International Journal of the Physical Sciences Vol. 6(1), pp. 8-14, 4 January, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS10.582
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

The effectiveness of groundwater recharges well to mitigate flood

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Accepted 20 December, 2010

Management of urban storm-water is characterized by the use of hydraulic structures like culvert, man-made channels, water ways, detention basins, infiltration trench, spillway, dams and other drainage structures to either convey or store the storm-water downstream. But in some cases these structures may not be effective to either convey or store the excess runoff because of some inherent factors like topography, soil type, and other factors could include high rain intensity over a long duration and poor drainage design. In the case of Batu Pahat, Johor, Malaysia, some of the contributing factors include; flatness of the catchment area and low infiltration rate of the top layer soil (clayey). The method of injecting some of the storm-water into the ground (aquifer) through a recharge well (perforated pipe), so as to reduce the peak flow rate reaching these structures was adopted to mitigate flood. This method was evaluated by means of carrying out experiment on a physical model and on an actual site. The determination of the effectiveness of this method was carried out by simulating storm-water accumulation in a reduced scaled physical model. This small scaled model had a rainfall simulator fitted with a sand tank, the sand tank contained soil materials of different grain size and different coefficient of permeability. The model is 100 x 60 x 40 cm in dimension and a perforated pipe of 3.5 cm is fixed in the model to simulate recharge well. By varying the rainfall intensity and rainfall duration on the model a relationship was established between the rainfall characteristics and movement of storm-water into the ground by using the recharge well to mitigate flood. The results obtained from the physical model are then compared with results obtained from an actual site where an actual recharge well is present. On the physical model the reduction in rainwater when the recharge well is present is about 6.07% of the total rainwater on average and on the prototype is 2.8, 7.2 and 3.5% of the total rainwater that fell on a catchment of 100,000 m^2 for three different rain events. Apart from the high water table noticed at the actual site, other data obtained from the actual site indicated that the recharge well system will be successful when it is adopted to mitigate flood in a site similar in physical and soil properties to the physical model.

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

INTRODUCTION

Over the last decades the world has witnessed a growing number of floods in urban areas due to the climate change and rapid urbanization. These floods have lead to loss of millions of lives, destruction of properties, displacement of millions of people and spread of diseases at almost everywhere in the world. Places that have never experienced flood before have been experiencing it now and places that have ever been

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experiencing flood are having larger and more devastating storm due to climate change.

LITERATURE REVIEW

Location of the study area

Adila and Tjahjanto (2008) carried out an investigation on the study area (Batu Pahat, Malaysia) with respect to flooding. Among their findings are that the study is located in Batu Pahat, a district under the state of Johor, Malaysia. The land surface 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 an average rainfall intensity of 2,400 mm/year.

Past methods used in mitigating flood

Both structural and non-structural flood mitigation methods have proved quite effective, but there is no doubts that devastating flood still exist in places where expensive structures is put in place to mitigate flood. Saybet (2006) made an analysis on how some of these structural methods end up contributing to causing disasters rather than mitigating flood. According to Saybet (2006), 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 sewers systems 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) also buttressed this concept by shedding more light on the disadvantages of relying totally on existing structures.

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 systems that will facilitate nature's process; that is direct the storm water back into the soil. These and other important past research formed the background and basis of this research. The method of mitigation applied in this study is quite related to what Osman and Robert proposed. It involves directing the storm water back into the soil, in order to mitigate flood and probably recharge a depleted aquifer.

Injecting water through recharge well back into the soil

Lots of researches in the past have been conducted with respect to injecting water through recharge well back into the soil for different reasons. In 1970 publication the US department of Agriculture states: "the use of injection wells is confined largely to areas where surface spreading is not feasible because extensive and thick impermeable clay layer overlie the principal water-bearing deposits. (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. (Ritcher and Robert, 1961).

In India a researcher 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 presence of pervious strata in the aquifer. An average recharge rate of 10.5 l/s due to individual recharge well was observed which was reasonably good (Kalendhonkar, 2003). To achieve one of the objectives of the research which is the determination of the effectiveness of using an artificial recharge well to mitigate flood in a scaled a model, a rainfall simulator was adopted. The rainfall simulated was coupled to a small scaled groundwater physical model. Other researchers in the past have also adopted the method of using a rainfall simulator to determine various parameters. The other objective involves the actual recharge of an aquifer with storm water directed from the roof of a building at the actual site.

