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Full Length Research Paper

The effectiveness of using a recharge well to mitigate flood measured in a physical model

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A structural method that involves the use of a recharge well to mitigate flood in a flat area is adopted as a mitigation method for this research. The determination of the effectiveness of this method was carried out by simulating storm-water accumulation in a reduced scaled physical model. The physical model had a rainfall simulator fitted to a sand tank which contained soil materials of different grain size and different coefficient of permeability. Size of the sand tank is 100 cm 60 cm × 40 cm and a perforated pipe of 3.5 cm are fixed in the model to simulate recharge well. By varying the rainfall intensity and rainfall duration a relationship was established between the rainfall characteristics and movement of storm-water into the ground. An average of 43.3% increase in recharge rate was observed when the model was tested with the recharged well as compared to a condition in which recharge well is not present. The reduction in rainwater when the recharge well exists is 6.07% of the total rainwater.

Key words: Physical model, recharge well, groundwater, flood, rainfall simulator.

INTRODUCTION

It has been reported that the world has witnessed a growing number of floods in urban areas due to the climate change and rapid urbanization. These floods have led to loss of millions of lives, destruction of properties, displacement of millions of people and spread of diseases at almost everywhere in the world. Also, places that have never experienced flood before have been experiencing it now and places that have ever been experiencing flood are experiencing more devastating storm due to climate change (http://www.searo.who.int).

Flood has been reported to be the world's most recurrent and damaging types of disasters which can lead to critical environmental emergency situations affecting the integrity of large infrastructures and the life of many living beings. Unfortunately, frequency and severity of flood damages are increasing in every part of the world (http://www.searo.who.int). During the latter half of twentieth century floods were the most common type of geophysical disaster, generating over 30% of all disasters between 1945 and 1986. One way of scaling the world's flood problem is to examine estimates of people and properties located in flood-prone areas. Some estimates have been produced, which are flood-prone. Typical numbers are 3.5% in France, 4.8% in the United Kingdom, 9.8% in the United States, over 50% in Netherlands and 80% in Bangladesh.

Malaysia is a country that has not been spared of these disasters. Several major floods have been experienced in the last few decades in Malaysia, as far back as 1886, a severe flood with gale-force winds caused extensive damages to Kelantan. The flood of 1926, supposedly the worst in living memory in Malaysia, affected most of the Peninsular Malaysia, resulting in extensive damages to property, road systems and agricultural land and crops. In 1987 disastrous floods surged across the Kelantan, Terengganu and Perak river basins, taking 55 lives. Flood occurred at Kota Tingga at the end of 2006 and the beginning of 2007. Flood occurrences seem to be getting more frequent in recent years in some cities like Kuala Lumpur, Penang and Kuching where rapid urbanization is taking place (Bulletin Igenieur, 2004).

This paper focuses on the use of a physical model to determine the effectiveness of a method that involves

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reducing accumulated storm-water right from the upstream before it is being conveyed downstream. Unlike past methods that involved the use of culvert, storm sewers and gutters to convey the water downstream and the use of retention basin, detention basin and dams to store this storm-water either temporarily or permanently, this method involves reducing the storm-water before it reaches these hydraulic structures. This can be achieved by injecting some of the storm-water directly back into the soil by means of perforated wells penetrating through the impermeable layer into the more permeable layers of the soil. This paper will focus on the results obtained from the physical model.

LITERATURE REVIEW

Location of the study area

The study area in which this research was carried out is of importance because of the peculiar nature of the top soil presence in the study area. Adila and Tjahjanto (2008) carried out an investigation on the study area with respect to flooding. The study area is located in Batu Pahat, a district under the state of Johor, Malaysia. Administratively, this district covers an area of approximately 900 km^2. There are two main channels that is Parit Karjo and Parit Botak which end at the straits of Malacca. It was found that the land is flat and only 1 to 2 m above sea level and the top soil is dominated by soft clay and peat soils. For a long time ago, during raining season the area has always been flooded by an average of 0.5 m water depth and average rainfall intensity of 2,400 (mm/year). Most of the natural phenomenal were simulated in the physical model.

Past methods used in mitigating flood

Various methods have been adopted in mitigating flood in the past among which can be categorized into structural and nonstructural methods. Both of these mitigation methods have proved quite effective, but there are no doubts that flood devastating effect still exist in places where expensive structures are put in place to mitigate this flood.

Thomas (2006) made an analysis on how some of these structural methods end up contributing to causing disasters rather than mitigating flood. According to the researcher, the rapid growth of urban areas over the past few decades create the need for construction of extensive storm drainage facilities. Runoff collected by the proliferating paved streets and gutters was collected by storm sewersystems and conveyed directly to the nearest practical disposal point. Over the years, however, it has become apparent that the customary exclusive reliance on storm sewers for surface water disposal creates a series of new problems.

Ralph and Wesley (2002) made more explanation on the disadvantages of relying totally on existing structures, they made mention in their text that in the late nineteenth century until the mid-twentieth century, storm water management was usually considered the successful collection and disposal of increased surface runoff. The solution was usually a comprehensive design of roof gutters, downspouts, swales, curbed gutters, sewer inlets and sewers pipes to collect, convey and discharge surface runoff streams, rivers lakes and other water bodies in the most efficient manner possible. The central theme of storm-water management design was to collect and transport the runoff to nearby body of water as quickly as possible; riddling the developed site of excess runoff. Little thought was given to the effect of excess runoff and decreased infiltration to the surrounding water shed.

