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Optimization of irrigation cropping pattern by using linear programming: Case study on irrigation area of Parsanga, Madura Island, Indonesia

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Abstract

The irrigation area of Parsanga is located in Sumenep Regency, Madura Island of Indonesia. This irrigation area is 500 ha and the existing cropping pattern is paddy–paddy–second crop. There is water discharge deficiency due to the existing cropping pattern mainly in the dry season. Thus, this study intends to optimize the cropping pattern for 3 condition so that it can produce the maximum benefit of agricultural product. The first cropping pattern is paddy/second crop–second crop–paddy/second crop; the second proposition is paddy/second crop –paddy/second crop–second crop; and the third proposition is paddy–second crop–paddy/second crop. The optimization analysis is carried out by using the linear programming. The suggested three cropping patterns are not only able to solve the water deficiency; they can also present the more production benefit than the existing condition.

Key words: *cropping pattern, irrigation, linear programming, optimization, Parsanga*

INTRODUCTION

Management of water resources is not an easy job mainly when the problem is as the national wide. It becomes harder if an area is considered unstable or when the events and climate are unpredictably [INWRDAM 2001]. The regional decision making is considered to a variety of the technical aspects that need to have to be decided. It is an interplayed of the factual base of information about the system, the methods to process this information and the interpretation of the results [GUPTA, ZAAG 2007; PAVONI *et al.* 2001]. The main objective of water resources management is to solve the formula of demand and supply of water resource for a specific area taking into account various dimensions like space, time, economy, politics, environment, and other aspects. Also, water management means the reconciliation of all users, preservation of water and related land resources, and previous of enough water for constantly expanding needs [GUPTA *et al.* 2010; LIMANTARA 2010a].

Some rivers in Indonesia were progressive developed latterly. The restriction of surface water resources, mainly in the dry season intensify the need for an optimum capacity and operation for the multi purposes reservoir systems [GAKPO *et al.* 2006; SATTARI *et al.* 2006]. Furthermore, the monitoring of surface water resources in the terms of quantity is necessary to determine the availability of water, to verify the norms of consumption (e.g. for irrigation) and to calculate the load of substances leaving the catchment

[MIATKOWSKI, SMARZYŃSKA 2017]. Thus, it is needed to allocate the water use as efficient as possible. To reach this target, it is needed to make a system model for the optimization. Optimization analysis would give more information for allocating the water of each objective function [HOESEIN, LIMANTARA 2010].

Agricultural sector is a key driver in the worldwide economic and social development. It plays a substantial role in achieving, among other, food security, economic diversification, poverty eradication, and human welfare. Its role is highly emphasized while the international community, in particular developing countries, is struggling to cope with the impacts of the climate change and the implementation of response measures in a sustainable manner. The adjustment of planting dates and crop variety, and crop re-allocation are among the selected planned adaptation actions in the agricultural sector [IPCC 2007]. Due to the rapid change in population and urbanization, land and water resources are becoming very limited. Subsequently, crop optimization has received extensive attention in recent years and mathematical models have been developed to determine the optimal use of the available resources for maximizing the net benefits subjected to some constraints [ABDULKADER *et al.* 2012].

The various modelling approaches have been applied to optimize the cropping pattern worldwide including the linear and nonlinear optimization models [HAOUARI, AZAIEZ 2001; KAUR *et al.* 2010; MONTAZAR, RAHIMIKOB 2008; SINGH *et al.* 2001], deterministic linear programming and chance-constrained linear programming models [SETHI *et al.* 2006], the interactive fuzzy multi-objective optimization approach [ZHOU *et al.* 2007], the goal program approach [VIVEKANADAN *et al.* 2009], the multi-objective fractious. The various techniques for optimization have been developed for making the most efficient use of the available resources. Among these different models, linear programming has been found to be one of the best and simple techniques for optimizing an irrigated area where various crops are competing for a limited quantity of land and water resources [OSAMA *et al.* 2017].

Parsanga has the area irrigation of 500 ha. Irrigation network of Parsanga is located in the authority area of the Water Resource General Work Institution of Sumenep Regency. The problem is there is deviation of the cropping pattern balance due to the less attention of water availability. Therefore, it is directly happened the waste of water use which causes the wild tapping anywhere [PRIYANTORO, LIMANTARA 2011]. Based on the problem as above, it is seen necessary to carry out the optimization of agricultural area for improving the agricultural system in recent year by optimizing the area and the available water discharge. Besides that, it is hoped to produce the maximal agricultural product benefit.

