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MODELING SURFACE WATER QUALITY OF UI RECHARGE POND USING NUMERICAL METHOD

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ABSTRACT

During the last decade, water scarcity in terms of quantity and quality degradation has become a major issue in Indonesia. In 2006, Universitas Indonesia (UI) supported by the Ministry of Public Works built a recharge pond as a field model to overcome flood and drought in Jakarta and its surroundings. However, since then, a lack of research has been conducted to monitor and analyze the rate of change in water quality in the UI recharge pond. The purposes of this study are to identify the characteristics of UI recharge pond and evaluate the surface water quality changes. Water samples were taken from the pond and analyzed in the laboratory for water quality tests. The evaluation method used for simulation of water quality was a numerical model using Runge-Katta Order 4. Laboratory analysis results show concentrations of Mn, Fe, BOD and COD are exceeding the water quality standards (GR No.82/2001). The water purification process in the pond was found to be faster in response to BOD (λ= 0.5 d^{-1}) and for Mn, Fe, and COD are found to have similar results at λ= 0.4 d^{-1}. The 95% response time of the pond was found to be longer for Mn, Fe, and COD (t_{95} = 7.5 d) and the faster rate is BOD (t_{95} = 6.0 d). The result of numerical modeling demonstrates Mn concentration in the pond will be doubled (0.45 mg/L) on the day-15th and asymptotically converges on a steady state. The Fe, BOD, and COD reaches the steady state concentration around on the day-11th (0.95 mg/L), on the day-13th (56.6 mg/L), and on the day-17th (224 mg/L), respectively.

Keywords: Numerical model; Simulation and observation; UI recharge pond; Water quality changes; Water quality modeling

1. INTRODUCTION

Universitas Indonesia's (UI) recharge pond which was constructed in 2006 was initially aimed to store inflow discharge from river, storm water, runoff, and to let it to infiltrate and percolate as ground water recharge. The construction was supported by the Ministry of Public Works and it was built with the long-term goal as a field model to overcome drought and flood disaster in Jakarta (Hartono et al., 2010) and the surroundings. As a model in a field-scale, UI recharge pond has the values and significance in terms of quantitative and qualitative aspect (Legowo and Sudinda, 2009). However, after the five years of development it has reached to an alarming stage. The physical condition of the supporting building such as control-house and sluice-gate were dysfunctional, the physical and chemical situation of the pond water has also shown worrying signs. In addition, the volume of pond water, especially in the dry season is lessening; it is seen from the mark of water level lines on the main recharge pond's wall (Suwartha & Pramadin, 2012).

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This is due to limited water supply both from rainfall (intensity and number of rainy days) and water discharge from the river (low water level) so that inflow water into the recharge pond is uncommon. Furthermore, related research on water quality test shown several water parameters value exceeding the quality standards for raw water (Joko, 2011; Suwartha & Pramadin, 2012). The water source of recharge pond mainly originated from 6 artificial lakes (Kenanga, Agatis, Mahoni, Puspa, Ulin, Salam) at the upstream area, which also were indicating several water quality parameters above the allowable threshold of the quality standards (Sutopo, 2008; Sutjiningsih & Anggraheni, 2011).

Considering the pond function as a rechargeable media and conserves groundwater, the quality of ground water is greatly influenced by the recharged water quality. Apart from the self purification process, recharging pond water quality could be worse when the concentration of pollutants entering the pond remains high, while the dimensions of pond storage are fixed and are slowly being subjected to decaying processes. In this regard, the dynamic change of water quality and quantity as well as internal processes that occur need to be monitored through an integrated and sustainable operation and maintenance activities. This is very closed related to water quality management, which aims to control the physical, chemical and biological characteristics of water (UNEP, 1996). Evaluation both on the water quantity and quality is essentially required to ensure the pond function works properly and the water quality that is recharged into ground water is to remain within the permissible level. However, up to the present, a sustainable research activity to monitor and analyze the rate of change in water quality of the recharge pond has never been done. The purposes and originality of this paper are twofold: First, we identify the characteristic of UI recharge pond covers the eigen value, transfer function, assimilation factor, residence time, and response time. Second, we evaluate the surface water quality changes over time. The evaluation method used for the simulating water quality is numerical model using Runge-Katta Order 4.

