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Infiltration on Canal as a Method for Recharging Groundwater Storage

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Abstract: Water losses in a designed irrigation area for paddy fields is necessary to be examined. Water losses in conveyance canal consists of evaporation and infiltration. The infiltrating water becomes groundwater storage and is distributed along the canal.

Semi-empiric equation of infiltration on canal was developed by Moritz (1913) and the semi-graphic equation was developed by Bouwer (1965). Forchheimer (1930) has developed a formula based on dynamic balance of water flow to calculate the permeability coefficient value of soils and was continued by Dachler (1936) and Sunjoto (2002) that computed the shape factor of a well based on those formulas. Further, it can be developed a formula of water losses in the conveyance canals to complete the two existing formulas of Moritz and Bouwer.

This research aimed to get a field data and had measured water losses directly in the canal of Sukawati Irrigation Region in Comal, Central Java, Indonesia. The results of the measurement are compared to the calculating results derived from the three formulas of Moritz, Bouwer and the proposed formula, based on the field data and for soil coefficient of permeability is 8.333×10^{-6} m/s. An analysis of the result is conducted using a least square and linear regression method. The result of the comparison are as follows: the proposed formula has the smallest deviation, followed by the Bouwer formula in the middle, and finally the Moritz formula has the biggest deviation.

Key words: Canal, water losses, evaporation, infiltration, irrigation efficiency, groundwater storage.

Introduction

The designing of an irrigation area needs data of water losses in the canal to find accurate area of the paddy field. Water losses in the canal consist of evaporation on the surface of canal. Infiltration in the wet perimeter of the canal becomes ground water. Value of evaporation can be found by using some methods, but this water loss is not the focus of this paper.

Direct measurement of infiltration can only be carried out when the water in the canal has already been used to irrigate the paddy field but this data is needed in the designing step or before constructing the canal. For this reason, Moritz (1913) has developed a semi-empirical formula of computation and Bouwer (1965) also proposed a semi-graphical formula.

The aim of this paper is to propose similar formula for both formulas above, which is developed analytically based on the principle of Forchheimer (1930) to calculate the coefficient of permeability of soil and Sunjoto's (2002) former formula which calculates dimension of recharge well.

The study carried out direct measurements in irrigation canal of Sukawati, Tegal, Central Java, Indonesia as project cooperation among Department of Civil Engineering, Gadjah Mada University and Sub-Project of Pemali-Comal, Tegal, Department of Public Works, Government of Indonesia. The research project was held in 1980 when the author was one of the team members which handled a plan of study to measure, calculate and analyze the data of the study. Measurement of water losses on site can be carried out by three methods.

Infiltration Method

By this method, the canal in a certain length, usually between two gates, have to be closed simultaneously and it means there is no water inflow and outflow from this section of the canal. Decrease of the elevation of water surface in the canal is recorded, in a certain period and by those data, the volume of water losses can be calculated. In this test the water losses consist of infiltration and evaporation. Due to the tests that were carried out in a certain period, the evaporation must be taken into consideration and it can be found by direct measurement or by calculation method. Finally the amount of infiltration is the difference of total water losses and value of water evaporated.

Inflow-outflow Method

The second method is the direct measurement of discharge in the same time of two cross sections in a certain length of the canal. From the difference of upstream and downstream cross section discharge, the water losses in a certain length of the canal can be found. The evaporation is neglected since this measurement is carried out simultaneously.

Computational Method

There are two existing equations to calculate water losses in the conveyance canal:

Moritz (1913)

Moritz (1913) formula is a semi-empirical method in which water losses depend on layer of the canal, discharge, velocity of flow, depth of the canal, base width and slope of the canal. All data can be measured in the field directly except the daily water losses through layer of the canal, it can be found from Table 1, and the equation is as follows:

$$S = 0.0116 \times C \left[\frac{Q}{V} \left\{ (N+Z)^{0.5} + \frac{2\left(Z^2+1\right)^{0.5} - Z}{(N+Z)^{0.5}} \right\} \right]^{0.5} \quad (1)$$

where S is water losses in the canal (m^3/s/km), C - daily water losses (m/day), see Table 1, Q - discharge of canal (m^3/s), V - flow velocity (m/s), N - ratio between base to depth of canal, and Z is slope of bank (Z = *horizontal* when *vertical* = 1).