Also, Osman and Robert (1966) brought up a very important trend in which places experiences a situation where water table has dropped sharply because of insufficient recharging of the groundwater whereas extensive flood occurs downstream on a more and more frequent basis. They concluded the statement by stating that if we continue in this manner, problems will increase to the point where we will be faced with costly damage of great magnitude and the obvious approach would be to design a storm drainage system that will facilitate nature’s process; that is direct the storm water back into the soil.

Injecting water through recharge well back into the soil

One of the basic methods adopted for this research is the use of artificial recharge well to recharge an aquifer. The use of artificial recharge wells has long been used for other purposes. Abandoned wells, or wells specifically designed for artificial recharge, have been used for many years to inject water into the ground. The U.S department of Agriculture Publication (1970), states: "The use of injection wells is confined largely to areas where surface spreading is not feasible because extensive and thick impermeable clay layer over lie the principal water-bearing deposits”. This is similar to what is available at the location chosen for this study. They may also be economically used in metropolitan areas where land values are too high to use the common basin, flooding and ditch-and-furrow methods (Boswell, 1954).

The transportation laboratory of the California department of transportation in a 1969 report discussed recharge or "drainage" wells as follows: "drainage wells are basically water supply wells operating in reverse of recharge well, although in practice, they have many unique features and problems”. There are also several types, ranging from simple gravel-filled shafts to highly sophisticated pump injection wells. Like basins, they have both good and bad features. Wells requires a minimum of space and may be designed with a very little unsightly surface structure. They can be extended through impervious soils down to permeable sand or gravel, and will drain a small area fairly rapidly when surface runoff is of satisfactory quality (Ritcher et al, 1961).

In India, Kalendhonkar et al in 2002 used two recharge tube wells installed in the bed of old Sirsa branch canal to recharge the depleting groundwater artificially. The location and depth of recharge tube wells were selected based on the results of the resistivity survey to ensure better chances of recharge due to the presence of pervious strata in the aquifer. Filter pit was provided to prevent the entry of sediments and suspended solids in recharging water. The recharge tube wells performed well during the entire experimental period covering two monsoon seasons without any drastic reduction in recharge rate. An average recharge rate of 10.5 l/s due to individual recharge well was observed which was reasonably good (Kalendhonkar, 2002).

To achieve the objectives of the research which is the determination of the effectiveness of using an artificial recharge well to mitigate flood in a scaled model, a rainfall simulator was adopted. The rainfall simulated was coupled to a small scaled groundwater physical model.

In another related research Jinn-Shuh Jean and Chao-Chin Hung (1998) used a rainfall simulator to describe a water-storage method that is more reliable than reservoirs, and to study the efficacy of interception and storage of surface runoff in the ponds. The methodology of their research is related to the methodology adopted for this research. In this research as well, rainfall simulator was used to study the effectiveness of recharge well on groundwater to mitigate flood. While their research focuses on using rainfall simulator with varying rainfall intensity on a ground model that considers slope, the study carried out in this research considers a groundwater model that does not consider slope; the catchment is considered to be flat topographically. In their research they concluded by establishing that the runoff rates are reduced greatly by the layout of ponds along a stream bank. Interception from surface runoff can infiltrate into 19 subsurface media and ponds, and this interception can be 2.6 times as great as that without dug ponds. Thus, the efficacy of interception and storage from surface runoff in a series of ponds can be increased. They also discovered that the more impervious the areas, the higher the runoff rates and interception and storage rate in pond, but the lower the infiltration rates. If the land is vegetated, the infiltrations are higher than those on bare soils without vegetation, in which case the runoff rates and interception and storage rates in ponds are lower. The layout of a series of pond along a stream bank on well-developed land with extensive impervious areas can intercept more runoff and thus infiltrate into sub-surface media and stored in ponds. Thus, the runoff rates can be reduced greatly.

Due to the wide temporal and spatial intensity variation of natural rainfall another researcher decided it is best if the study is taken to the laboratory with the use of a rainfall simulator. In this particular research the methodology of using a rainfall simulator was adopted for substantiating the impact of pesticide on runoff. Zhang (1997) showed that storm intensity pattern may have a substantial impact on pesticide, and was applied to 0.14 m^2 soil trays. Atrazine (6-chloro-*N* -ethyl-*N* –(1-methylethyl)-1,3,5-triazine-2,4-diamine) runoff for the pattern that reached peak intensity most quickly was two-fold greater than other patterns. Although this research is in no way related to use of pesticide but the methodology adopted in their research is much related to the aspect of using rainfall simulator in the laboratory to establish a relationship between variables.