2. METHODOLOGY

In general, this research can be divided into two main activities; first, on the site (survey, measurements, and water sampling), second, in the laboratory (water quality test, and numerical modeling of the pond water quality changes over time).

2.1. Site Description

Field observations were conducted inside the UI campus Depok area, just downstream of Lake Salam (Figure 1). The recharge pond is located at about $6^{o}20'52.19"$S and $106^{o}49'52.18"$E. The surface area of the UI recharge pond is about 3,102.75 m^2, consisting of two compartments; first, the outer recharge pond ($A = 3{,}002.75$ m^2) and second, the main recharge pond ($A = 100$ m^2). The outer recharge pond is directly connected to the river flow at the intake channel and outlet channel (drainage and spillway), while between the outer recharge pond and the main recharge pond is connected by a control gate at the main recharge pond's wall side. The depth of main recharge pond is approximately 6.75 m, and the outer recharge pond is about 2.6 m.

2.2. Sampling Activity

Prior to sampling activity, field observation and measurements (water depth, rainfall intensity, and evaporation) were conducted occasionally to obtain general data related on water availability, recharge rate, and characteristics of the pond. Water samples were collected from three sampling points; SP1 at the river side before the intake channel, SP2 at the outer recharge pond, and SP3 at the main recharge pond (Figure 2). The three sampling points were selected to understand the water quality differences between outside and inside the recharge pond.

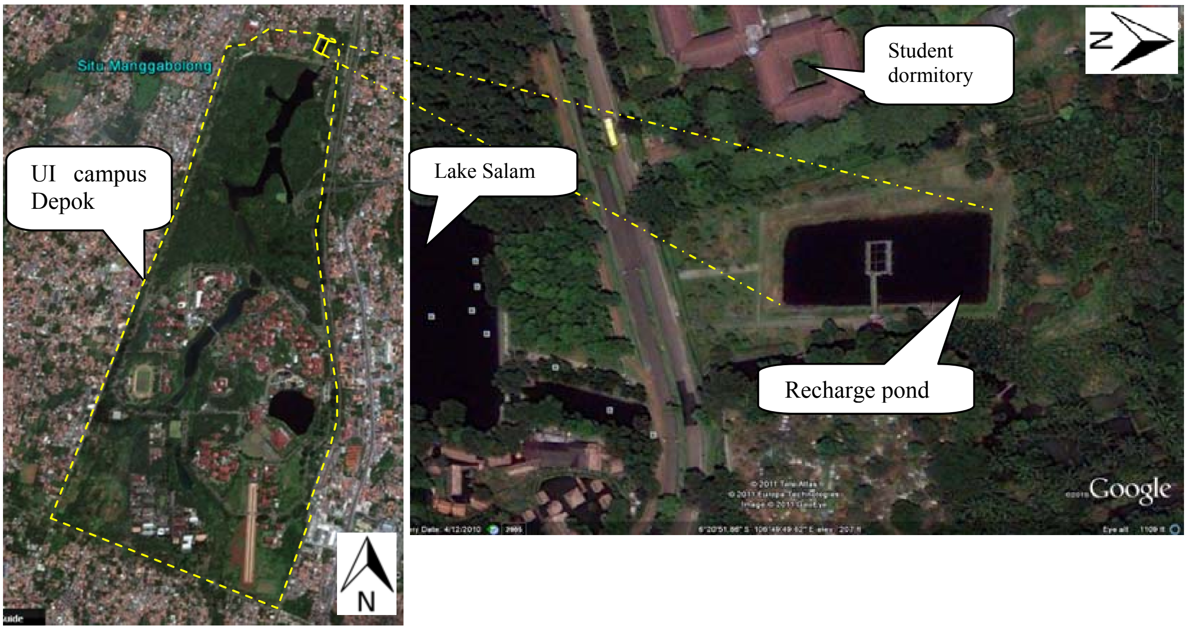

Figure 1 Location of UI campus Depok and the recharge pond

The method of composite sampling was applied at each sampling points (Blomqvist, 2001). Since the pond depth is <10 m, the amounts of water were sampled manually by using a bottle sampler at two different depths; 20 cm below the water surface, and near the bed of the pond (Effendi, 2012). The water sampled from both depths was mixed together in a 1.5 L storage bottle to be a composite sample. Both of the hydrometrical measurements and water sampling were carried out during May, July, and October 2012.