Table 1: Value of C of Moritz (1913)

Soils	*C (m/d)*
Concrete	0.02
Cement gravel with hardpan sandy loam	0.10
Clay and clay loam	0.12
Sandy loam	0.20
Volcanic ash	0.21
Volcanic ash and same sand	0.30
Volcanic ash, sand and clay	0.37
Sand and gravel	0.51
Sand loam with gravel	0.67

Based on the field data measurement tabulated in Table 2, the parameters are width of the canal base, width of water surface, depth of water and daily water losses is equal to the real coefficient of permeability of soil layer, so $C = 8.333 \times 10^{-6}$ m/s and water losses can be calculated by Eq. (1). The result of water losses along the section of the canal and each measurement step can be seen in Table 3.

Bouwer (1965)

The formula of Bouwer (1965) is a semi-graphical method, which depends on a coefficient of permeability of soil, position of canal and ratio of water surface elevation to the groundwater table. This formula, which is supported by curves, was found by electric analog test in three conditions (Figure 1) and the value of I_s/K can be found from Figure 2. Finally, water losses can be computed by the equation as follows:

$$q = (I_s / K).k.W_s \quad (2)$$

where, q is water losses (m^3/s/m), I_s/K - value from the graph (Figure 2), k - coefficient of permeability of soil (m/s), and W_s is width of water surface (m).

Besides using the formula Eq. (2), the diagram must be initially used by knowing the situation of water elevation surface of the canal towards groundwater table, and also layering on permeable and impermeable layer on that canal location which is combined by canal data dimension. From field data of water surface situation of the canal, surface of ground water and position of soil layer, it can be concluded that this area of study is in accordance with ‘A condition’ as is being described in Figure 1. Then by substituting related geometric data to Figure 2, the value of $I_s/K = 1.90$ for all of the length of the canal tested. Using the real soil permeability’s coefficient $k = 8.333 \times 10^{-6}$ m/s and data from Table 2, and implementing Eq. (2) to calculate the loss of water for each section of the canal, the result can be seen in Table 3.

Table 2: Water losses and geometric data of each section for four steps measurements