Vahabi and Mahdian (2008) carried out a research in which use of rainfall simulation was adopted for the study of the effects of efficient factors on run-off rate. Two sets of simulated rainfall events with 24.5 and 32 mm/h intensity were applied on 145 experimental plots with dimension 1.2 x 0.289 m in Teleghan watershed, Iran, and the relevant run-off amounts were measured in each experimental plot. As stated earlier to establish the effectiveness of the method of mitigation adopted in this research a physical model and a field work were used and compared. Prasuhn (1992) stated that the key to proper modeling of hydraulic phenomena is the establishment of similitude between model and prototype. The three types of similitude are geometric, kinematic and dynamic similitude.

Geometric similitude

Is the requirement that the model be geometrically similar to the prototype. Strictly speaking, this means that each dimension in the model bears exactly the same

Figure 1. Showing rain simulator.

relationship to the corresponding dimension in the prototype Prasuhn (1992). Warnock (1950) stated that geometric similarity exists between two objects or systems if the ratio of all corresponding linear dimensions is equal. This relationship is independent of motion of any kind and involves only similarity in form.

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. Both the results obtained both from the physical model and the actual site is then compared.

Physical model

As part of the research a small scaled model was used to determine the effectiveness of using the system of recharge well to mitigate flood in a flat area. 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 and also obtaining the increase in recharge rate when the recharge well system is introduced into 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.

Scaling of 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;

$$L_r - \frac{L_m}{L_p}, L_m - 30\ cm, L_p - 1000\ cm$$

Therefore $L_r = \frac{30}{10000} = 0.003$

The length ratio 0.003 was used in reducing the actual well into the physical model, that is, every length; width and breadth of the actual field were reduced using 0.003 as a ratio. The material placed in the physical model is 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. The well log of the actual site gave a good representation of the differences in the properties of soil at different strata and the soil property document of the area also gave soil property like coefficient of permeability. Table 1 shows the values of depth of different layers of soil used in the model.

Field work

In addition to the experiments carried out on the physical model , field work were also carried to ascertain the effectiveness of 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 was done by using the water balance method; runoff estimate at the study area 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 determned 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 estimate at the study area and the transmissitivity of the subsurface at the site will be discussed in the following section.

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 clayeys 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 PVC pipes. The roof is gauged by gutter to collect all the rain water 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 SCS (SCS National Engineering Handbook [1985]) curve number method an estimate of runoff that can be generated for actual site was obtianed. 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 eqaution in equation 3 was used to obtain the value for trasmissivity.

$$T = \frac{43.08\,Q}{S_W} \quad (3)$$

Where: Q = the constant well discharge in ft^3/day.

S_w = the stabilized drawdown

RESULTS AND DISCUSSION

A resistivity test was carried out on the actual site for the design of the physical model. Figures 2 and 3 shows the