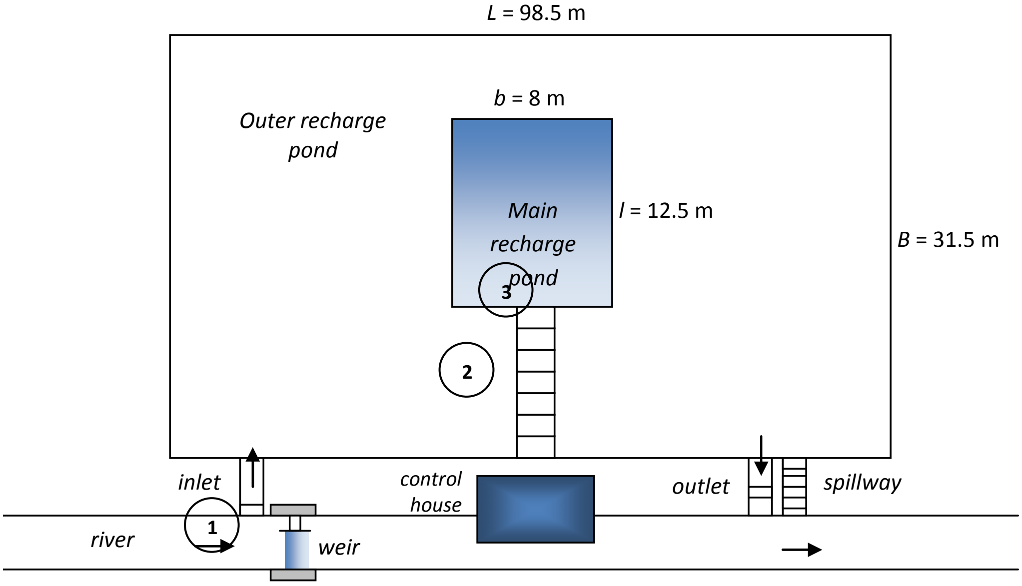

Figure 2 Sketch of the recharge pond and location of the sampling point

2.3. Water Quality Analysis

Parameters to be analyzed in laboratory was focused on parameters that are generally investigated for monitoring ground water or surface water quality as a raw water source. It covers the physical, chemical and biological parameters. Standard analyses of water quality were carried out included; pH (SNI 06-6989.11-2004), temperature (SNI 06-6989.23-2005), color (6989.80:2011), and turbidity (SNI 06-6989.11-2004). Dissolved solids which are transferred to groundwater are also measured, including Total Dissolved Solid (TDS), Iron (Fe) (SNI 6989.4:2009), Manganese (Mn) (SNI 6989.5:2009), and Chloride (Cl) (SNI 6989.19:2009). Organic contents which indicate contaminations by leachate and wastewater were also measured to study the potential of organic contamination to the groundwater, which included Biological Oxygen Demand (BOD) (SNI 6989.72:2009), and Chemical Oxygen Demand (COD) (SNI 6989.73:2009). The three metal parameters (Fe, Mn, and Cl) were chosen as representative of metal-chemical parameters, since their concentrations were found to be relatively high in the recharge pond (Sutopo, 2008).

The range of pH and temperature levels were measured in-situ using Lutron pH-201 and Hach multiparameter sensors, respectively. Other parameters were measured in the laboratory within one hour of sampling or otherwise conserved in 4^{o}C temperature until measurement was achieved. Color, turbidity, Fe and Mn was measured using Spectrophotometer DR 2000. Total dissolved solids were measured from 100 ml sample filtered with Whatman Grade 934 AH 1.5 μm, and evaporated at 105^{o}C. BOD was measured using the Winkler method and COD was measured using closed reflux method and titrimetry.

In order to determine the quality of water samples and degree of environmental water pollution, the laboratory analyses results were compared to the quality standards issued by Government Regulation No.82 Year 2001 on Water Quality Management and Water Pollution Control (Anonymous, 2001).