Vahabi and Mahdian (2008) carried out a research in which the use of rainfall simulation was adopted for the study of the effects of efficient factors on run-off rate. In this research, the rainfall simulators were considered as an inexpensive method to acquire data in ungauged catchments. The catchments are also known to be lacking sufficient recorded data from the real rainfall events, so the use of rainfall simulators in the field and laboratory were recommended to simulate runoff in different soil, vegetation cover, slope and rainfall. A rainfall simulator (a portable non-pressurized type) was used to examine the effects of slope steepness, vegetation cover, clay, sand, silt and antecedent soil moisture content on the runoff amount. Two sets of simulated rainfall events with 24.5 and 32 mm/h intensity were applied on 145 experimental plots with dimension 1.2 × 0.289 min. Teleghan watershed, Iran and the relevant run-off amounts were measured in each experimental plot. Based on the results obtained from the correlation matrix, the most influential factors on run- off were vegetative cover, antecedent soil moisture cover, clay, sand, silt and slope, for rainfall intensity of 24.5 mm/h. While for the rainfall intensity of 32 mm/h, vegetation cover, sand, silt, clay and slope were the most influential factors. Two regression equations were also developed for predicting surface runoff with different field and rainfall condition.

MATERIALS AND METHODS

The method adopted for this research can be categorized into two broad parts, the first part involves the use of a reduced scale physical model to determine the effectiveness of using artificial recharge well to mitigate flood and the second involves carrying out the same procedure on an actual site. The results from the experiments carried out on the actual site are not contained in this paper.

Physical model

A small scaled model was used to determine the effectiveness of

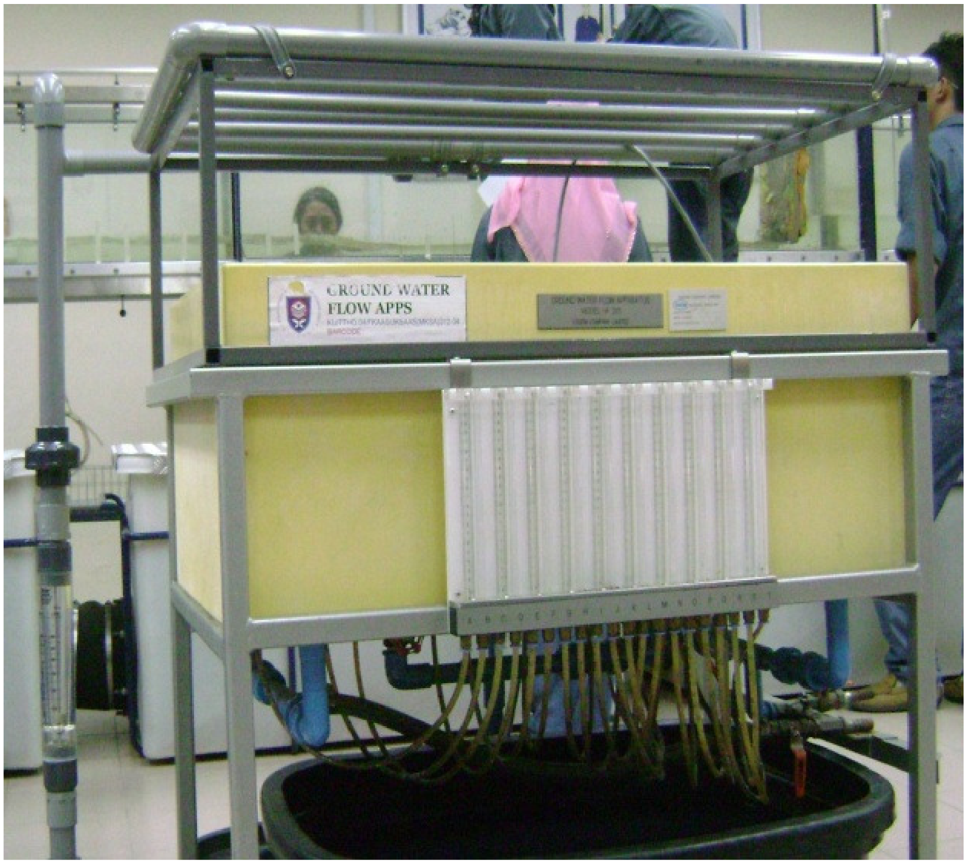

Figure 1. Showing rain simulator.

Table 1. Values of depth of different layers of soil used in the model.

S/N	Layers	Predominant type of soil	Depth on actual site (m)	Depth in model (m)
1	1st	Tuff	70	0.21
2	2nd	Sand	8	0.024
3	3rd	Clay	22	0.066

using the system of recharge well to mitigate flood in a flat area. The model was scaled down using a length ratio of $L_r = \frac{l_m}{l_p}$. This was done by comparing the depth of the actual well as contained in the well log and the height of the simulated recharge well in the physical model. This was measured on the reduced scaled physical model by obtaining the reduction in volume of storm-water when the recharge well system is introduced into the physical model also obtaining the increase in recharge rate when the recharge well system is in the physical model. The design of the physical model is based on what is obtained from the geometrical similitude of the physical model and strata of soil in the site for 100 m depths. Figure 1 shows the actual reduced scaled physical model used.

The material placed in the physical model was also designed based the coefficient of permeability of three different strata of soil layer available on the actual site. The variation in the properties of the strata was obtained by means of resistivity test and also data were obtained from two different documents available for the actual site. Table 1 shows the values of depth of different layers of soil used in the model.