MATERIALS AND METHOD

The irrigation network of Parsanga is located in the catchment area of Anjuk River. However, administratively, it is located in the 3 district areas which

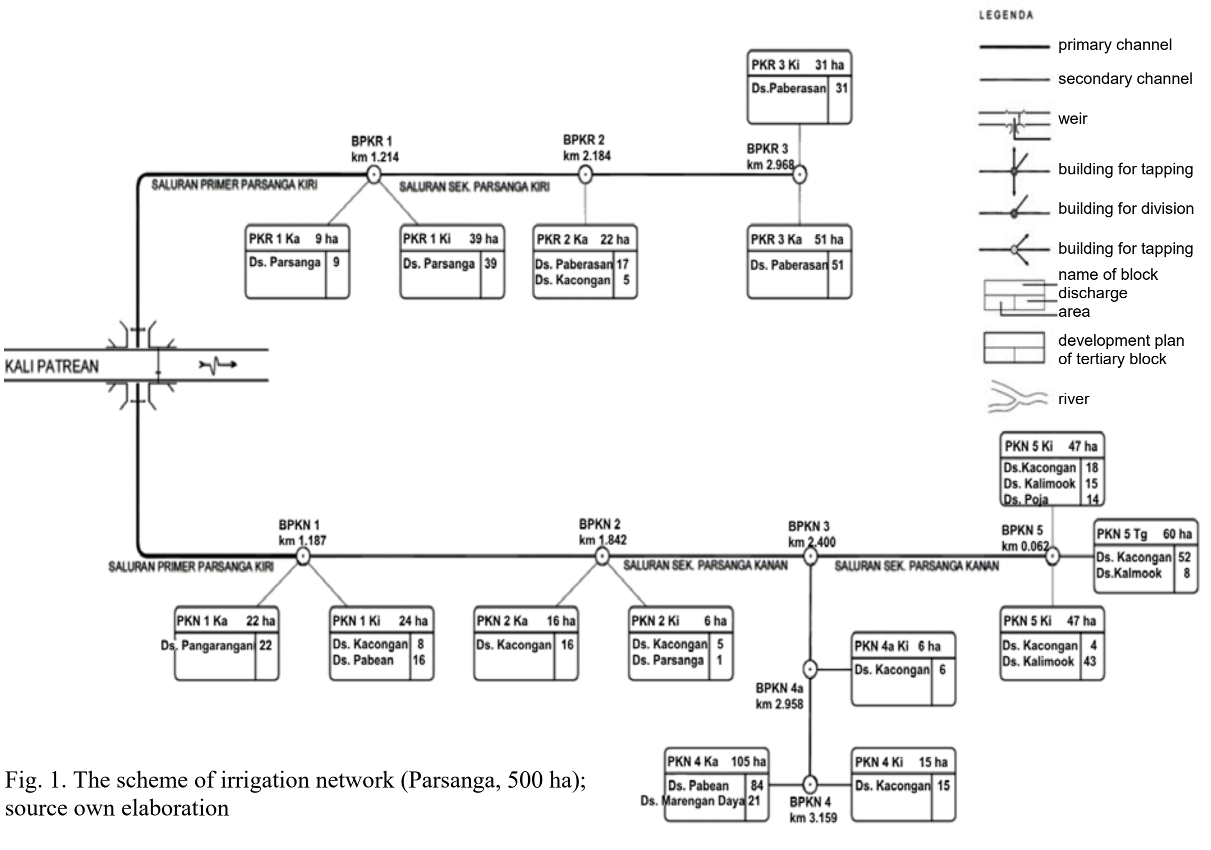

Fig. 1. The scheme of irrigation network (Parsanga, 500 ha); source own elaboration

consist of 8 villages. The irrigation area is 500 ha and the scheme of irrigation network is presented as in the Figure 1.

Figure 2 presents the map of rainfall stations. There are 4 rainfall stations in the Parsanga watershed such as the rainfall stations of Parsanga, Sumenep city, Kebonagung, and Manding.

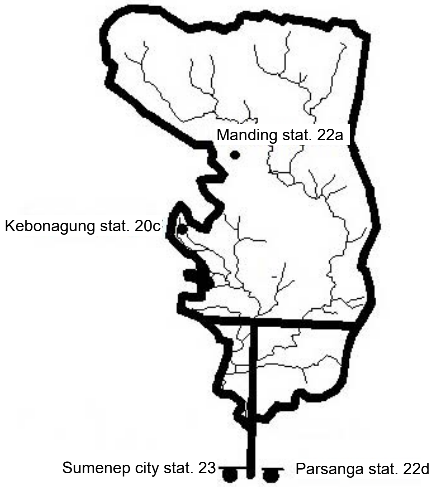

Fig. 2. Map of rainfall station; source: own elaboration

The methodology in this study consists of the analysis of rainfall, discharge, crop water requirement, irrigation water requirement, water need at intake, water balance for determining the available discharge that can fulfil the need or not; and the optimization of cropping pattern. The optimization of water allocation on the tertiary plot is carried out by using the Linear Programming with the objective function is to maximize the production yield and the constraints are the water availability and irrigation water requirement. Type of discharge which is used in this study is the dependable discharge of 80% which is as one of the constraints. However, cropping pattern means as a schedule with terms of cropping. Each cropping pattern consists of three cropping periods that mentions as the cropping season. Due to the discharge constraint, there is carried out the optimization analysis with the scenario of 4 cropping pattern as follow:

1) existing cropping pattern: paddy – paddy/second crop – paddy/second crop (It means that in the cropping season I is cropped paddy, in the cropping season II is cropped paddy and second crop, and in the cropping season III is cropped paddy and second crop);
2) proposition-1 cropping pattern: paddy (cropping season I) – paddy (cropping season II) – paddy/second crop (cropping season III);
3) proposition-3 cropping pattern: paddy/second crop (cropping season I) – paddy/second crop (cropping season II) – second crop (cropping season III);
4) proposition-3 cropping pattern: paddy/second crop (cropping season I) – second crop (cropping season II) – paddy/second crop (cropping season III).