2.4. Modeling Concentration Changes

2.4.1. Mass-balance Principle

The basic principle of water quality models is that of mass balance. Instead of the main recharge pond, the outer recharge pond was selected in the modeling since it was more directly influenced with the inflow and outflow. The outer recharge pond was assumed as a continuously stirred tank reactor (CSTR) which is very appropriate to receive water where the contents are insufficiently well-mixed so that become equally distributed (Chapra, 1997). At a finite time period, the mass balance for the CSTR system can be expressed as follows:

$$V\frac{dc}{dt} = W_{(t)} - Qc - kVc - vA_s c \tag{1}$$

where V dc/dt is accumulation; depending on the volume of the reactor and rate of concentration change, W is mass loading rate (MT-1) as a function of time (t), Q is inflow discharge into system (L3T-1), c is average concentration of the inflow discharge (ML-3), k is a constant of the reaction rate at the first-order which is equal to v/H (T-1), v is settling velocity (LT-1), and As is surface area of the pond (L2).

2.4.2. Lake Characteristics

Assimilation factor (a)

Assimilation capacity is defined as the ability of water or water sources to receive wastewater pollutant loads without causing a decline in water quality designation established in accordance with standards. The mathematical equation to find the value of assimilation factor is (Chapra, 1997):

$$a = Q + kV + vA_s \tag{2}$$

Transfer function (β)

According to Chapra (1997), the transfer function is defined as the process by which inputs are transformed or transferred into outputs. Mathematically, the transfer function can be expressed as:

$$\beta = \frac{Q}{Q + kV + vA_s} \tag{3}$$

Residence time (τ_w)

Residence time is the length of time or the duration of water to remain in the lake. In other words, it is the amount of time that would be required for the outflow to replace the quantity of water in the pond. In general, a large and deep lake is having a longer residence time than the shallow lake at the average inflow rate. Mass balance equation for pollutant residence times is as follows (Chapra, 1997).

$$\tau_w = \frac{V}{Q} \tag{4}$$

Eigen value (λ)

Eigen value is a parameter that describes the characteristics of water bodies response to pollution. The larger eigen value indicates the faster water purification process (self purification) in a water body (Chapra, 1997). The eigen value can be calculated using following equation.

$$\lambda = \frac{Q}{V} + k + \frac{v}{H} \tag{5}$$

Response time (t_φ)

Because basically the process of purification of pollutants will not be 100% to eliminate the pollutants, the parameters used to measure the time when pollutants are reduced enough is the response time (t_φ), where φ is percentage reduction of pollutants that have occurred. The size that often be used is t_{95} (see Table 1) which is the time required to remove the body of water pollutant concentrations redemptions of 95% of the initial concentration (Chapra, 1997).

Table 1 response times (Chapra, 1997)

Response time	t_{50}	t_{75}	t_{90}	t_{95}	t_{99}
Equation	0,693/λ	1,39/λ	2,3/λ	3/λ	4,6/λ

2.4.3. Loading

In a natural state, the loading function of a pollutant can be varied over time. The realistic loading often makes it difficult to discern model behavior (Chapra, 1997), in contrast with an idealized loading function that provides an uncomplicated view. In this study, the step loading system was assumed as the pollutants' continuous source into the pond and was applied for the modeling. This assumption was based on a basic consideration that there is river flow and six artificial lakes at the upstream area which potentially contribute continuous pollutant flows into the pond. Step loading is a pollutant loading whose magnitude is constant over time. The loading is expressed as $W(t<0) = 0$, and $W(t\geq 0) = W$, where W is the new constant level of loading (MT^{-1}). The particular solution of step loading $c = \frac{m}{\lambda V}\left(1 - e^{-\lambda t}\right)$ provides concentration changes that form an exponential curve.

2.4.4. Numerical Model

Numerical method of Runge-Kutta Order 4 was employed to modeling surface water quality of the recharge pond. The general equation of Runge-Kutta method can be formulated as follows.

$$c_{i+1} = c_i + \phi h \tag{6}$$

where $\varnothing$ is slope (also called as increment function), h is step size (= $t_{i+1} - t_i$), c_i and c_{i+1} is concentration at a present and a future time t_i and t_{i+1}, respectively. Most of Runge-Kutta method which has been widely been used is the fourth-order that has the form:

$$c_{i+1} = c_i + \left[\frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4)\right] h \tag{7}$$

whereas:

$$k_1 = f(t_i, c_i) \tag{8}$$

$$k_2 = f(t_i + \frac{1}{2}h, c_i + \frac{1}{2}hk_1) \tag{9}$$

$$k_3 = f(t_i + \frac{1}{2}h, c_i + \frac{1}{2}hk_2) \tag{10}$$

$$k_4 = f(t_i + h, c_i + hk_3) \tag{11}$$

The slope is represented by the averaged k ranging from 1 to 4, which indicates the order of degree.