No.	*Section of canal*	*Length of section (m)*	*Water losses (m^2/s)*	*Area of cross section A (m^2)*	*Width of water surface W_s(m)*	*Wet perimeter of canal P(m)*	*Width of canal base W_b (m)*	*Depth of canal H_w (m)*
Measurement I								
1	PA - BCm_1	1000	0.0587	13.6513	19.625	22.850	18.179	0.723
2	BCm_2 -BCm_3	900	0.1639	11.3746	9.625	11.135	6.861	1.382
3	BPt_1 - BPt_2	650	0.0246	6.0350	8.825	9.335	7.331	0.747
4	BPt_4 - BPt_5	475	0.0376	5.4206	9.750	10.390	8.565	0.953
5	BPt_5 - BPt_6	450	0.0977	3.4340	8.650	9.300	7.815	0.418
6	BPt_7 - BPt_8	500	0.0143	2.8432	7.200	7.840	6.362	0.419
7	BPt_9 - BRd_1	550	0.0156	1.2195	2.788	3.580	1.706	0.419
8	BRd_1 - BRd_2	760	0.0628	1.2761	2.975	3.975	1.934	0.520
Measurement II								
1	PA - BCm_1	1000	0.0698	11.1544	19.250	20.260	18.053	0.599
2	BCm_2 -BCm_3	900	0.0744	9.2663	10.475	10.955	8.519	0.978
3	BPt_1 - BPt_2	650	0.0437	3.9026	7.125	10.955	5.928	0.599
4	BPt_4 - BPt_5	475	0.0988	4.1164	11.125	11.625	10.360	0.383
5	BPt_5 - BPt_6	450	0.0808	2.4264	8.530	9.175	7.941	0.295
6	BPt_7 - BPt_8	500	0.0441	2.2388	7.010	7.188	6.341	0.334
7	BPt_9 - BRd_1	550	0.0090	0.9887	2.775	3.090	1.935	0.420
8	BRd_1 - BRd_2	760	0.0365	1.1938	2.700	3.160	1.587	0.556
Measurement III								
1	PA - BCm_1	1000	0.4200	19.678	20.375	21.255	18.347	1.014
2	BCm_2 -BCm_3	900	0.1880	12.185	10.500	11.564	7.840	1.330
3	BPt_1 - BPt_2	650	0.0985	7.7430	9.300	9.871	7.451	0.925
4	BPt_4 - BPt_5	475	0.0906	6.7133	11.850	12.149	10.344	0.596
5	BPt_5 - BPt_6	450	0.0334	3.4815	9.250	9.374	6.819	0.478
6	BPt_7 - BPt_8	500	0.0383	3.4621	7.775	8.024	6.826	0.474
7	BPt_9 - BRd_1	550	0.0219	0.6992	2.550	2.765	1.925	0.313
8	BRd_1 - BRd_2	760	0.0144	1.5869	3.500	2.765	2.428	0.536
Measurement IV								
1	PA - BCm_1	1000	0.2741	22.3621	20.750	21.630	18.481	1.135
2	BCm_2 -BCm_3	900	-	-	-	-	-	-
3	BPt_1 - BPt_2	650	0.1995	6.4332	8.310	7.050	6.581	0.864
4	BPt_4 - BPt_5	475	0.0334	5.8559	11.725	10.525	10.680	0.523
5	BPt_5 - BPt_6	450	0.0428	4.3804	9.200	9.350	8.191	0.505
6	BPt_7 - BPt_8	500	0.0746	3.7288	7.750	8.275	6.719	0.515
7	BPt_9 - BRd_1	550	0.0620	0.8749	2.675	2.585	1.912	0.381
8	BRd_1 - BRd_2	760	0.0090	1.4489	3.560	3.697	2.616	0.472

Measurements

The measurement on site consists of measurement of inflow and outflow discharge in the upstream and downstream from one section of the canal. Water losses can be calculated from the difference of two discharges. In this research, measurement was applied on 17 sections of the canal, but this research is only using eight due to complicity of the data. Chosen sections were PA-BCm_1, BCm_2-BCm_3, BPt_1-BPt_2, BPt_4-BPt_5, BPt_5-BPt_6, BPt_7-BPt_8, BPt_9-BRd_1, and BRd_1-$BRd_.$ Besides applying discharge measurement, this study is also using