IRRIGATION WATER REQUIREMENT

Irrigation water requirement is an amount of water which is needed by the crop on the optimal growth condition without water deficiency and it is expressed as the net from requirement (*NFR*). *NFR* means as the net water requirement for irrigation.

WATER BALANCE METHOD

Irrigation water requirement (on the rice field) is as follow:

a) for paddy:

$$NFR = Cu + Pd + NR + P - R_{\text{eff}} \tag{1}$$

b) for the second crop:

$$NFR = Cu + P - R_{\text{eff}} \tag{2}$$

Where: NFR = water need on the rice field (1 mm·day^{-1} · 10,000/(24·60·60) = 0.11 dm^3·s^{-1}·ha^{-1}); Cu = crop water requirement (mm·day^{-1}); Pd = water need for land processing (mm·day^{-1}); NR = water need for nursery (mm·day^{-1}); P = percolation (mm·day^{-1}); R_{eff} = effective rainfall (mm·day^{-1}).

CROPPING PATTERN

Cropping pattern is an activity of regulating time, place, type, and crop area in the irrigation area. However, the aim of cropping pattern is to make the use of irrigation water availability as efficient as possible so the crop can well grow.

DEPENDABLE DISCHARGE

The fulfilled possibility is determined in amount of 80%. It means that the possibility of river discharge under the dependable discharge is 20%. The dependable discharge in this study is analysed for half monthly period. The average discharge of river is analysed based on the data of daily river discharge. The procedure of dependable discharge analysis is as follow [LIMANTARA 2010c]:

1) to analyse the average of discharge every year;
2) to rank the data from the biggest to the smallest one;
3) to analyse the probability of each data by using the formula of Weibull as follow [LIMANTARA 2010c]:

$$p = \frac{m}{n+1} 100\% \tag{3}$$

Where: p = probability (%); m = number of discharge data; n = the amount of data.

OPTIMIZATION

This study uses the method of linear programming. It is based on the consideration that Linear Programming is simple enough on the formulation as well as the stage of solving, so it does not need the difficult solving level [LIMANTARA 2007; LIMANTARA, SOETOPO 2011]. The selection of the method is due to the use of Linear Programming which has the some advantages as follow [LIMANTARA 2010b; 2011]: 1) this method can be used for solving a system with many enough of variables and constraints; 2) the using of this method is easy and in addition it is supported by the many program packages that have been circulated; 3) the mathematical functions are simple; and 4) the result is good enough.

LINEAR PROGRAMMING

Decision variable is as the variable which will be found and giving the best value for the aim that will be reached. However, objective function is a mathematical function which has to be maximized or minimized and it reflects the aim that will be reached [LIMANTARA, SOETOPO 2011]. The mathematical model of linear programming is as follow:

$$\max Z = \sum_{n=1}^{n} c_n x_n \quad (4)$$

Where: Z = objective function (in this study is to maximize the benefit of agricultural yield) (Rp); c_n = net benefit of rice field yield (Rp·ha^{-1}); x_n = irrigation area (ha).

Constraint is as a mathematical function which becomes as the constraint for making effort to maximize or minimize the objective function and it represents the constraint which has to be reached.

CONSTRAINT OF DISCHARGE VOLUME

$$\sum_{n=1}^{n} a_{mn} x_n \leq b_m \quad (5)$$

and

$$x_n \geq 0$$

Where: x_n = variable (in this study is the irrigation area) (ha); a_{mn} = constant (in this study is the volume of irrigation water requirement) (m^3·ha^{-1}); b_m = volume of the water availability (m^3); c_n = net benefit of the irrigated area/rice field (Rp·ha^{-1}); m = the amount of constraint; n = the amount of decision variable.

CONSTRAINT OF AREA

$$X_1 + X_2 \leq X_m \quad (6)$$

Where: X_1 = area of the rice field (ha); X_2 = area of the second crop field (ha); X_m = the available area (ha).

RESULTS AND DISCUSSION

ANALYSIS OF RAINFALL DATA

The evaluation of data accuracy and the relation among the stations is carried out by using the consistency test based on the double mass curve. This method is comparing the yearly rainfall cumulative from one station with the average of the other stations on the same year [LIMANTARA 2010c]. For example, the consistency test for the rainfall station 1 (Parsanga) is compared to the average cumulative of the other three rainfall stations (Sumenep city, Kebonagung, Manding) and it is presented in the Figure 3. There are also carried out each for the other 3 rainfall stations with the same procedure.

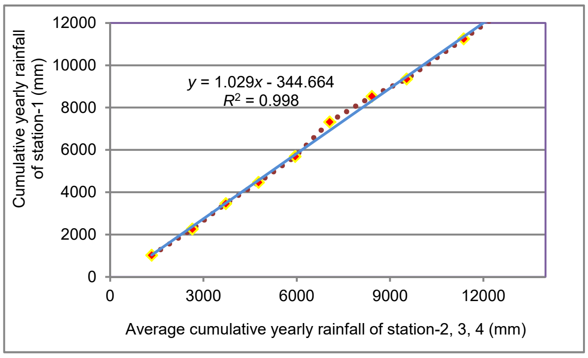

Fig. 3. The relation between cumulative yearly rainfall from rainfall station-1 (Parsanga) to the average cumulative rainfall from rainfall station-2,3,4 (Sumenep city, Kebonagung, and Mading); source: own study

The accuracy of data and the relation among the stations can be seen from the value of determination coefficient. If the determination coefficient is increasingly close to 100%, so the data of every station is assumed accurate and it is related with the other station. The result of consistency test is presented as in the Table 1.