3. RESULTS AND DISCUSSION

3.1. Water Quality Analysis

Table 2 shows the laboratory analysis results for temperature, pH, TDS, color, turbidity, Mn, Fe, Cl, BOD, and COD values for different sampling point during hydrometrical measurement in the dry (May and July) and wet (October) seasons of 2012. Results show that concentration of most parameters lie in ranges either above or below the threshold of water quality standard (GR No.82/2001 Class I), except for Mn, Fe, BOD, and COD that exceeds the quality standard (shown by the bold characters). The averaged Mn concentrations varied from 0.1 to 0.5 mg/l, Fe varied from 0.1 to 0.8 mg/l, BOD varied from 16.6 to 39.7 mg/l, and COD concentrations varied from 20.0 to 477.0 mg/l in both dry and wet seasons.

Table 2 Water quality data

Parameter	Unit	SP1		SP2		SP3	
		May-11	Jul-5	May-11	Jul-5	May-11	Jul-5
Temperature	^{o}C	28.7	28.1	29.9	29.5	29.1	28.5
pH	-	7.1	7.2	6.5	6.9	6.9	7.0
TDS	mg/l	109.9	116.3	100.6	97.6	107.2	104.6
Color	Pt-Co	84	130	71	113	54	26
Turbidity	NTU	8.1	13.2	7.7	7.3	7.5	3.6
Mn	mg/l	**0.4**	**0.3**	**0.5**	**0.2**	**0.5**	**0.2**
Fe	mg/l	**0.6**	**0.8**	**0.6**	0.3	**0.6**	0.1
Cl	mg/l	16.1	17.1	16.2	16.9	8.1	7.7
BOD	mg/l	n/a	**35.0**	n/a	**36.6**	n/a	**39.7**
COD	mg/l	n/a	**477.0**	n/a	**208**	n/a	**112.0**

Table 2 (cont.)

Parameter	SP1			SP2			SP3		
	Oct-8	Oct-22	Oct-31	Oct-8	Oct-22	Oct-31	Oct-8	Oct-22	Oct-31
Temperature	30.6	29.2	30.5	30.9	29.7	29.8	30.7	30.1	30.0
pH	6.7	7.3	7.5	6.7	6.7	6.8	6.7	7.0	7.1
TDS	134.8	142.2	130.8	125.2	111.8	106.7	110.	110.2	110.8
Color	138.0	132.0	121.0	126.0	120.0	125.0	19.0	13.0	12.0
Turbidity	15.0	12.6	12.9	11.5	13.0	15.0	3.5	3.9	3.0
Mn	**0.3**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	0.1	0.1	0.1
Fe	**0.8**	0.3	**0.4**	0.3	**0.5**	**0.6**	0.03	0.1	0.1
Cl	13.7	22.1	15.3	19.5	17.9	16.4	6.2	11.0	9.6
BOD	**31.8**	**20.6**	**22.3**	**35.8**	**23.9**	**23.8**	**33.7**	**19.1**	**16.6**
COD	**132.0**	**184.0**	**266.4**	**116.0**	**220.0**	**107.2**	**102**	**20.0**	**85.2**

As depicted in Figure 3, although showing a declining trend, concentration of Mn for all sampling point is found >0.1 mg/l (threshold of the quality standard GR No.82/2001 class I for raw water source), except for SP3 (main recharge pond) is declining to the quality standard in the wet season. Generally there is a relation between concentration of Manganese and water color (Abdur & Budi, 2004).