Table 3: Result of water losses by measurement and result of computation

No.	Section of Canal	Length of Canal (m)	Water Losses (m^3/s) X	X^2	Moritz (m^3/s) U	X.U	Bouwer (m^3/s) V	X.V	Proposed (m^3/s) W	X.W
Measurement I										
1	PA - BCm_1	1000	0.0587	0.003446	0.07221	0.004239	0.31072	0.018239	0.20496	0.012031
2	BCm_2 - BCm_3	900	0.1639	0.026863	0.04532	0.007428	0.13715	0.022479	0.21542	0.035307
3	BP_4 - BPt_2	650	0.0246	0.000605	0.02615	0.000643	0.09082	0.002234	0.08784	0.002161
4	BPt_4 - BPt_5	475	0.0376	0.001414	0.02310	0.000869	0.07875	0.002961	0.08788	0.003304
5	BPt_5 - BPt_6	450	0.0977	0.009545	0.01535	0.001500	0.06163	0.006021	0.03578	0.003496
6	BPt_7 - BPt_8	500	0.0143	0.000204	0.01489	0.000213	0.05700	0.000815	0.03562	0.000509
7	BPt_9 - Rd	550	0.0156	0.000243	0.00759	0.000118	0.02215	0.000346	0.02126	0.000332
8	BRd_1 - BRd_2	760	0.0628	0.003944	0.01245	0.000782	0.03580	0.002248	0.03874	0.002433
Measurement II										
1	PA - BCm_1	1000	0.0698	0.004872	0.06785	0.004736	0.30478	0.021274	0.16986	0.011856
2	BCm_2 - BCm_3	900	0.0743	0.005520	0.04408	0.003275	0.14926	0.011090	0.17032	0.012655
3	BPt_1 - BPt_2	650	0.0437	0.001910	0.02107	0.000921	0.07334	0.003205	0.06376	0.002786
4	BPt_4 - BPt_6	475	0.0988	0.009761	0.01911	0.001888	0.08367	0.008267	0.03936	0.003889
5	BPt_5 - BPt_6	450	0.0808	0.006529	0.01390	0.001123	0.06077	0.004910	0.02524	0.002039
6	BPt_7 - BPt_8	500	0.0441	0.001945	0.01377	0.000607	0.05549	0.002447	0.02840	0.001252
7	BPt_9 - BRd_1	550	0.0090	0.000081	0.00810	0.000073	0.02416	0.000217	0.02250	0.000203
8	BRd_1 - BRd2	760	0.0365	0.001332	0.01179	0.000430	0.03249	0.001186	0.03826	0.001396
Measurement III										
1	PA - BCm_1	1000	0.1290	0.016641	0.08097	0.010445	0.32259	0.041614	0.28628	0.036930
2	BCm_2 - BCm_3	900	0.1880	0.035344	0.04784	0.008994	0.14962	0.028129	0.22090	0.041529
3	BPt_1 - BPt_2	650	0.0985	0.009702	0.02874	0.002831	0.09571	0.009427	0.10920	0.010756
4	BPt_4 - BPt_6	475	0.0906	0.008208	0.02199	0.001992	0.08676	0.007860	0.06084	0.005512
5	BPt_5 - BPt_6	450	0.0334	0.001116	0.01468	0.000490	0.05539	0.001850	0.03778	0.001262
6	BPt_7 - BPt_8	500	0.0383	0.001467	0.01628	0.000624	0.06155	0.002357	0.04166	0.001596
7	BPt_9 - BRd_1	550	0.0219	0.000480	0.00704	0.000154	0.02221	0.000486	0.01662	0.000364
8	BRd_1 - BRd_2	760	0.0144	0.000207	0.01415	0.000204	0.04211	0.000606	0.04410	0.000635
Measurement IV										
1	PA - BCm_1	1000	0.2471	0.061058	0.08449	0.020877	0.32853	0.8117976	0.32048	0.079191
2	BCm_2 - BCm_3	900	0	0	0	0	0	0	0	0
3	BPt_1 - BPt_2	650	0.1995	0.039800	0.02597	0.005181	0.08552	0.017061	0.09624	0.019200
4	BPt_4 - BPt_6	475	0.1334	0.017796	0.02152	0.002871	0.08818	0.011763	0.05436	0.007252
5	BPt_5 - BPt_6	450	0.0428	0.001832	0.01687	0.000722	0.06555	0.002806	0.04364	0.001868
6	BPt_7 - BPt_8	500	0.0746	0.005565	0.01659	0.001238	0.06135	0.004577	0.04488	0.003348
7	BPt_9 - BRd_1	550	0.0620	0.003844	0.00768	0.000476	0.02329	0.001444	0.02026	0.001256
8	BRd_1 - BRd_2	760	0.0090	0.000081	0.01386	0.000125	0.04284	0.000386	0.04006	0.000361
	Σ		**2.3147**	**0.281356**	**0.83540**	**0.086069**	**3.10918**	**0.319486**	**2.72250**	**0.306709**

