47.3	soil channel
BBrkr 5-BBrkr 6	0.35	1.44	0.44	0.63	0.42	1.21	0.30	0.37	58.0	soil channel
BBrkr 6-BBrkr 7	0.44	1.70	0.40	0.68	0.57	2.34	0.25	0.58	84.9	soil channel
BBrkr 7-BBrkr 8	0.34	1.31	0.43	0.56	0.42	1.54	0.31	0.47	84.4	soil channel
BBrkr 8-BBrkr 9	0.82	3.09	0.33	1.02	0.44	1.14	0.70	0.80	78.3	soil channel
BBrkr 9-BBrkr 10	0.32	0.95	0.80	0.77	0.61	1.79	0.37	0.67	87.3	stone masonry channel
	The mean of the actual water conveyance efficiency								**74.1**	
	The design water conveyance efficiency								**90.0**	

Explanations: BBrkr = Baro Kiri primary channel.
Source: own study.

the Baro Kanan secondary channel was 9.1% of the design condition efficiency. Based on the results of the field observation, the channel efficiency was decreased due to the length of the primary channel lining from the ground, overgrown by weeds. Furthermore, sediment in the channel and damaged irrigation structure were also identified. The obstacles of weeds and sediments in the scope of research and the irregularity of the cross section were the main reason for the water discharge delivery to reach the irrigated land.

Table 4 indicates that the actual water conveyance efficiency of the Baro Kiri primary channel was 74.1%. So, the water loss in the Baro Kiri primary channel was 15.9% of the design condition efficiency of 90%. Based on the analysis results and the field observation, the reduced channel efficiency was due to some primary channels were lining from the ground resulting in a lot of weeds, the sediment deposition in the channel, and the damage of the irrigation structures such as the sluice gate not functioning as the regulators and gauge.

The actual water conveyance efficiency of the Baro Kiri secondary channels was 81.3%, meaning that the water loss in the channel was 8.7% of the design condition efficiency. The results of analysis and field observations revealed that the decreased channel efficiency was due to the length of secondary channels lining from the ground causing weeds overgrown several segments, the sediment deposition, illegal water tapping and many damages of irrigation structures such as the sluice gate not working as a regulator and gauge.

This study did not perform measurements on the tertiary channels. The efficiency of tertiary channels referred to the design efficiency of 80%. The actual efficiency reaching the rice fields was obtained by multiplying the efficiency values of the primary, secondary and tertiary channels. The actual efficiency values of Baro Kanan and Baro Kiri is 56% and 48% accordingly [DWIRATNA *et al.* 2018]. Both values were lower than design efficiency (65%) – Table 5.

Table 5. Summary of the actual and design efficiency for study reaching the cross sections (rice fields of Baro Kanan and Baro Kiri)

Channel	Design efficiency	Actual efficiency Baro Kanan	Actual efficiency Baro Kiri
	%		
Primary	90.0	86.8	74.1
Secondary	90.0	80.9	81.3
Tertiary	80.0	80.0	80.0
On rice fields	65.0	56.0	48.0

Source: own study.

In more detail, the reasons of the decreased channel efficiency were the length of Baro Kiri and Baro Kanan secondary channels as well as the Baro Kiri primary channel lining from the ground, landslide/cliff erosion, sediment in the channel, the illegal water tapping, and the damaged irrigation structure. Some of the cross section made of soil structure included the Baro Kiri primary and Baro Kanan secondary channels: secondary Busu, secondary Cumbok, secondary Nicah, Lamkabuen front channel, Jeumpa front channel, and Titue secondary, and Baro Kiri secondary channels: Reuboh and Lala secondary.

Some cross sections studied showed the collapsed slope erosion, some of them were at coordinates 46 N 0820180 / UTM 0585071, 46 N 0823832 / UTM 0591098, 46 N 0823832 / UTM 0591098, 46 N 0824573 / UTM 0582211, 46 N 0827649 / UTM 0584434, 46 N 0826490 / UTM 0583308 and 46 N 0827898 / UTM 0589569. The maximum collapsed slope erosion occurred on the Bintang secondary channel (BBt) at the coordinate of 46 N 0824573 / UTM 0582211 (BBt 5-BBt 6 / between BBt 6c-BBt 6) and 46 N 0827649 / UTM 0584434 (BBt 9- BBt 10 / between BBt 10-BBt 10). The total sediment volume along the Baro Kiri and Baro Kanan of channels was 174,122.93 m^3 and the total volume of channel cross section was 615,961.74 m^3. The decreased total volume of the channel cross section due to sedimentation was 441,838.81 m^3 or 28.3%.