Scaling of the model

For the design of the physical model a geometrical similitude was adopted to reduce the actual field to a reduced scaled model. By applying the geometric similitude law where the length ratio $L_r = \frac{L_m}{L_p}$ was determined by comparing the depth of the actual well as contained in the well log and the height of the simulated well in the model;

$$L_r = \frac{L_m}{L_p}, \quad L_m = 30\ cm, \quad L_p = 10000\ \text{cm}$$

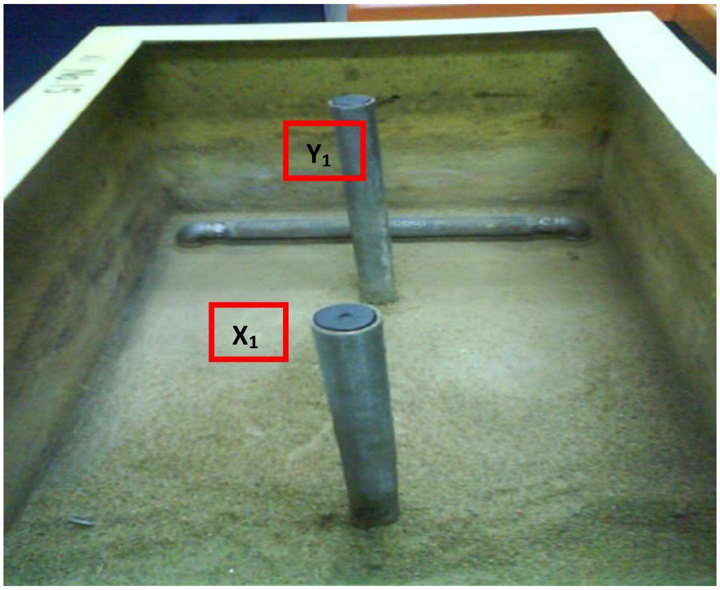

Figure 2. Showing perforated pipes for groundwater flow (Y_1) and recharge well (X_1).

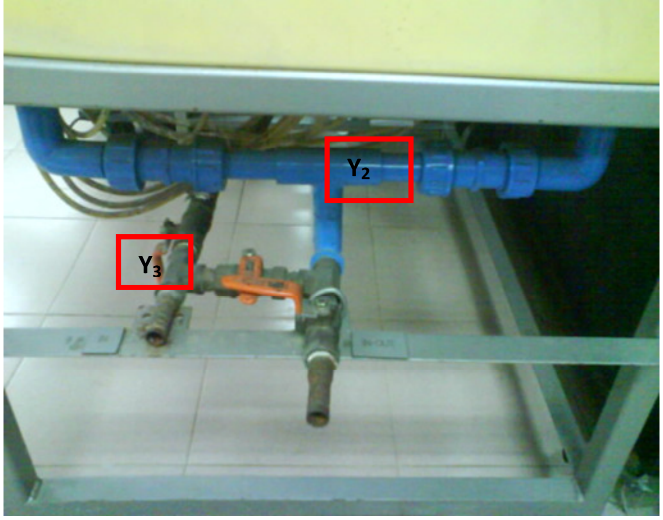

Figure 3. Showing outlet pipes (Y_2) and valves (Y_3) groundwater flow.

Therefore

$$L_r = \frac{30}{1000} = 0.003$$

Mechanism of the model

The model is a groundwater model fitted with a rainfall simulator. The sand tank contains four perforated pipes, two of which are erected in the sand box and two are laid down in the sand box. The two erected are used to simulate recharge well while the two laid down are for simulating groundwater flow. Figure 2 shows in details what the inside mechanism look like. X1 indicates the recharge well and Y1 indicates the pipes used to simulate groundwater flow. Underneath the sand tank are valves and pipe that allows water out of the sand tank, by referring to Figure 3, the part labeled Y2 is used to allow water flow freely out of the sandbox through the pipes (Y1) which simulates groundwater flow. The outlet for this pipe (Y2) is marked Y3. In the same light the pipe marked X1 in Figure 2 simulates recharge well and the part marked X3 in Figure 4 is the pipe that allows water to flow out of the recharge well.

Field work

In addition to the experiments carried out on the physical model, field work were also carried out to ascertain the effectiveness of

Figure 4. Showing outlet for recharge well.

using artificial recharge on groundwater to mitigate flood in a flat area. Among the experiments carried out on the field are: recharge estimate at the study area and was done by using the water balance method; runoff estimate at the study area and was estimated by using the SCS method; the amount of water that can be collected from this particular roof was determined empirically; the transmissitivity of the subsurface at the site was also determined empirically and the possibility of injecting water into the subsurface was also determined empirically. Not all the results from the field work will be included in this paper. The results from the runoff of estimate at the study area and the transmissitivity of the subsurface at the site will be discussed subsequently.

An actual recharge/pump well was installed at the site to test the feasibility and ease of using this method to mitigate flood in an area with flat topography and clayey, as its top most layer soil. The recharge well system on the actual site comprises of a 100 m deep well connected to a roof with the use of polyvinyl chloride (PVC) pipes. The roof is gauged by gutter to collect all the rainwater falling on the particular roof and the PVC pipes act as conveyors that convey water from the roof to the recharge well that is connected to an aquifer.

The essence of the set up is to determine in practicality the effect of injecting storm water from the roof into the aquifer through a recharge well for the purpose of mitigating flood.

By adopting the soil conservation service (SCS) (SCS National Engineering Handbook, 1985) curve number method an estimate of runoff for the actual site was obtained. The actual site is characterized by an open space, grass cover is about 50 to 70% as at the time when the research was carried out and top layer soil is clay loam soil.