Table 1. Consistency test of rainfall data on 2004 until 2013

Name of station	Number of		Determination coefficient
	station	test station	
Parsanga	22d	station-1	0.994
Sumenep city	23	station-2	0.998
Kebonagung	20c	station-3	0.996
Manding	22a	station-4	0.997

Explanations: stations' numbers as in Fig. 2.
Source: own study.

The dependable and effective rainfall are analysed based on the 10 daily rainfall of the average monthly rainfall during the last 10 years (from 2004 until 2013) from the 4 rainfall stations as mentioned above. The effective rainfall is analysed by using the basic year method which the steps as follow:

1) the yearly rainfall during 10 years are sorted from small to large.
2) to analyse R_{80} for paddy and R_{50} for the second crop with the formula as follow:

$$R_{80} = \frac{n}{5} + 1 = \frac{10}{5} + 1 = 3$$

$$R_{50} = \frac{n}{2} + 1 = \frac{10}{2} + 1 = 6$$

3) based on the result, there is determined the basic year of using the rainfall data for paddy and the

second crop, as presented in the Table 2; for paddy is used the 3rd rank of the year such as 2005 (R_{80}) and for the second crop is used the 6th rank of the year such as 2011 (R_{50}).

The effective rainfall for paddy is determined by 70% of dependable rainfall of 80% (R_{80}). However, for the second crop, it is analysed based on the actual evapotranspiration, rainfall, and water availability which can be used by the crop and it is based on the root depth. Analysis result of the dependable and effective rainfall is presented as in the Tables 2 and 3.

Table 2. Dependable rainfall

Data of rainfall			Rank of data			Note
No	year	rainfall mm	No	year	rainfall mm	
1	2004	1,073	1	2012	825	–
2	2005	1,019	2	2008	1,003	–
3	2006	1,239	3	2005	1,019	R_{80}
4	2007	1,202	4	2004	1,073	–
5	2008	1,003	5	2007	1,202	–
6	2009	1,223	6	2011	1,203	R_{50}
7	2010	1,615	7	2009	1,223	–
8	2011	1,203	8	2006	1,239	–
9	2012	825	9	2010	1,635	–
10	2013	1,901	10	2013	1,901	–

Source: own study.

ANALYSIS OF POTENTIAL EVAPOTRANSPIRATION

After obtaining the dependable and effective rainfall, then it is continued by analysing the potential evapotranspiration by using the Penman method. The climate data which is used is from 2004 until 2013 and the result is presented as in the Table 4.

The dependable discharge is analysed by using Weibull formula with the steps are as follow:
1) to analyse the average discharge for every year;
2) to rank the data from small to large;
3) to analyse the probability of each data with the Weibull formula as follow (for example for discharge data on 2014 as in the Table 5);

$p = \frac{m}{N+1} 100\% = \frac{1}{10+1} 100\% = 9.09\%$ etc. for the other data

Where: p = probability (%); m = the serial number of data; N = the amount of data.

Table 5 presents the probability of discharge data from 2004 until 2013 with the Weibull formula.

Table 3. Analysis of dependable rainfall (R_{80}) and effective rainfall (R_{eff})

Month	Period	R_{80} mm	R_{eff}-paddy mm	R_{eff}-paddy mm·day^{-1}	R_{eff}-second crop mm	R_{eff}-second crop mm·day^{-1}
Jan	1	138.0	96.6	9.66	39.230	3.92
	2	62.0	43.4	4.34	17.608	1.76
	3	51.0	35.7	3.57	14.484	1.45
Feb	1	74.0	51.8	5.18	21.016	2.10
	2	49.0	34.3	3.43	13.916	1.39
	3	32.0	22.4	2.24	9.088	0.91
Mar	1	112.0	78.4	7.84	31.808	3.18
	2	10.0	7.0	0.70	2.840	0.28
	3	30.0	21.0	2.10	8.520	0.85
Apr	1	14.0	9.8	0.98	3.976	0.40
	2	123.0	86.1	8.61	34.932	3.49
	3	0.0	0.0	9.00	0.0	0.0
May	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0
Jun	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0
Jul	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0
Aug	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0
Sep	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0
Oct	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0
Nov	1	0.0	0.0	0.0	0. 0	0.0
	2	0.0	0.0	0.0	0.0	0.0
	3	25.0	17.5	1.75	7.100	0.71
Dec	1	66.0	46.2	4.62	18.744	1.87
	2	103.0	72.1	7.21	29.252	2.93
	3	130.0	91.0	9.10	36.920	3.69
Total		1019.0	713.3	71.33	289.434	28.94

Source: own study.

Water from the Parsanga Dam is intended for irrigating the agricultural area in the Parsanga. Based on the analysis as in the Table 5 by using the Weibull formula, the probability of 80% is happened on the 2010, so the discharge data on the 2010 will be used for analysing the dependable discharge in the Parsanga. Table 6 presents the dependable discharge and discharge on 2010 in the Parsanga.