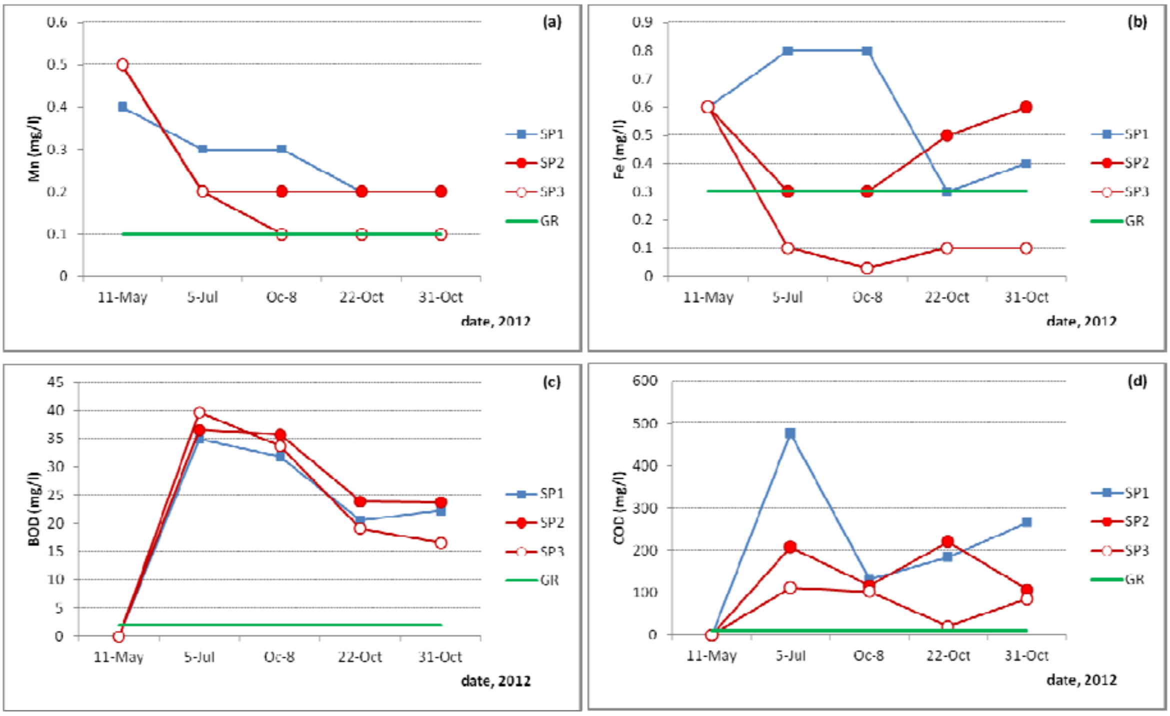

Figure 3 Concentration changes in each sampling point; (a) Mn; (b) Fe; (c) BOD; (d) COD

Concentrations of Fe in most natural waters are small–at less than 0.3 mg/l. While in this study, Fe concentration at SP1 and SP2 are higher (≥0.3 mg/l) relative to SP3 which decline below the quality standard. These results are also in line with Sutopo (2008) research result. Fe concentration in the natural water bodies is ranging from 0.05-0.2 mg/l (Boyd, 1988). The concentration of Fe at water bodies whose get enough aeration (aerob) is usually never higher than 0.3 mg/l. The raising Fe concentration at SP1 and SP2 might be caused by not enough aeration during the dry season (no water flow into the pond), while during the rainy season Fe concentration was added from the rain water supply which contains Fe about 0.05 mg/l (McNeely et al., 1979).

In general, concentrations of BOD and COD are obviously exceeding the water quality standard. This indicates that there is a lot of readily decomposable organic matter in the pond. Both BOD and COD are showing more and less similar trends for all sampling points; there is a declining concentration from dry to wet season (no measurement of BOD and COD on 11-May). This might be due to dilution and natural aeration effect during rainfall.

The results are further compared to the three other classes (class II-IV) in the Quality Standard GR No.82/2001. These classes have a higher limit due to their different target usage which regulates water quality for recreational, fishery, plantation, and other non-domestic usage. However, BOD and COD concentrations of the recharge pond still exceed the limit for Class II, III and IV water. This signifies that the recharge pond cannot directly be used as a water source for any activity without any particular treatment. Water quality in the Great Jakarta area often exceeds regulatory levels due to contamination by wastewater and leachate from solid waste (Palupi et al., 1995).

3.2. Characteristics of the Recharge Pond

Based on the measurement results of the mean depth and employing the pond data (width and length) it can be estimated that the average volume of water in the recharge pond is about 9107.98 m^3 (outer recharge pond is about 8439.5 m^3 and main recharge pond is about 668.5 m^3). The recharge rate of the pond was found to be about 3.2 mm/d during dry season and 6.1 mm/d during wet season (Suwartha & Pramadin, 2012).