The illegal water tapping structure was found in the secondary section of Iboih (BIb): 1-BIb BIB 2 / between the BIb 2a-BIb 2b at the coordinates of 46 N 0831678 / UTM 0587922. The severely damaged structures were BBt 5c (waterfall) at the coordinates of 46 N 0823487 / UTM 0580676, BBt 5d (waterfall) at the coordinates of 46 N 0823597 / UTM 0580848, BBt 6b (waterfall) at the coordinates of 46 N 0824391 / UTM 0581911, Bjm 3b (waterfall) at the coordinates of 46 N 0827649 / UTM 0584434, BNi 3 (building tapping) at the coordinates of 46 N 0821569 / UTM 0578735, BBu 4a) at the coordinates of 46 N 0822471 / UTM 0581549, BLk 5 (illegal water tapping structure), BLa 6b (bridge) at the coordinates of 46 N 0820592 / UTM 0586262, and BBrkn 9c (waterfall) at the coordinates of 46 N 0821892 / UTM 0584642.

The low actual efficiency value indicates the needs to increase efficiency by fixing the damaged irrigation channels. The water loss is caused by damaged channel lining which is in line with LITRICO and FROMION [2009], sedimentation in the channels cross section, leakage, and illegal water tapping in the irrigation channels. The government should work with the P3A (the Association of Farmers Using Water) that has not run well so far to reduce the channels' damages and improve farmers' understanding of irrigation. The government, especially the Water Resources Department of Pidie Regency, should be more assertive in punishing to perpetrators of illegal water tapping.

WATER BALANCE ANALYSIS

The water balance optimization was conducted in two conditions: the condition of design and actual efficiency. According to the design condition, the area of irrigated land during the planting season I, II, and III was 9,496 ha (paddy), 4,818 ha (paddy), and 11,950 ha (onion) respectively. However, due to the decreased irrigation performance indicated by the reduced value of water conveyance efficiency, water balance analysis required to be done in accordance with CAHYONO *et al.* [2016]. In line with HARSOYO [2011], water balance analysis for the Krueng Baro irrigation scheme was needed to calculate the real irrigation land that can be optimally irrigated after the decreased efficiency value. The results of the water balance optimization for the Krueng Baro irrigation scheme are presented in Figure 4. The final objective values and sensitivity analysis is provided in Table 6.

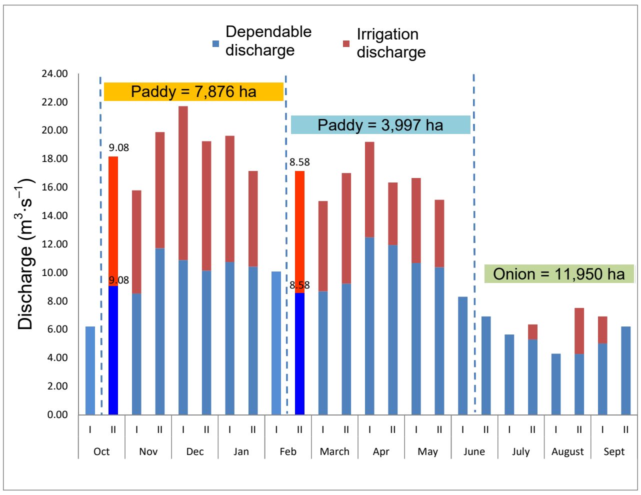

Fig. 4. The optimized pattern of water balance; source: own study

Table 6. The objective function values and sensitivity analysis

Name	Final value	Reduced value	Objective coefficient	Allowable increase	Allowable decrease
	ha				
Baro $Kanan_{paddy\text{-}I}$	5,879	0	1	1E+30	0.142
Baro $Kiri_{paddy\text{-}I}$	1,997	0	1	0.166	3.944
Baro $Kanan_{paddy\text{-}II}$	2,983	0	1	1E+30	0.142
Baro $Kiri_{paddy\text{-}II}$	1,013	0	1	0.166	3.944
Baro $Kanan_{onion}$	8,920	0	1	1E+30	1.000
Baro $Kiri_{onion}$	3,030	0	1	1E+30	3.944

Source: own study.

Based on the operating pattern of the existing weir, the water supply began in October II. Based on the water balance optimization (Fig. 4), the irrigable areas in planting season I, II and III were 7,876 ha (paddy), 3,997 ha (paddy), and 11,950 ha (onion) respectively. The area of irrigated land was decreased in planting season I and II due to the decrease in the actual conveyance efficiency. The dependable water discharge was limited in the planting season I, at the beginning of planting (Oct II), also in the second planting season (Febr II). However, throughout other time of the year, the water was sufficient. Water shortage always occurs during the land preparation due to of the local community adopting a land flooding system. The system requires far more water compared to other systems such as furrow [IRMAK *et al.* 2011]. On the contrary, in the planting season III, the water is sufficient for the entire land because the union does not need as much water as the paddy.