The transmissitivity of the subsurface was obtained by a pumping test carried out on the actual site on a single well. The Theim equation that was modified by Boonstra and De Ridder (1981) was used to obtain the value for transmissivity. The modified Thiem equation in Equation 3.0 was used to obtain the value for transmissivity.

$$T = \frac{43.08\,Q}{S_W} \qquad (1)$$

where Q = the constant well discharge in feet^3/day and S_w = the stabilized drawdown.

RESULTS AND DISCUSSION

As earlier stated, a resistivity test was carried out on the actual site for the design of the physical reduced scale model. Figures 5 and 6 show the results of the resistivity tests. The field procedure of the resistivity test carried out on the actual site involves the use of Lund spread cable, stainless steel electrode, galled lead-acid battery, cable jumpers, ABEM Terramater SAS 4000 and cable joints. With these equipments, an image of the subsurface of the actual site was obtained. These images are represented in Figures 5 and 6. By proper correlation of the images from the field work with standard typical ranges of electric resistivity of geological materials table, a clearer description of the image can be made.

At about 61 m deep, the subsurface image in Figure 4.1 shows that the geological material at this point has 600 to 3000 ohm m, which suggests that gravel, sand and water are present at this depth, moving away and towards the ground surface the resistivity of the geological material have lower resistance which indicate values of 500 to 5 ohm m materials that have such resistance value are clays and tills. At about 30 m from

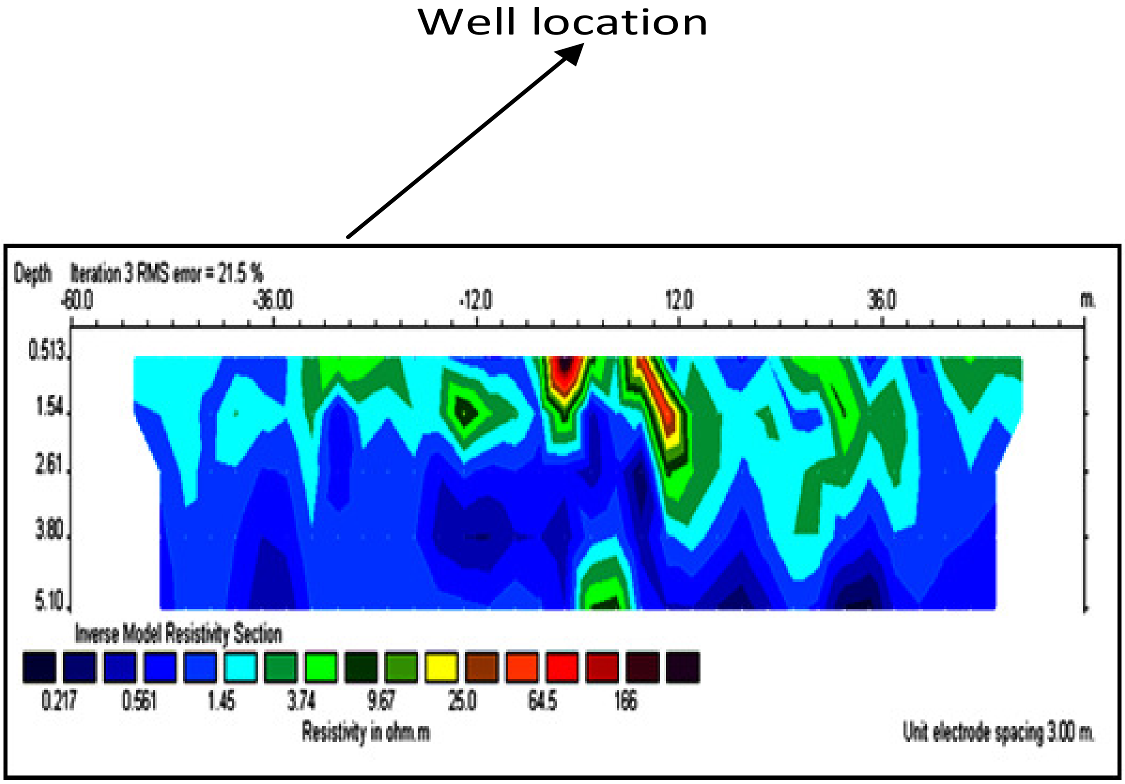

Figure 5. Subsurface image of research site (5 m below ground surface).

the ground surface, the presence of water was noticed with resistance of 0.95 ohm m and this extends towards the ground surface and at a much lower depth from the ground surface geological materials have a bit of gravel, sand and clay.

Data obtained from the resistivity test, coupled with data obtained from a well log and a soil properties test were used to design the physical model used in the research.

A well log and a soil property test document of the actual site were obtained for the purpose of this research, with the well log and the soil property test the variation in soil particle size in the actual site for 100 m were obtained and the coefficient of permeability of the soil material present at the actual site for 20 m was also obtained. For accurate simulation of the actual site in terms of geometric similitude, a sieve analysis test and coefficient of permeability test of the material placed in the physical model were carried out on various materials. Figures 7, 8 and 9 are the results of the sieve analysis carried out on the materials selected for the three different strata of soils laid in the physical model. While Figure 7 is the results of the materials placed in the 3rd stratum and Figures 8 and 9 contains results for the 2nd and 1st strata, respectively.