Analysis of water requirement for the land preparation is carried out by using the method of Van De Gor and the result is presented in the Table 7.

Table 4. Results of the evapotranspiration analysis by using the Penman method

Item	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (T)	°C	27.3	27.2	27.9	28.4	27.9	28.1	27.5	27.6	28.6	29.3	29.2	28.4
Wind velocity (u)	m·s^{-1}	3.60	3.60	1.54	2.06	2.06	3.0	4.12	4.12	3.60	3.70	2.93	1.70
Relative humidity (Rh)	%	88.0	87.0	87.0	86.0	87.0	83.3	79.0	79.0	78.0	79.0	81.0	85.0
Sun brightness (n:N)	%	65.0	56.0	77.0	79.0	76.0	80.9	89.0	100	100	99.0	88.0	61.0
Evapotranspiration	mm·day^{-1}	6.26	5.92	5.61	5.02	4.44	4.68	5.57	6.84	8.28	8.64	7.80	5.82

Explanations: n = time of real sun brightness in a day (hour), N = potential time of sun brightness in a day (12 hours).
Source: own study.

Table 5. The probability of discharge data from 2004 until 2013 with the Weibull formula

Data of discharge Q			Rank of data			p	Result
No	year	Q $m^3 \cdot s^{-1}$	No	year	Q $m^3 \cdot s^{-1}$	%	
1	2004	0.188	1	2004	0.188	9.09	–
2	2005	0.329	2	2005	0.329	18.18	–
3	2006	0.506	3	2009	0.438	27.27	–
4	2007	0.468	4	2007	0.468	36.36	–
5	2008	0.473	5	2008	0.473	45.45	–
6	2009	0.438	6	2006	0.506	54.55	–
7	2010	0.572	7	2012	0.523	63.64	–
8	2011	0.547	8	2011	0.547	72.73	–
9	2012	0.523	9	2010	0.572	81.82	Q_{80}
10	2013	1.424	10	2013	1.424	90.91	–

Source: own study.

ANALYSIS OF IRRIGATION BENEFIT

Based on the existing cropping pattern, there are obtained the crop, rice field, and the intake water requirement. The water balance based on the dependable discharge of 80% is presented in the Figure 4. It is seen that there is the water deficit in several month, so it is needed to be carried out the optimization of water allocation. The recapitulation of total water irrigation is presented in the Table 8 and the benefit of irrigation per ha is presented in the Table 9.

Table 10 presents the volume of available water in the Sentong secondary channel and Table 11 presents the irrigation water requirements. The two analysis results are needed for the input in the optimization analysis.

Table 6. The dependable discharge ($Q_{dependable}$) and discharge on 2010 in the Parsanga (Q_{2010})

Month	Period	Q_{2010} $m^3 \cdot s^{-1}$	$Q_{dependable}$ $m^3 \cdot s^{-1}$
Dec	1	0.10	0.10
	2	0.94	0.94
	3	1.34	1.34
Jan	1	0.94	0.94
	2	1.28	1.28
	3	1.44	1.44
Feb	1	1.28	1.28
	2	1.28	1.28
	3	1.28	1.28
Mar	1	1.28	1.28
	2	1.30	1.30
	3	1.30	1.30
Apr	1	1.28	1.28
	2	0.71	0.71
	3	0.37	0.37
May	1	0.17	0.17
	2	0.10	0.10
	3	0.27	0.27
Jun	1	0.31	0.31
	2	0.37	0.37
	3	0.37	0.37
Jul	1	0.37	0.37
	2	0.37	0.37
	3	0.37	0.37
Aug	1	0.27	0.27
	2	0.27	0.27
	3	0.14	0.14
Sep	1	0.12	0.12
	2	0.12	0.12
	3	0.12	0.12
Oct	1	0.12	0.12
	2	0.12	0.12
	3	0.12	0.12
Nov	1	0.12	0.12
	2	0.12	0.12
	3	0.12	0.12

Source: own study.

Table 7. Analysis of water need for the land preparation by using the method of Van De Gor and Zijlstra (2004–2013)

Parameter	Unit	Value in the month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_o	$mm \cdot day^{-1}$	6.257	5.924	5.607	5.024	4.439	4.681	5.572	6.835	8.278	8.639	7.800	5.817
$E_o = ET_o \cdot 1.1$	$mm \cdot day^{-1}$	6.883	6.516	6.168	5.527	4.883	5.149	6.129	7.519	9.106	9.502	8.580	6.399
P	$mm \cdot day^{-1}$	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
$M = E_o + P$	$mm \cdot day^{-1}$	8.883	8.516	8.168	7.527	6.883	7.149	8.129	9.519	11.106	11.592	10.580	8.399
t	day	31	29	31	30	31	30	31	31	30	31	30	31
S	mm	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0
$k = (M \cdot t)/S$	–	0.918	0.823	0.844	0.753	0.711	0.715	0.840	0.984	1.111	1.189	1.058	0.868
$LP = Me^k/(e^k–1)$	$mm \cdot day^{-1}$	14.789	15.181	14.329	14.231	13.524	13.997	14.305	15.205	16.560	16.542	16.206	14.477
Water need	$dm^3 \cdot s^{-1} \cdot ha^{-1}$	1.712	1.757	1.658	1.647	1.565	1.620	1.656	1.760	1.917	1.915	1.876	1.676

Explanations: ET_o = potential evapotranspiration, E_o = evaporation during the land preparation, P = percolation, M = water need for the changing water loss due to the evapotranspiration and percolation in the saturated rice field; t = duration of land preparation; S = the need for saturating of upper layer; e = Napier's constant (2.71828); LP = water need for the land processing.
Source: own study.