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

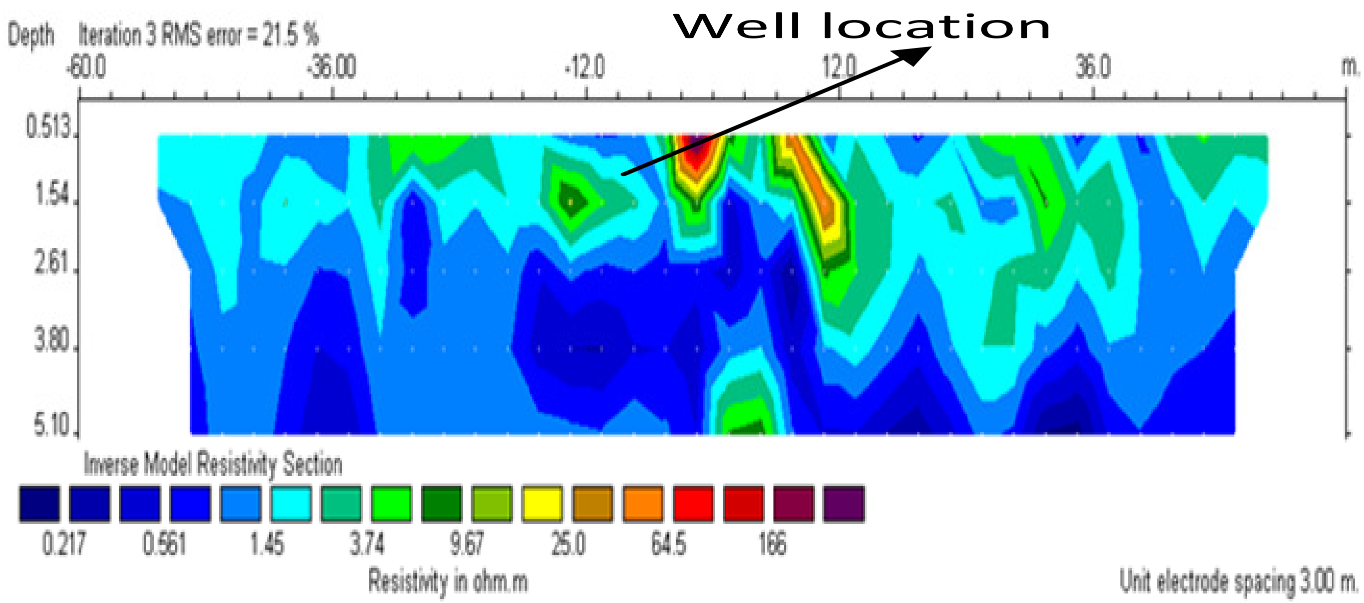

Figure 2. Subsurface image of research site (5 m below ground surface).

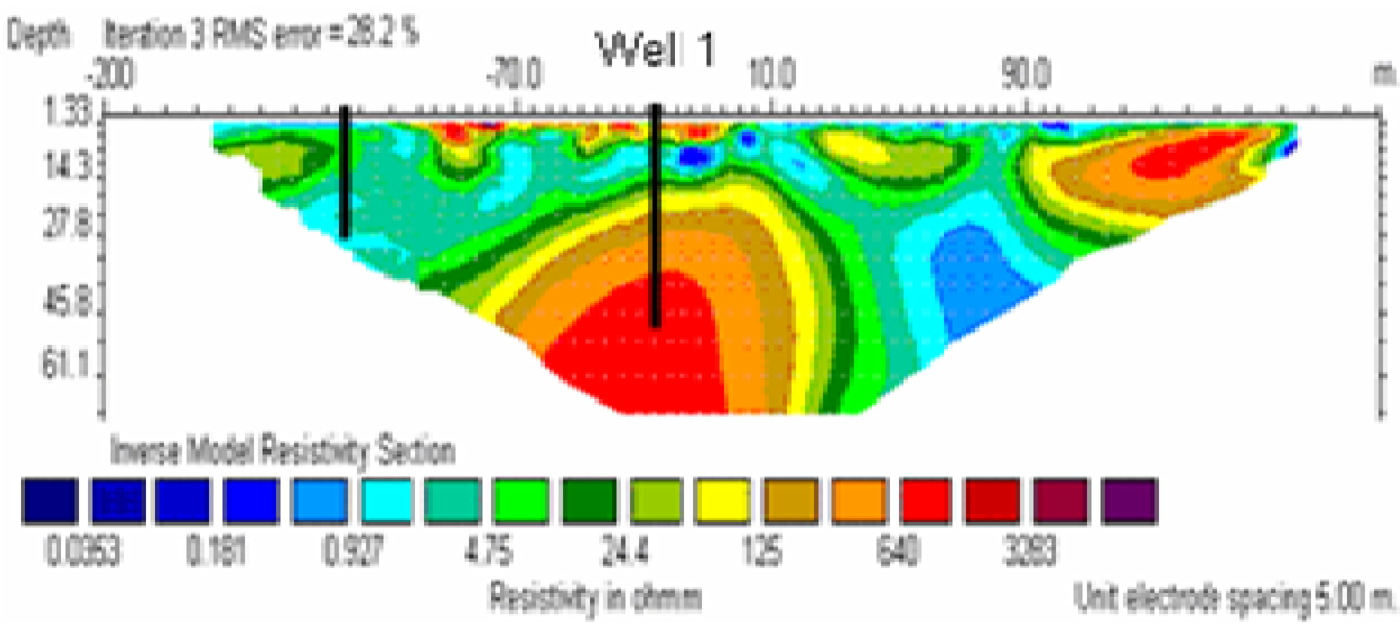

Figure 3. Subsurface image of recess site (61.1 m) (adopted from Sabriah, 2008).