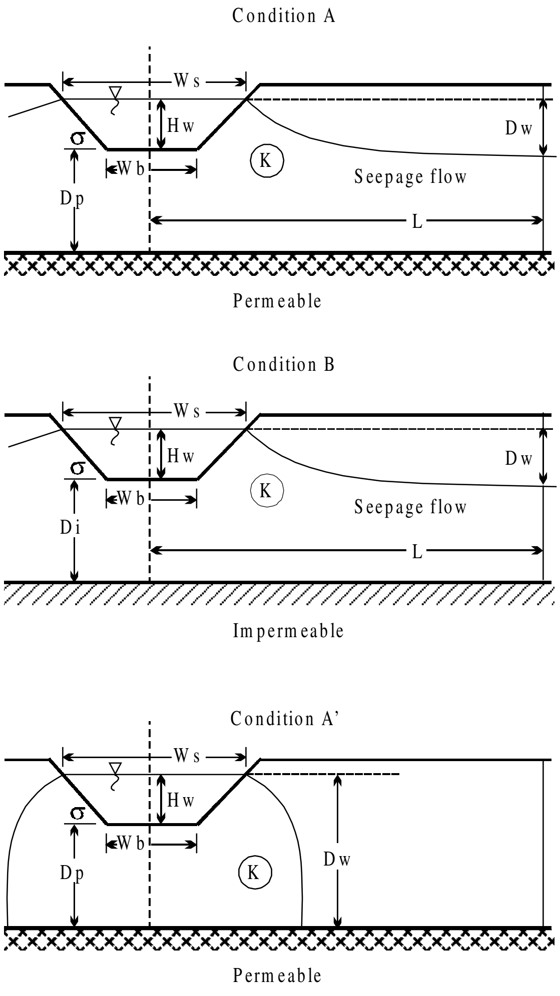

Figure 1: Three conditions of flow by Bouwer.

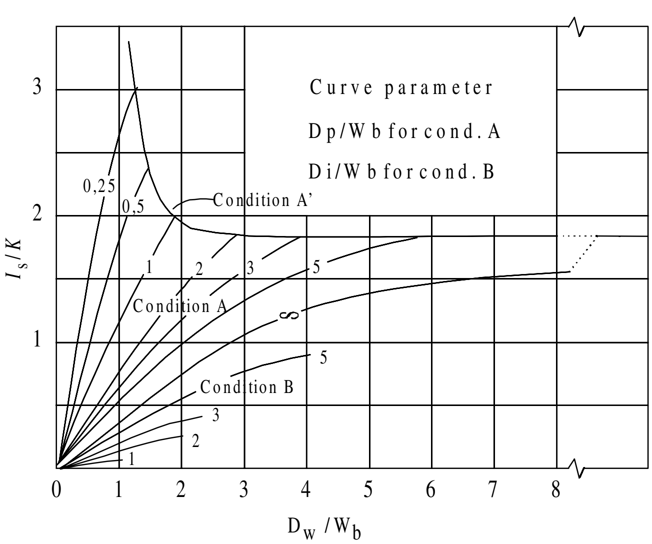

Figure 2: Value of I_s/K by Bouwer.

infiltration rate of the soil around the canal with the assumption that soil is homogenous and isotropic and these data can be used to calculate soil permeability coefficient.

Coefficient of Permeability

Double ring infiltration-meter used in this infiltration measurement is a cylinder without closing part on the top and bottom. This cylinder is put on the striped soil surface and filled in by the water until certain altitude levels; then decreasing of water level function of time is measured and the result is usually a curve in exponentials form. Beside those data, it has to be measured permeability coefficient by the field test. From the various field tests, average permeability coefficient is 8.333×10^{-6} m/s. This value becomes a calculation basis for Moritz (1913), Bouwer (1965) and proposed formula.

Discharge Measurement

There are many ways to measure discharge flow of a canal, but as the flow of the canal cannot be closed and according to adequacy of the equipment, *area velocity* method with *mid section procedure* was chosen. The location has to be on a straight canal, has a constant water surface and is free of hydraulic disturbance like turbulence or water jump and the technique of measurement is as follows:

1. Canal surface is divided into some pieces. A canal with more than two metres width is divided into one metre each and a canal with less than two metres width is divided into 0.50 metre each.
2. Velocity of flow is measured by using current metre in the middle of piece. For the depth of water which is less than one metre, velocity is measured one point on 0.6 H_w and for the depth which has more than one metre, it is measured on 0.20 H_w and 0.80 H_w and H_w is the depth of the water in the canal.
3. The discharge is average velocity multiplied by average surface area.
4. Water losses will be calculated from the difference between upstream and downstream discharge of each of canal. Carrying out of four times measurement with different period, different season and different discharge data are presented in Table 4. Beside those data, it can also be collected geometrically consisting of base width of canal (W_b), width of water surface (W_s) and depth of water (H_w). Based on these data each of Moritz, Bouwer and proposed formula can be calculated and the result of calculation tabulated in Table 3.