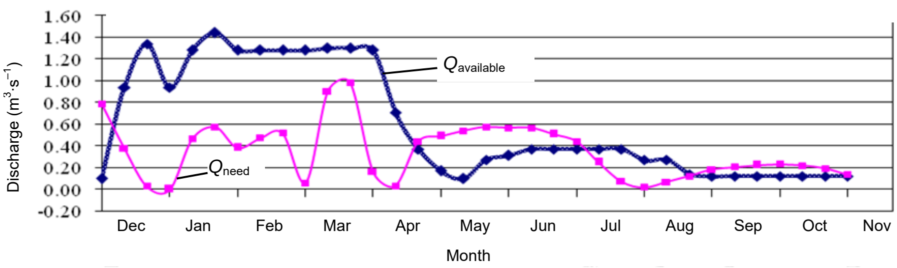

Fig. 4. Water balance based on the dependable discharge of 80%; source: own study

Table 8. Recapitulation of irrigation water total in the irrigation area of Parsanga

Cropping pattern (CP)	Cropping season	Irrigation water requirement $dm^3 \cdot s^{-1} \cdot ha^{-1}$	
		paddy	second crop
Existing CP	I II III	7.216 9.184 0.000	0.000 5.522 8.513
Proposition-1 CP	I II III	5.030 0.000 14.044	0.000 0.000 8.513
Proposition-2 CP	I II III	7.216 9.184 0.000	3.835 5.552 8.513
Proposition-3 CP	I II III	7.216 0.000 16.077	0.000 0.000 8.513

Source: own study.

Table 9. Net benefit of rice field per ha

Type of crop	Yield	Sale value	Total	Production cost	Benefit
	$t \cdot ha^{-1}$	$USD \cdot t^{-1}$	$USD \cdot ha^{-1}$		
Paddy	5	295.26	1,476.30	269.50	1,206.80
Second crop	3	295.26	885.78	216.72	669.06

Explanations: this net benefit of rice field per ha is suitable for the existing cropping pattern, and the proposition-1, -2, -3 of cropping pattern.
Source: own study

Table 10. The volume of available water (Q_{2010}) in the Sentong secondary channel

Dependable discharge in irrigation area of Parsanga	Water volume $\cdot 10^6$ m^3 in cropping season		
	I	II	III
Dependable discharge of 80%	1.568	1.505	1.061

Explanations: the volume of available water (Q_{2010}) in the Sentong secondary channel is available for the existing cropping pattern, and the proposition-1, -2, -3 of cropping pattern.
Source: own study.

Table 11. Irrigation water requirements

Cropping pattern (CP) in irrigation area of Parsanga	Cropping season	Water requirement $m^3 \cdot ha^{-1}$	
		paddy	second crop
Existing CP	I II III	574.637 1,048.142 1,258.165	0.000 532.305 681.864
Proposition-1 CP	I II III	574.637 1,048.142 1,258.165	0.000 0.000 681.864
Proposition-2 CP	I II III	574.637 862.841 0.000	184.854 532.205 681.684
Proposition-3 CP	I II III	424.733 0 1,258.165	184.854 532.205 681.864

Source: own study.

ANALYSIS OF OPTIMIZATION

Table 12 presents the benefit per ha for paddy and the second crop.

Table 12. Benefit per ha for paddy and the second crop

Cropping season	Benefit ($USD \cdot ha^{-1}$)	
	paddy	second crop
I, II, III	757.99	213.13

Source: own study.

Explanation for objective function: Z = benefit of paddy ($USD \cdot ha^{-1}$) · area of paddy (X_n, ha) + benefit of second crop ($USD \cdot ha^{-1}$ · area of second crop (X_n, ha)

Objective function for cropping seasons:

$$Z = 757.99\left(\sum_{n=1}^{15} X_n\right) + 213.13\left(\sum_{n=16}^{30} X_n\right)$$

Table 13 presents the list of variables which are used in the optimization model and Table 14 presents the list of each irrigation area in the Parsanga.