The sensitivity analysis was conducted to examine the effect of the changing circumstances of the irrigated area. What is the percentage of changes occurred in the area (believed to cause the difference) so that the water balance is acceptable. The sensitivity report is presented as follows:

– if the initial problem is stating that the margin for all planting seasons is 1, it is reported in the sensitivity report that this value may change to a specific range such that the optimal solution does not change (i.e., the area listed in column (2));
– based on Table 7, we can identify that in planting season I (Baro $\text{Kanan}_{\text{paddy-I}}$), the margin of the area may decrease up to 0.142 ha or increase to the maximum area so that the optimal solution remains at 5.879 ha. If the margin of the area, for example, increases above the maximum area of the Baro Kanan area, the optimal solution must have changed. The case applied for the other planting season on Krueng Baro Kanan and Kiri.

CONCLUSIONS

Most irrigation systems experience water shortage. Consequently, water allocation and distribution is essential. Some improvements are essential in water use and hydraulic management of the irrigation networks to achieve the goal of rational irrigation. The water balance analysis is a useful tool for providing information concerning the water shortage. The water balance analysis in this study identifies the decrease of the irrigable area due to the reduced water conveyance efficiency. The analysis is beneficial to (i) routinely evaluate the irrigation performance irrigated by Keumala weir, (ii) appropriately measure to improve the water allocation efficiency, and (iii) estimate the potential water to improve the irrigation efficiency. The efficiency needs to be improved by repairing the damaged irrigation channels. The irrigation channels and structures are also required to be rehabilitated. For long-term use, it is necessary to build a reservoir in the upstream of the irrigation scheme as the optimization shows that water is only available at certain times due to the runoff river.

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REFERENCES

ALAM M., TROOIEN T.P., ROGERS D.H., DUMLER T.J. 2002. An efficient irrigation technology for alfalfa growers [online]. Journal of Extention. Vol. 40. No. 3. [Access date 17.10.2018]. Available at: https://www.joe.org/joe/2002june/rb5.php

ARIF C., SETIAWAN B.I., MIZOGUCHI M., DOI R. 2012. Estimation of water balance components in paddy field under non-flooded irrigation regimes by using Excel Solver. Journal of Agronomy. Vol. 11(2) p. 53–59.

AZMERI, HADIHARDAJA I.K., SHASKIA N., ADMAJA K.S. 2017. Completion of potential conflicts of interest through optimization of Rukoh reservoir operation in Pidie District, Aceh Province. AIP Conference Proceedings. Vol. 1903. Iss. 1. Palembang, Indonesia. DOI 10.1063/1/5011611.

Balai Wilayah Sungai Sumatera I. 2017. Final Report Penyusunan penilaian kinerja dan AKNOP jaringan irigasi kewenangan pemerintah pusat (D.I. Krueng Baro) [Final Report. Preparation of performance appraisal and irrigation network AKNOP of central government authority (D.I. Krueng Baro)]. Banda Aceh.

BHALAGE P., JADIA B.B., SANGALE S.T. 2015. Case studies of innovative irrigation management techniques. Aquatic Procedia. Vol. 4 p. 1197–1202. DOI 10.1016/j.aqpro.2015. 02.152.

BOBOJONOV I., BERG E., FRANZ-VASDEKI J., MARTIUS C., LAMERS J.P.A. 2016. Income and irrigation water use efficiency under climate change: An application of spatial stochastic crop and water allocation model to Western Uzbekistan. Climate Risk Management. Vol. 13 p. 19–30. DOI 10.1016/j.crm.2016.05. 004.

CAHYONO P., ASTUTI N.K., RAHMAT A. 2016. Analysis of water balance to determine water requirement of pineapple (*Ananas comusus* L. Merr.) in pineapple Plantation Lampung, Indonesia. In: Proceeding of ICC 2016. International Conference on Climate Change. Eds. A. Kent, K. Hiramatsu, D. Purnamo, J. Syamsiyah, A. Herawati. Kentingan. Graduate School, Universitas Sebelas Maret p. 255–257. DOI 10.15608/iccc. y2016.572.

DIAO X., DINAR A., ROE T., TSUR Y. 2008. A general equilibrium analysis of conjunctive ground and surface water use with an application to Morocco. Agricultural Economics. Vol. 38 p. 117–135.