The results of the coefficient of permeability tests are contained in Table 2 for the three strata; also in the table is the reduced thickness of each layer obtained after applying the geometric similitude ratio of 0.003.

Readings were taken under different experimental condition of various rainfall characteristics of both rainfall intensities and rainfall duration. Rainfall characteristics of 16, 28 and 40 mm/min of rainfall intensities were varied for different rainfall durations of 1, 2 and 3 min under a condition that involves the use of recharge well and a condition that involves no well. Figure 10 shows the results of the recharge rate for each of the experiments under different rainfall characteristics.

By close observation it can be seen that for all the experiments, the recharge rate considerably increased when a recharge well is present in the physical model. Although a particular pattern was not observed, but it was ascertained that the present of the recharge well in the system obviously increased the recharge rate as compared to when a recharge well was absent for the same rainfall characteristics.

Readings were also taken with regards to the reduction in storm-water in the physical model for both when recharge well was present in the physical model and when recharge well was not present in the physical model, another observation taken into consideration in the physical model is the comparison of draining time for when well was present in the physical model and when well was not present in the physical model. The results are both contained in Figures 11 and 12, respectively. For the results obtained with regards to the reduction in

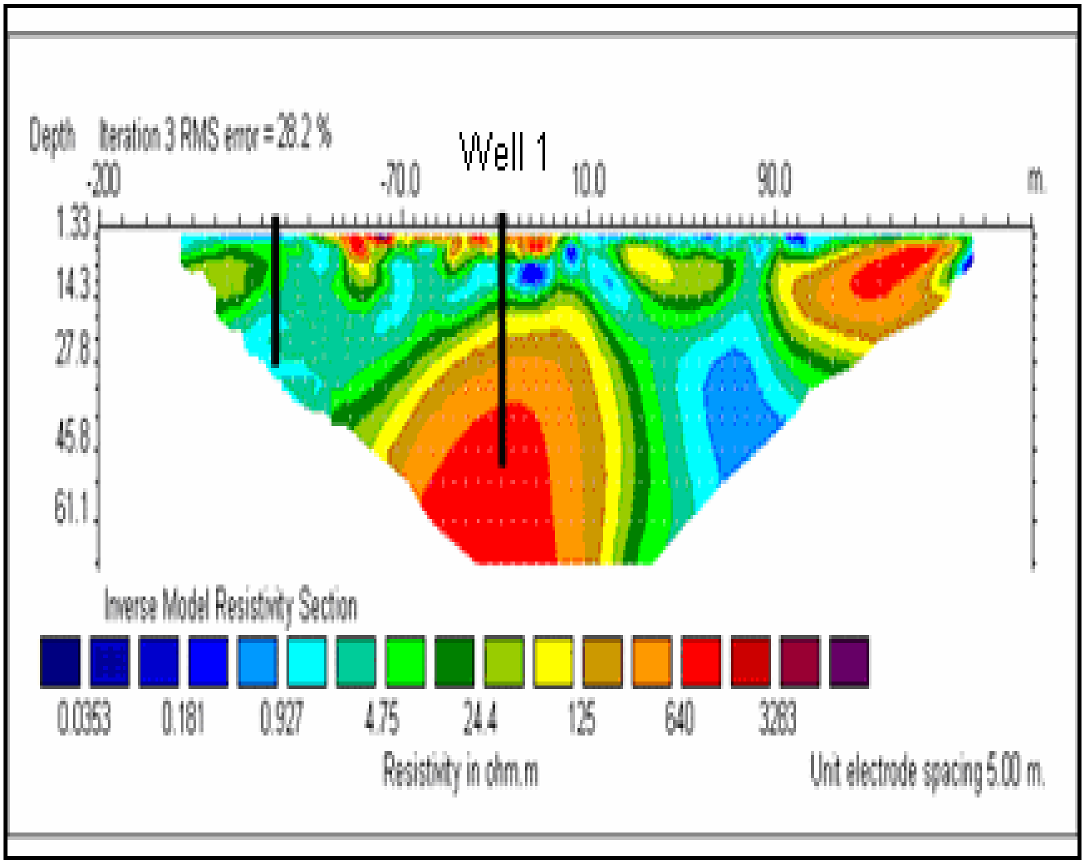

Figure 6. Subsurface image of recess site (61.1 m) (Sabariah, 2008).