Table 13. List of variables used in the optimization model

No	Area's kind	Irrigation area'	Variable
1	paddy	PKR-1 ka	X_1
2	paddy	PKR-1 ki	X_2
3	paddy	PKR-2 ka	X_3
4	paddy	PKR-3 ka	X_4
5	paddy	PKR-3 ki	X_5
6	paddy	PKN-1 ka	X_6
7	paddy	PKN-1 ki	X_7
8	paddy	PKN-2 ka	X_8
9	paddy	PKN-2 ki	X_9
10	paddy	PKN-4 ka	X_{10}
11	paddy	PKN-4 ki	X_{11}
12	paddy	PKN-4a ki	X_{12}
13	paddy	PKN-5 ka	X_{13}
14	paddy	PKN-5 ki	X_{14}
15	paddy	PKN-5 tg	X_{15}
16	second crop	PKR-1 ka	X_{16}
17	second crop	PKR-1 ki	X_{17}
18	second crop	PKR-2 ka	X_{18}
19	second crop	PKR-3 ka	X_{19}
20	second crop	PKR-3 ki	X_{20}
21	second crop	PKN-1 ka	X_{21}
22	second crop	PKN-1 ki	X_{22}
23	second crop	PKN-2 ka	X_{23}
24	second crop	PKN-2 ki	X_{24}
25	second crop	PKN-4 ka	X_{25}
26	second crop	PKN-4 ki	X_{26}
27	second crop	PKN-4a ki	X_{27}
28	second crop	PKN-5 ka	X_{28}
29	second crop	PKN-5 ki	X_{29}
30	second crop	PKN-5 tg	X_{30}

Source: own study.

Table 14. List of irrigation area

No	Irrigation area	Area, ha
1	PKR-1 ka	9
2	PKR-1 ki	39
3	PKR-2 ka	22
4	PKR-3 ka	51
5	PKR-3 ki	31
6	PKN-1 ka	22
7	PKN-1 ki	24

No	Irrigation area	Area, ha
8	PKN-2 ka	16
9	PKN-2 ki	6
10	PKN-4 ka	105
11	PKN-4 ki	15
12	PKN-4a ki	6
13	PKN-5 ka	47
14	PKN-5 ki	47
15	PKN-5 tg	60
Total		500

Explanations: codes of irrigation area as in Table 13.
Source: own study.

CONSTRAINT FOR IRRIGATION WATER VOLUME ON THE SECONDARY CHANNEL OF PARSANGA

Dependable discharge of 80% and for irrigation area

The coefficients and constants of each constraint for the constraints of K1 until K12 are presented in the Table 10 and 11, however for the constraints K13 until K27 are presented in the Table 14. K1 until K12 is the constraint for available discharge (dependable discharge which is hoped can be fulfilled the irrigation requirement). However, K13 until K27 is the constraint for the irrigation area.

Constraint for irrigation water volume

Explanation:

For every cropping pattern, there are three periods of cropping season, for example: K1, K2, and K3 are the constraint of water irrigation volume each for the first, second, and third period of cropping season. Each constraint is as follow:

- irrigation water requirement for paddy ($m^3 \cdot ha^{-1}$) · area of paddy for the 15 irrigation area (number 1 until 15) (ha) + irrigation water requirement for second crop ($m^3 \cdot ha^{-1}$) · area of second crop for the 15 irrigation area (number 16 until 30 (ha) ≤ available water volume (m^3);
- irrigation water requirement of paddy and second crop each cropping season period for each proposition of cropping pattern is presented as in the Table 11. However, the available water volume for each period of cropping season is presented as in the Table 10.

a. Existing cropping pattern

$$K1 = \left(574.637 \sum_{n=1}^{15} X_n\right) + \left(0 \sum_{n=16}^{30} X_n\right) \le 1.568 \cdot 10^6$$

$$K2 = \left(1048.142 \sum_{n=1}^{15} X_n\right) + \left(532.305 \sum_{n=16}^{30} X_n\right) \le 1.505 \cdot 10^6$$

$$K3 = \left(1258.165 \sum_{n=1}^{15} X_n\right) + \left(681.864 \sum_{n=16}^{30} X_n\right) \le 1.061 \cdot 10^6$$

b. Proposition-1 cropping pattern

$$K4 = \left(574.637 \sum_{n=1}^{15} X_n\right) + \left(0 \sum_{n=16}^{30} X_n\right) \le 1.568 \cdot 10^6$$

$$K5 = \left(1048.142 \sum_{n=1}^{15} X_n\right) + \left(0 \sum_{n=16}^{30} X_n\right) \le 1.505 \cdot 10^6$$

$$K6 = \left(1258.165 \sum_{n=1}^{15} X_n\right) + \left(681.864 \sum_{n=16}^{30} X_n\right) \le 1.061 \cdot 10^6$$

c. Proposition-2 cropping pattern

$$K7 = \left(574.637 \sum_{n=1}^{15} X_n\right) + \left(184.854 \sum_{n=16}^{30} X_n\right) \le 1.568 \cdot 10^6$$

$$K8 = \left(862.841 \sum_{n=1}^{15} X_n\right) + \left(532.205 \sum_{n=16}^{30} X_n\right) \le 1.505 \cdot 10^6$$

$$K9 = \left(0 \sum_{n=1}^{15} X_n\right) + \left(681.864 \sum_{n=16}^{30} X_n\right) \le 1.061 \cdot 10^6$$

d. Proposition-3 cropping pattern

$$K10 = \left(424.733 \sum_{n=1}^{15} X_n\right) + \left(184.854 \sum_{n=16}^{30} X_n\right) \le 1.568 \cdot 10^6$$

$$K11 = \left(0 \sum_{n=1}^{15} X_n\right) + \left(532.205 \sum_{n=16}^{30} X_n\right) \le 1.505 \cdot 10^6$$

$$K12 = \left(1258.165 \sum_{n=1}^{15} X_n\right) + \left(681.864 \sum_{n=16}^{30} X_n\right) \le 1.061 \cdot 10^6$$

Constraint for irrigation area:

Explanation for the constraint of irrigation area:

Kn: constraint number: area for paddy (number variable – 1, 2, … 15) + area for second crop (number variable – 16, 17, … 30) ≤ available area (Tab. 14).