Since the outer recharge pond is directly connected to inflow and outflow channel, hence, further discussion regarding pond characteristics, and water quality modeling are focused solely on this site (SP2) based on water quality analysis and pond data.

The results shown the assimilation factor (a) for Mn, Fe, BOD, and COD is 3629.8 m^3d^{-1}, 3638.5 m^3d^{-1}, 4256.6 m^3d^{-1}, and 3567.8 m^3d^{-1}, respectively. It can be understood that the recharge pond has a different ability to receive pollutant loads within various capacities. The transfer function β for each parameter Mn, Fe, BOD, and COD is 0.8, 0.8, 0.6, and 0.8, respectively. This indicates that pond's removal mechanism for Mn, Fe, and COD in the recharge pond is weak relative to its supply mechanism ($\beta \rightarrow 1$). In this case the pollutant level will approach that of the inflow. In other words the pond's assimilative capacity is minimal (Chapra, 1997). The recharge pond's flushing rate is shown by the residence time that is about 3.05 d. This is because of the pond's volume is large and the flow is small so that the pond has a long residence time; this mean that the recharge pond is having a slow flusher. This situation in the end led to an increase in the degree of pond contamination by pollutants. Based on the comparison between pollutant residence times over the water residence time which is found > 0.6, it can be stated that the recharge pond water is polluted by Mn. Fe, BOD, and COD. The pond's ability for self-purification against pollutants shows the fastest for BOD (λ= 0.5 d^{-1}), while at the same for Mn, Fe, and COD at λ= 0.4 d^{-1}. This result closely related to the response time of the recharge lake, where for the 95% response time of the pond was found longer for Mn, Fe, and COD (t_{95} = 7.5 d) and the faster is BOD (t_{95} = 6.0 d).

3.3. Pond Water Quality Modeling

The model was developed for predicting Mn, Fe, BOD, and COD concentration changes at SP2 (outer recharge pond) during the wet season on October 2012. The results of numerical modeling using Runge-Kutta Order 4 with step-loading function were verified using an analytical solution. Overall, the simulation model is able to reproduce and approach the calculation value of the analytical method. As for model validation, the simulation results were then compared with the observation data along with rainfall data and government regulation of water quality standards as shown in Figure 4.

In general, the figures show that the numerical model is over-estimating the concentration changes. According to the model prediction, Mn concentration will be doubled about 0.45 mg/l on the day-15th (23 Oct) and asymptotically it converges on a steady state (Figure 4.a). The Fe, BOD, and COD reach the steady state concentration on the day-11th at 0.95 mg/l, on the day-13th at 56.6 mg/l, and on the day-17th at 224 mg/l, respectively. On the other hand, the observed concentrations of Mn and BOD tend to response oppositely. In contrast, Fe shows an inclining trend of concentration which corresponds to the predicted values, and COD to some degree demonstrates better conformity between predicted and observed values (Figure 4.d).