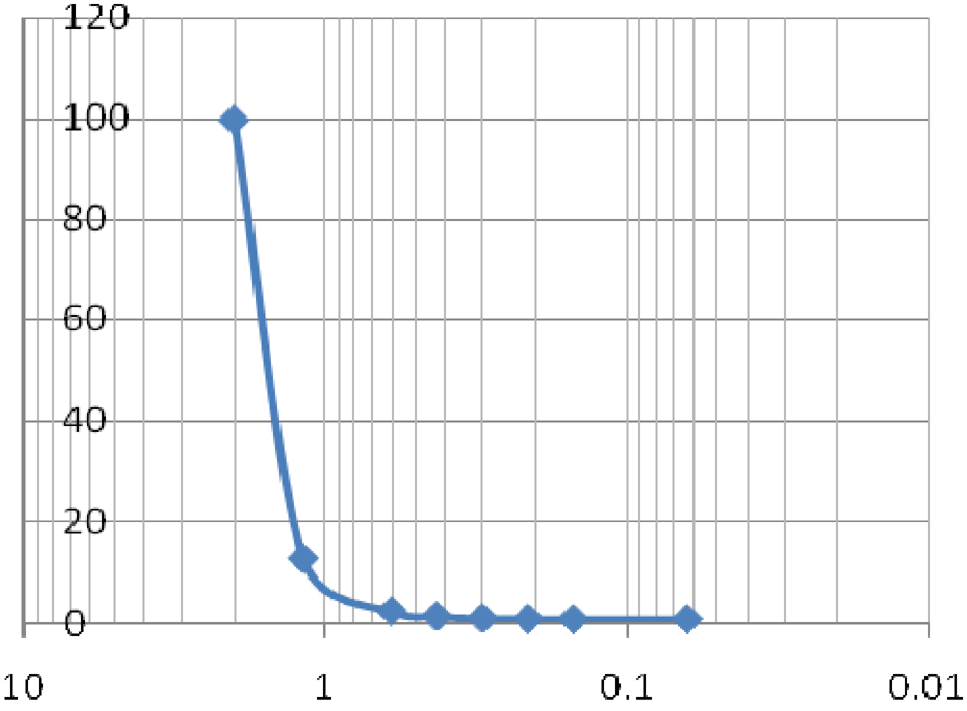

Figure 7. Plot of percent finer vs. grain size for sample for 3rd layer.

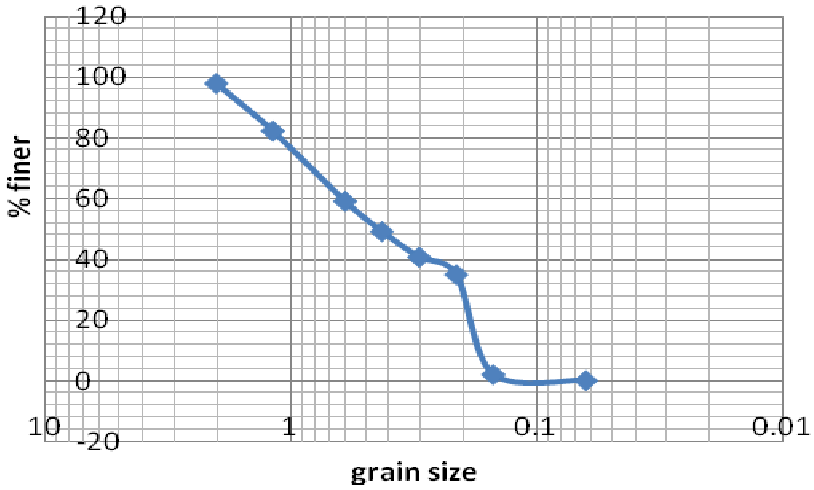

Figure 8. Plot of percent finer vs. grain size for sample for 2nd layer.

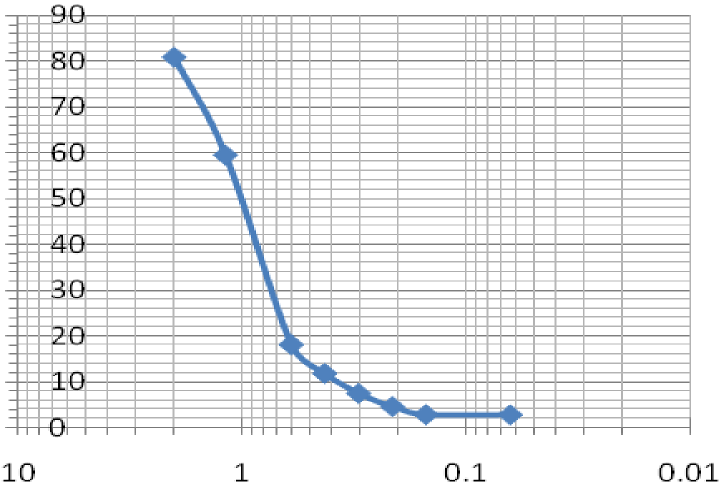

Figure 9. Plot of percent finer vs. grain size for sample on 1st layer.

storm-water in the physical model, it was observed that there was an increase in the amount of storm-water reduced in the system for the same rainfall characteristic that involves experiments of both well condition and no-well condition. The comparison of the draining time for experiments that involve both well and no-well conditions also showed that with a well condition the draining time is reduced.

Model verification

To verify the results from the model, field work were carried out on a prototype which involves an actual site. The field works that were carried out on the prototype are as follows:

1. How much of rainwater was the system able to reduce when the recharge well was present for various rainfall characteristics?
2. How much increase in recharge rate was attained in the physical model when the system of recharge well was present in the physical model?