$K13 = X_1 + X_{16} \le 9$
$K14 = X_2 + X_{17} \le 39$
$K15 = X_3 + X_{18} \le 22$
$K16 = X_4 + X_{19} \le 51$
$K17 = X_5 + X_{20} \le 31$
$K18 = X_6 + X_{21} \le 22$
$K19 = X_7 + X_{22} \le 24$
$K20 = X_8 + X_{23} \le 16$
$K21 = X_9 + X_{24} \le 6$
$K22 = X_{10} + X_{25} \le 105$
$K23 = X_{11} + X_{26} \le 15$
$K24 = X_{12} + X_{27} \le 6$
$K25 = X_{13} + X_{28} \le 47$
$K26 = X_{14} + X_{29} \le 47$
$K27 = X_{15} + X_{30} \le 60$

The process of optimization analysis in this study is using the linear programming with the solver facility of Microsoft Excel. By inserting the parameters value of objective function and constraints, it will produce the results such as the components of variable and the value of objective function. Optimization analysis is carried out by inserting the dependable discharge of 80% and the results for each condition of cropping pattern are presented as in the Table 15. The recapitulation for optimization result for the water allocation and irrigation area is presented as in the Table 16.

Table 15. Benefit of production yield based on the standard price of 2013 (dependable discharge is 80%)

Cropping season	Benefit of irrigation yield (USD)			
	existing	proposition-1	proposition-2	proposition-3
I	603,402.14	738,151.74	738,151.74	738,151.74
II	374,861.14	591,064.94	591,064.94	491,424.11
III	85,639.77	113,414.36	113,414.36	113,414.36
Benefit per year	1,063,903.05	1,442,631.04	1,442,631.04	1,322,990.21

Source: own study.

Table 16. Recapitulation of optimization result for the water allocation and irrigation area

Cropping pattern	Type of crop	Area ha	Rate of irrigation Q (m^3·ha^{-1})	Max benefit USD
Existing	cropping season I: – paddy – second crop	500 0	500 0	1,063,903.05
	cropping season II: – paddy – second crop	75 425	75 425	
	cropping season III: – paddy – second crop	0 125	0 125	
Proposition-1	cropping season I: – paddy – second crop	500 0	400 100	1,294,457.14
	cropping season II: – paddy – second crop	500 0	0 500	
	cropping season III: – paddy – second crop	0 128	200 300	
Proposition-2	cropping season I: – paddy – second crop	500 0	350 150	1,442,631.04
	cropping season II: – paddy – second crop	251 249	235 265	
	cropping season III: – paddy – second crop	0 128	0 300	
Proposition-3	cropping season I: – paddy – second crop	500 0	500 0	1,342,990.20
	cropping season II: – paddy – second crop	323 0	500 0	
	cropping season III: – paddy – second crop	0 128	250 250	

Source: own study.

CONCLUSIONS

1. Based on the basic year method which is analysed by using the rainfall data from 2004 until 2013, the dependable rainfall for paddy (R_{80}) is happened on the 2005 with the yearly rainfall is 1,019 mm. However, the dependable rainfall for the second crop (R_{50}) is happened on the 2011 with the yearly rainfall is 1,023 mm. Then, the analysis of effective rainfall for paddy and the second crop are based on the result as above.

2. Based on the data analysis by using the Weibull method, it is obtained the dependable discharge of 80% in the Parsanga irrigation area is in amount of 0.572 m^3·s^{-1}. The basic year of the dependable discharge is on the 2010.

3. The maximum benefit is obtained from the proposition-2 cropping pattern (paddy/second crop – paddy/second crop – second crop) that produces the benefit in amount of USD 1,442,631.03.

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Optymalizacja systemu nawadniania upraw za pomocą programowania linearnego – przykład nawadnianego obszaru Parsanga, wyspa Madura, Indonezja

STRESZCZENIE

Nawadniany obszar Parsanga znajduje się w dystrykcie Sumenep na wyspie Madura w Indonezji. Ma powierzchnię 500 ha, a system upraw tam stosowanych to ryż–ryż–drugi plon. W warunkach takiego systemu uprawy występują deficyty wody, szczególnie w porze suchej. Z tego powodu przedstawione badania miały na celu optymalizację systemu upraw w trzech systemach, aby uzyskać maksymalne korzyści w produkcji rolniczej. Trzy systemy to: 1 – ryż/drugi plon–drugi plon–ryż/drugi plon, 2 – ryż/drugi plon–ryż/drugi plon–drugi plon i 3 – ryż–drugi plon–ryż/drugi plon. Optymalizację wykonano z zastosowaniem programowania linearnego. Sugerowane trzy systemy są w stanie nie tylko rozwiązać problem deficytu wody, ale także dają korzyści produkcyjne większe niż obecnie uzyskiwane.

Słowa kluczowe: *nawadnianie, optymalizacja, Parsanga, programowanie liniowe, system upraw*