DWIRATNA S., BAFDAL N., ASDAK C., CARSONO N. 2018. Study of runoff farming system to improve dryland cropping index in Indonesia. International Journal on Advanced Science Engineering Information Technology. Vol. 8. No. 2 p. 390–396.

DWIRATNA S., NURPILIHAN B. 2016. Irrigation scheduling on runoff harvesting for dryland farming. In: The 2nd International Symposium on Agricultural and Biosystem Engineering. Eds. L. Sutiarso, H. Amanah. Yogyakarta, Indonesia p. A01.1–A01.8.

FAIRWEATHER H., AUSTIN N., HOPE M. 2012. Water use efficiency – An information package. Irrigation insights. No. 5. Canberra. Land and water Australia. ISBN 1 920860 09 6 pp. 67.

FAO 2013. FAO statistical yearbook 2013. Rome. World Food and Agriculture. Food and Agriculture Organization of the United Nations. ISSN 2225-7373 pp. 289.

FASAKHODI A.A., NOURI S.H., AMINI M. 2010. Water resources sustainability and optimal cropping pattern in farming systems: A multi-objective fractional goal programming approach. Water Resourses Manage. Vol. 24(15) p. 4639–4657.

FAURES J.-M., SVENDSEN M., TURRAL H. 2007. Reinverting irrigation. Chapt. 9. In: Water for food. Water for life: A comprehensive assessment of water management in agriculture. London. Earthscan, Colombo. International Water Management Institute p. 353–394.

FOLEY J.A., DEFRIES R., ASNER G.P., BARFORD C., BONAN G., CARPENTER S.R., CHAPIN F.S., COE M.T., DAILY G.C., GIBBS H.K., HELKOWSKI J.H., HOLLOWAY T., HOWARD E.A., KUCHARIK C.J., MONFREDA C., PATZ J.A., PRENTICE I.C., RAMANKUTTY N., SNYDER P.K. 2005. Global consequences of land use. Science. Vol. 309. Iss. 5734 p. 570–574. DOI 10.1126/science.1111772.

GEBRIYE S., SETEGN V.M., CHOWDARY B.C., YOHANNES M.F., KONO Y. 2011. Water balance study and irrigation strategies for sustainable management of a tropical Ethiopian lake: A case Lake Alemaya. Water Resources Management. Vol. 25 p. 2081–2107. DOI 10.1007/s11269-011-9797-y.

HARSOYO B. 2011. Analysis of water balance and aridity index in catchment and irrigation area of Jatiluhur dam. Thesis of Institute Technology Bogor.

IRMAK S., LAMECK O., ODHIAMBO W., KRANZ L., EISENHAUER D.E. 2011. Irrigation efficiency and uniformity, and crop water use efficiency. Biological Systems Engineering: Papers and Publications. Vol. 451 p. 1–9.

KERCHEVA M., POPOVA Z. 2010. Use of irrigation requirements and scheduling as drought indicator maize growth stages phases sowing late germination. In: Water Observation and Information System for Decision Support Conference. The Fourth International Scientific Conference BALWOIS. 25–29.05.2010 Ohrid, Republic of Macedonia p. 1–7.

KREBS J.R., WILSON J.D., BRADBURY R.B., SIRIWARDENA G.M. 1999. The second silent spring. Nature. Vol. 400 p. 611–612.

Kriteria Perencanaan-01 (KP-01). 2013. Bandung. Irrigation Network Planning Institute (KP-01). Public Work Department, Galang Persada. pp. 82.

LITRICO X., FROMION V. 2009. Modeling and control of hydrosystems. London. Springer. ISBN 978-1-4471-5785-4 pp. 409.

MEIJER K., BOELEE E., AUGUSTIJN D., VAN DER MOLEN I. 2006. Impacts of concrete lining of irrigation canals on availability of water for domestic use in southern Sri Lanka. Agricultural Water Management. Vol. 83. Iss. 3 p. 243–251. DOI 10.1016/j.agwat.2005.12.007.

NURPILIHAN B., DWIRATNA S. 2015b. Runoff Harvesting as One of Appropriate Technology in Integrated Dry Land Farming. In: Proceedings of International Conference on Appropriate Technology Development (ICATDev) 2015. Bandung, Indonesia p. 39–42.

NURPILIHAN B., DWIRATNA S., KENDARTO D.R. 2015a. Runoff management technology for integrated dry land agriculture in Jatinangor Research Center West Java Indonesia. Egyptian Journal of Desert Research. Vol. 65. Iss. 1 p. 1–11.