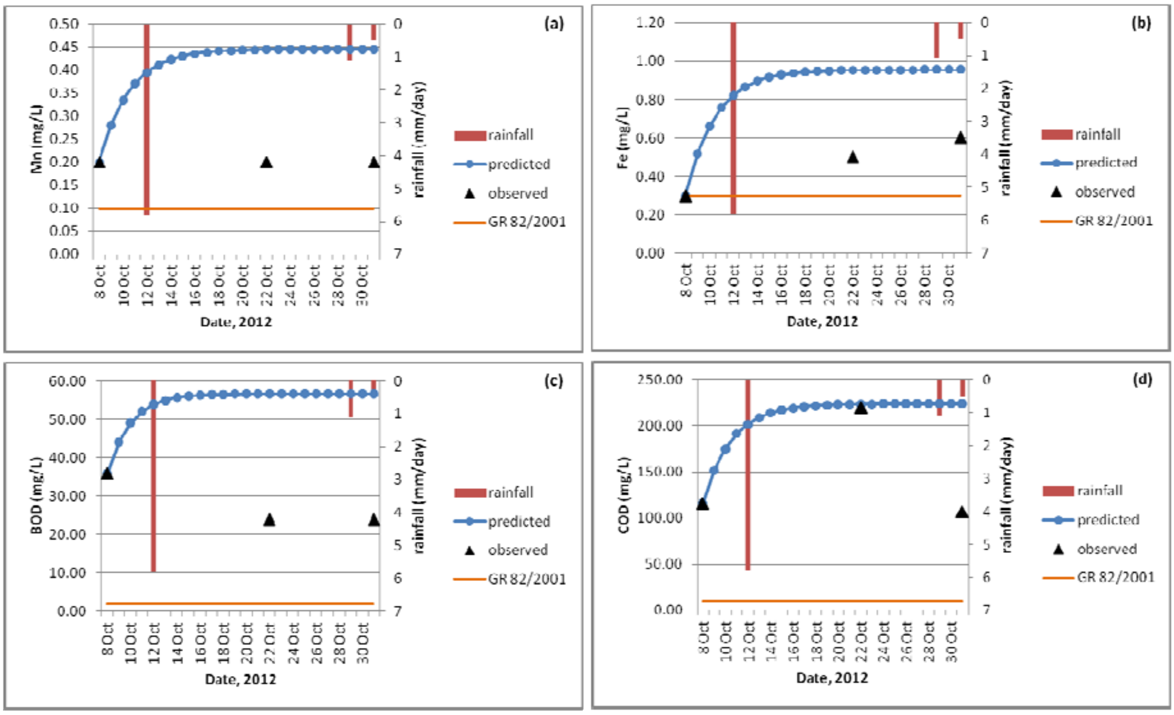

Figure 4 Comparison between predicted and observed concentration changes in the outer recharge pond: (a) Mn; (b) Fe; (c) BOD; (d) COD

The discrepancy between predicted and observed data may exist because either the model limitations, or the particular event we used to derive the result, does not accurately reflect the ideal condition of the flow. Below, we list and discuss potential causes for the discrepancy between model predictions and empirical observations.

Assuming a step loading—A fundamental assumption of our analysis was that the loading system we are considering into the pond is a continuous step-loading. It seems that the assumption was overconfident in the case of the actual situation in the field. During the observations the behavior was unexpectedly inconsistent. Despite the fact that the observation was conducted in rainy season (October), the flow discharge in river was mostly never reaching the maximum level. As a result, there were no steadily inflow discharges from the river into the pond and consequently additional flow concentration into the lake was not available.

Omissions of the model—Alternatively, the discrepancy between the empirically observed and model predicted concentration changes may arise from omitting biodegradation features in the relatively simple model. Whereas, in a natural state, matter transformations associated with both higher and lower tropic levels are known to affect nutrient dynamics, and at first glance these may be seen as potential modifiers of the nutrient index ratio (Ballantyne et al., 2010). In the case of BOD and COD, decay rates could be one of the possible factors that cause the disparity, since the decay rate indicates how an organic matter can be degraded naturally. The short-term fate of organic micro-pollutants in a water system is determined mainly by partitioning the water and organic particulate matter, and then by transport. Additional processes such as volatilization and degradation influence organic micro-pollutant concentrations, which, in contrast to heavy metals, do not decay (UNESCO, 2005). Thus, determining the appropriate initial decay rate as an input data for modeling could be a key factor for the model quality.

4. CONCLUSION

Based on the water quality analysis results, it can be concluded that UI recharge pond has been polluted and contaminated with Mn, Fe, BOD and COD. In this present study, the natural ability of the pond to degrade organic matter is low, which means the self-purification ability of the pond has decreased (λ= 0.4-0.5 d^{-1}). Moreover, the response time of the pond to reach 95% of its ultimate recovered level against those four contaminants is considerably time consuming (t_{95} = 6.0-7.5 d).

The results of numerical modeling using Runge-Kutta Order 4 and assuming input pollutant as step-loading shows an over predicted to the concentration changes. However, to a certain extent the model shows better fitness for COD concentration relative to the other three parameters. Following the model prediction results, the concentration of Mn will be doubled about 0.45 mg/l on the day-15th (23 Oct) and then it asymptotically converges on a steady state. While, the Fe, BOD, and COD reach the steady state concentration on the day-11th at 0.95 mg/l, on the day-13th at 56.6 mg/l, and on the day-17th at 224 mg/l, respectively.

5. ACKNOWLEDGEMENT

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