Table 4: Step of field measurements

No.	*Step*	*Period*	*Season*	*Discharge of canal*
1	I	26 - 30 September 1980	Dry	50 %
2	II	16 - 27 October 1980	-	50 %
3	III	07 - 13 November 1980	-	100 %
4	IV	16 - 22 December 1980	Rainy	100 %

Proposed Formula

Forchheimer (1930) has developed an equation to calculate permeability coefficient of soil from the field test with the formula as follows:

$$Q = F.K.H \tag{3}$$

where Q is discharge of infiltration, K - coefficient of permeability of soil, H - hydraulic head and F is shape factor.

Forchheimer's formula with Eq. (3) is designed to calculate the coefficient of permeability of soil from his field test by auger hole. For the auger hole with casing he defined shape factor as $F = 4\ R$ which is developed mathematically where R is radius of casing. For the equal condition with permeable lower casing as long as L, Dahcler (1936) has developed a formula of shape factor as follows:

$$F = \frac{2\pi L}{\ln\left\{\frac{L}{2R} + \sqrt{\left(\frac{L}{2R}\right)^2 + 1}\right\}} \tag{4}$$

where L is length of permeable lower casing and R is radius of casing.

From this equation when $L = 0$, Dachler's formula (1936) gives a value of $F = 0/0$ or indefinite value but Sunjoto (2002) developed a similar formula and when $L = 0$, the value of $F \neq 0$ is definite value and it means that this formula is in accordance with the physical condition and the formula is as follows:

$$F = \frac{2\pi L + 2\pi R \ln 2}{\ln\left\{\frac{L+2R}{2R} + \sqrt{\left(\frac{L}{2R}\right)^2 + 1}\right\}} \tag{5}$$

Sunjoto developed the above formula to calculate the depth of recharge well. Substituting Eq. (5) to Eq. (3), it can be manipulated mathematically to compute water losses in the canal by infiltration and propose a formula as follows:

$$q = \frac{4KH_w\sqrt{\lambda(W_b+W_s)}}{\ln\left\{\frac{H_w + 2\sqrt{\lambda(W_b+W_s)}}{2\sqrt{\lambda(W_b+W_s)}} + \sqrt{\left(\frac{H_w}{2\sqrt{\lambda(W_b+W_s)}}\right)^2 + 1}\right\}} \tag{6}$$

where q is water losses (m^3/s/metre), H_w - depth of canal (m), K - coefficient of permeability of soil (m/s), W_b - width of base canal (m), W_s - width of water surface (m), and λ is length of canal unit ($\lambda = 1$ metre).

Canal cross section described in Figure 3, and the data of length of section, water losses, area of cross section, width of water surface, wet perimeter of canal, width base of canal, and depth of water from the direct field measurement are tabulated in Table 2.

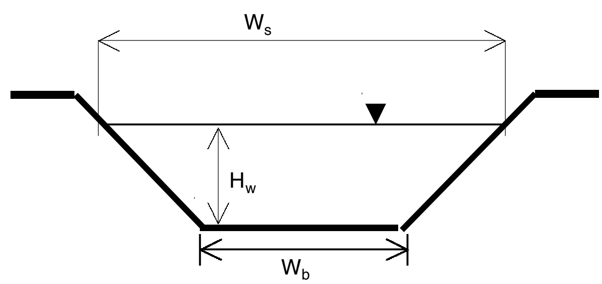

Figure 3: Cross section of canal (natural soil or permeable layer).

Results and Discussions

Results

From field observation, the area is sandy clay soil and from field test, the permeability of soils coefficient result is 8.333×10^{-6} m/s. This value is finally used for calculating Moritz, Bouwer and proposed formulas. From the measurement for each section we will be able to find profile data of section, which are: velocity, width of canal base, width of water surface, depth, area and wet perimeter. These data can be used to calculate discharge, based on width and slope of the canal in each section. Then the discharge of each section can be used to calculate water losses along the canal between two sections and the results tabulated in Table 3.