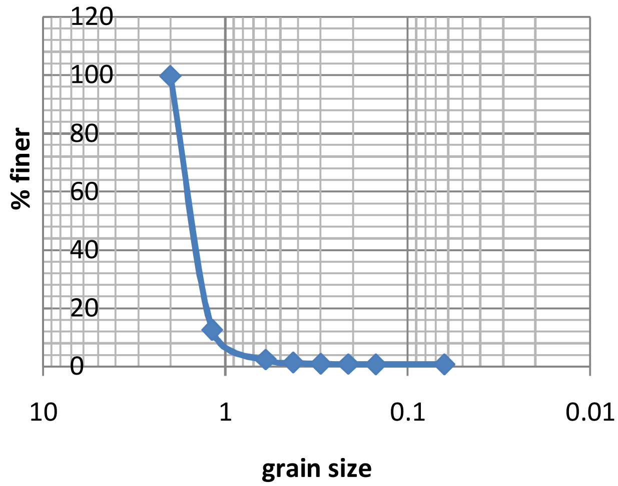

Figure 4. Plot of percent finer vs. Grain size for sample for 3rd layer.

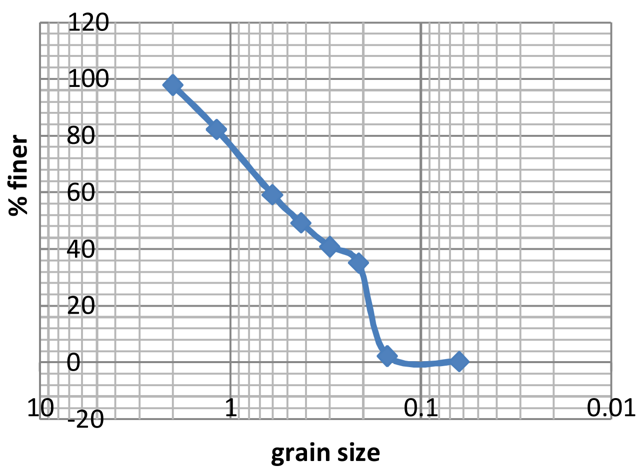

Figure 5. Plot of percent finer vs. Grain size for sample for 2nd layer.

result of the resistivity tests. After due investigation of the actual study area, which was done by a resistivity test and by the use of two important available documents (well log and soil property document) a length ratio of 0.003 was adopted in reducing the geometrical parameter on the actual size into the physical model. For the material placed in the physical model two tests were carried out to ascertain their soil properties. These tests are sieve analysis and coefficient of permeability of three different materials placed in the physical model. The results are contained in Figures 4, 5 and 6. Figures 7, 8 and 9 contain results of actual running of physical model for different parameters.

The experimental runs on the physical model involve variation in rainfall intensity and rainfall duration. Among the parameters represented in the graphs are; various recharge rate of different experimental runs for both 'well'