DISCUSSION

Three parameters were measured in the physical model to ascertain the effectiveness of using a recharge well to mitigate flood in a flat area. These results of these parameters are well represented in Figures 10, 11 and 12. Figure 10 contains results of recharge rate of different experiments involving both a condition of well and no-well condition. As it can be clearly seen for all of the

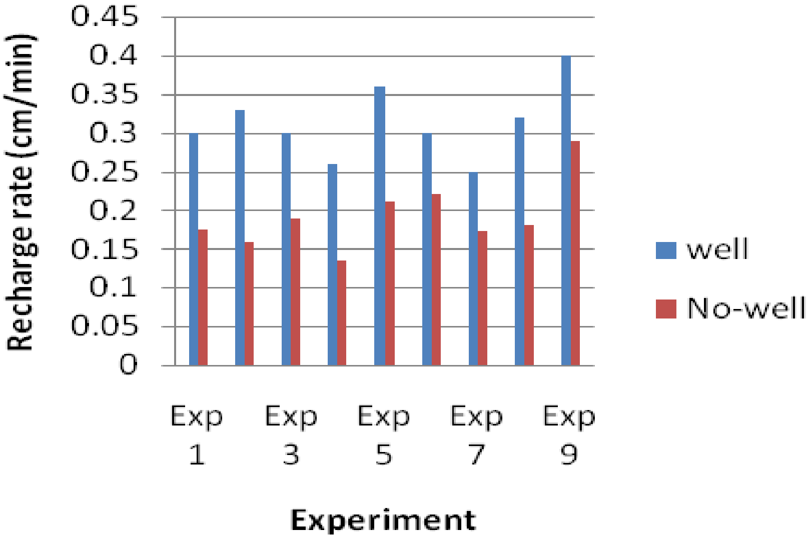

Figure 10. Graph of comparison of recharge rate.

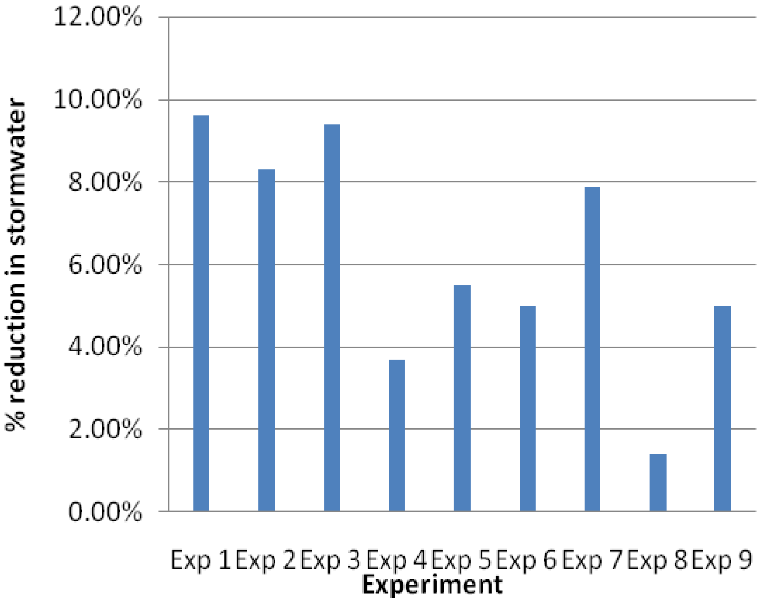

Figure 11. Graph of reduction in storm-water.

experiments, there was quite a significant increase in recharge rate when the well was introduced into the system as compared to when no well was present, this same trend goes for the parameter represented in Figures 11 and 12 which are, the amount of storm-water reduced in the system and difference of draining time of the system for experiments involving both well and no-well condition. The amount of storm-water reduced in the system when the recharge well was present was quite more than the amount of storm-water reduced in the system when a recharge well was absent and for the draining time, the results in Figure 12 showed that it takes less draining time for the same amount of storm-water accumulated to draining for when well is present as compared to when well is not present in the system.

Conclusion

It can be concluded that method of using recharge well to mitigate flood is to some extent effective in terms of recharge rate, with an increase in recharge rate of about 43.4% when the well is installed in the physical model. It can be concluded that for the ‘well’ condition, it takes

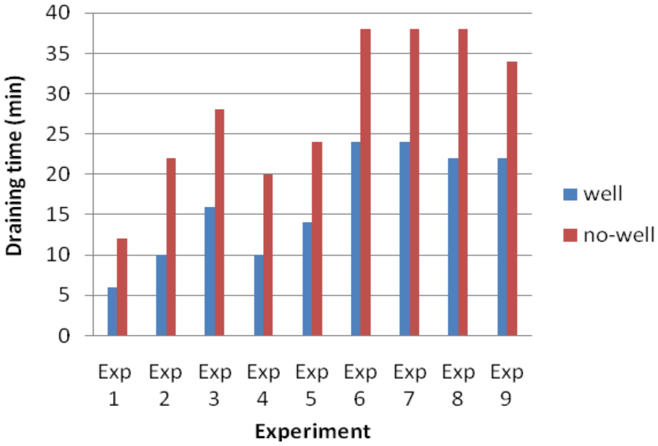

Figure 12. Graph of the comparison of draining time.

lesser time for the rainwater to be drained from the simulated surface of the physical model than during the 'no-well' condition. It was actually noted that, for experimental runs that involve smaller rainfall volume the draining duration during the 'well' condition is less than or equal to 50% of the draining duration during the 'no-well' condition and lastly the amount of storm-water reduced in the system for the various experiments showed that when a well is present a larger amount of storm-water is reduced in the system as compared to when a well is absent. From these, it can be concluded that results of using a recharge well to mitigate flood in a physical model is quite promising with an increase in recharge rate of about 43.4% when a recharge well is present.

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