SCHOUPS G., ADDAMS C.L., MINJARES J.L., GORELICK S.M. 2006. Sustainable conjunctive water management in irrigated agriculture: Model formulation and application to the Yaqui Valley. Water Resources Research. 42. W10417 pp. 9.

SINGH A. 2010. Decision support for on-farm water management and long-term agricultural sustainability in a semi-arid region of India. Journal of Hydrology. Vol. 391. Iss. 1–2 p. 63–76.

SINGH A. 2012. Optimal allocation of resources for the maximization of net agricultural return. Journal of Irrigation and Drainage Engineering ASCE. Vol. 138(9) p. 830–836.

SINGH A. 2014. Conjunctive use of water resources for sustainable irrigated agriculture. Journal of Hydrology. Vol. 519 p. 1688–1697. DOI 10.1016/j.jhydrol.2014.09.049.

SINGH A., PANDA S.N. 2012a. Effect of saline irrigation water on mustard (Brassica Juncea) crop yield and soil salinity in a semi-arid area of North India. Experimental Agriculture. Vol. 48(1) p. 99–110.

SINGH A., PANDA S.N. 2012b. Integrated salt and water balance modelling for the management of waterlogging and salinization. 1: Validation of SAHYSMOD. Journal of Irrigation and Drainage Engineering ASCE. Vol. 138(11) p. 955–963.

SINGH A., PANDA S.N. 2012c. Integrated salt and water balance modelling for the management of waterlogging and salinization. 2: Application of SAHYSMOD. Journal of Irrigation and Drainage Engineering ASCE. Vol. 138(11) p. 964–971.

TILMAN D., CASSMAN K.G., MATSON P.A., NAYLOR R., POLASKY S. 2002. Agricultural sustainability and intensive production practices. Nature. Vol. 418 p. 671–677. DOI 10.1038/nature01014.

VAN DAM J.C., SINGH R., BESSEMBINDER J.J.E., LEFFELAAR P.A., BASTIAANSSEN W.G.M., JHORAR R.K., KROES J.G., DROOGERS P. 2006. Assessing options to increase water productivity in irrigated river basins using remote sensing and modeling tools. International Journal of Water Resources Development. Vol. 22 p. 115–133.

VANINO S., NINO P., DE MICHELE C., BOLOGNESI S.F., PULIGHE G. 2015. Earth observation for improving irrigation water management: A case-study from Apulia Region in Italy. Agriculture and Agricultural Science Procedia. Vol. 4 p. 99–107. DOI 10.1016/j.aaspro.2015.03.012.

Azmeri AZMERI, Alfiansyah YULIANUR, Uli ZAHRATI, Imam FAUDLI

Wpływ działania systemu nawadniającego na bilans wodny na przykładzie systemu irygacyjnego Krueng Baro w prowincji Aceh, Indonezja

STRESZCZENIE

Nawodnienia Krueng Baro służą zwiększeniu produktywności upraw w dystrykcie Pidie w prowincji Aceh, Indonezja. Z powodu wieku infrastruktury irygacyjnej (ponad 30 lat) i rozległej sieci nawodnień konieczne jest zbadanie obecnej efektywności transportu wody. Przedstawione badania miały na celu ocenę efektywności transportu wody w kanałach pierwszego i drugiego rzędu w systemie irygacyjnym oraz stworzenie modelu bilansu wody na podstawie uzyskanych aktualnych danych. Z optymalizacyjnego modelu bilansu wodnego wynika, że zaprojektowany system może nawadniać 9 496 ha (pole ryżowe I), 4 818 ha (pole ryżowe II) oraz 11 950 ha (cebula). Wyniki pomiarów wskazują, że rzeczywista efektywność systemów Baro Kanan i Baro Kiri była mniejsza odpowiednio o 56% i 48% od efektywności projektowanej (65%). Straty wody wynikały z uszkodzeń umocnień kanałów, erozji skutkującej dużą sedymentacją, przecieków i nielegalnych ujęć wody. Te czynniki spowodowały zmniejszenie powierzchni nawadnianych pól. Na podstawie wyników uzyskanych w modelu optymalizacyjnym rzeczywistego bilansu wodnego powierzchnię nawadnianych pól zmniejszono do 7 876 ha (pole ryżowe I) i 3 997 ha (pole ryżowe II). Powierzchnia nawodnień obiektu „cebula" pozostała bez zmian. Aby zwiększyć efektywność, konieczne są regularne działania naprawcze uszkodzonej struktury irygacyjnej, zatrzymanie sedymentacji i ścisła kontrola nielegalnego poboru wody.

Słowa kluczowe: *bilans wodny, działanie systemu irygacyjnego, powierzchnia nawadniana, rzeczywista efektywność transportu wody*