Discussions

Using a least square method with placing the result of measurement as independent variable and the results of the three formulas as dependent variable the equation of linear regression for each formula of computation will be found.

Statistical calculation for the formula of linear regression (Ronald E. Walpole, 1993) can be calculated by Eq. (7), Eq. (8) and Eq. (9) as follows:

$$y = a + bx \tag{7}$$

$$b = \frac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{n\sum x^2 - \left(\sum y\right)^2} \tag{8}$$

$$a = \bar{y} - b\bar{x} \tag{9}$$

The average value of water losses $\bar{x}$, $\bar{u}$, $\bar{v}$ and $\bar{w}$, where $\bar{x}$ represents water losses by data measurement, $\bar{u}$, $\bar{v}$ and $\bar{w}$ represent Moritz's, Bouwer's and proposed formula computation respectively and based on data from Table 3, can be computed:

$\bar{x} = \Sigma x : n = 2.31470 : 31 = 0.074668$

$\bar{u} = \Sigma u : n = 0.83540 : 31 = 0.026948$

$\bar{v} = \Sigma v : n = 3.10918 : 31 = 0.100296$

$\bar{w} = \Sigma w : n = 2.72250 : 31 = 0.087823$

Using formulas in Eq. (7), Eq. (8) and Eq. (9) and based on data from Table 3, presented the linear equation of each method, related to the data of measurement and the equations as follows.

Method of Moritz (1913)

$$b = \frac{31 \times 0.086069 - 2.31470 \times 0.83540}{31 \times 0.281356 - 2.31470^2} = 0.21831$$

$a = 0.026948 - 0.074668 \times 0.21831 = 0.01065$

Equation of Moritz versus measurement

$$u = 0.01065 + 0.21831\,x \tag{10}$$

Method of Bouwer (1965)

$$b = \frac{31 \times 0.319486 - 2.31470 \times 3.10918}{31 \times 0.281356 - 2.31470^2} = 0.80472$$

$a = 0.100296 - 0.074668 \times 0.80472 = 0.04021$

Equation of Bouwer versus measurement

$$v = 0.04021 + 0.80472\,x \tag{11}$$

Proposed Method

$$b = \frac{31 \times 0.306709 - 2.31470 \times 2.72250}{31 \times 0.281356 - 2.31470^2} = 0.95304$$

$a = 0.087822 - 0.074668 \times 0.95304 = 0.01666$

Equation of Proposed Formula versus measurement

$$w = 0.01666 + 0.95304\,x \tag{12}$$

Using assumption that the field measurement result tends to close with the real situation, the result of regression equation will become $y = x$ or gradient line is 45^o or $b = 1$, which means that field measurement will be equal to the result of the calculation. From that three regression equations can be concluded: Moritz's formula on Eq. (10) has the most minimum slope or gradient line with $b = 0.21831$, Bouwer's formula on Eq. (11) has bigger gradient line with $b = 0.80472$, and proposed formula on Eq. (12) has the biggest gradient line with $b = 0.95304$ or the closest result with the field measurement.

Conclusions

In designing of irrigation areas whereon the direct field measurement cannot be carried out due to non-existing canal, with computation using these formulas especially proposed formula, it will be convenient to know the efficiency of the irrigation canal and also the contribution of the canal to the increasing of groundwater storage which is distributed along the canal. From the three regression equations it can be concluded that proposed formula has the most similar result with the water losses on field measurement and then followed by Bouwer and finally by Moritz.

When the dimensions are width of base canal in Length (W_b in L), width of water surface in Length (W_s in L), depth of water in Length (H_w in L), permeability coefficient of soil in Length per unit Time (K in L/T) and length of canal unit in Length ($\lambda = 1$ metre), the result will be in cubic Length per unit Time per metre length of canal (q in L^3/T/metre). Usually these dimensions are in metre and second and the result will be in m^3/s/m. The formula proposed is in accordance with physical condition and it complies with *dimension analyses* but not for both previous formulas i.e. Moritz and Bouwer.

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