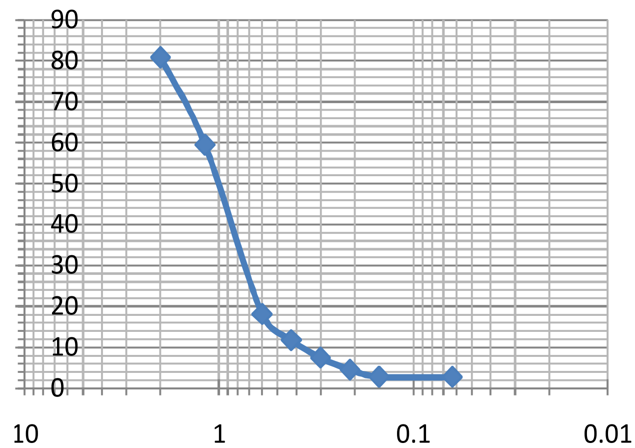

Figure 6. Plot of percent finer vs. Grain size for Sample on 1st layer

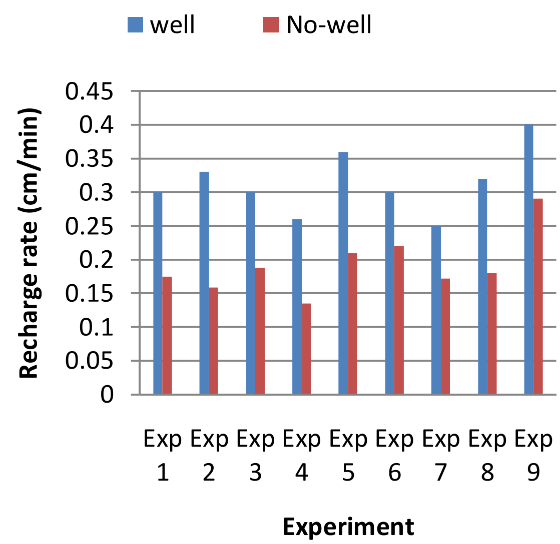

Figure 7. Graph of comparison of recharge rate.

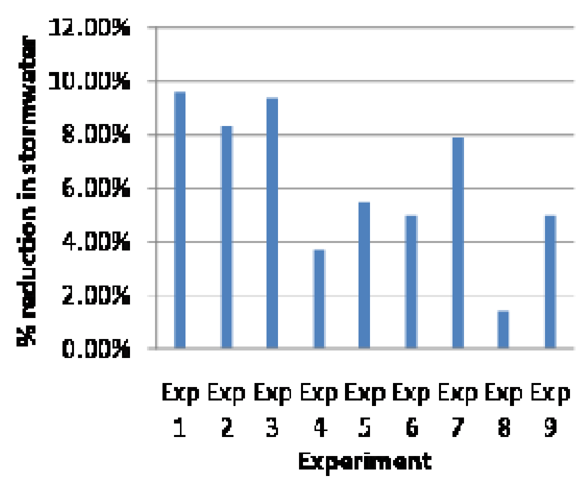

Figure 8. Graph of Reduction in Storm-water.

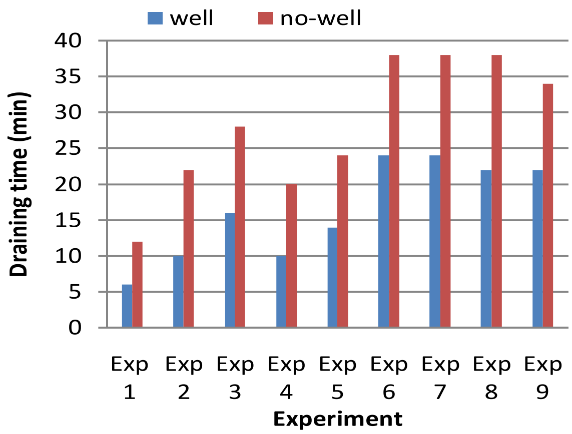

Figure 9. Graph of the comparison of draining time.

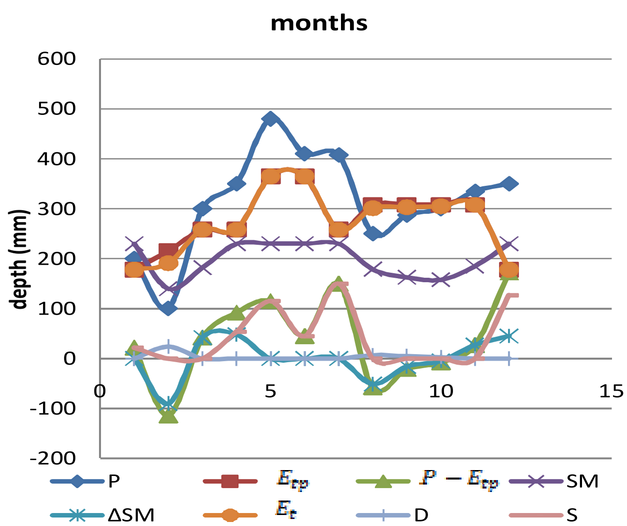

Figure 10. Estimated recharge for the study area for the year 2009.

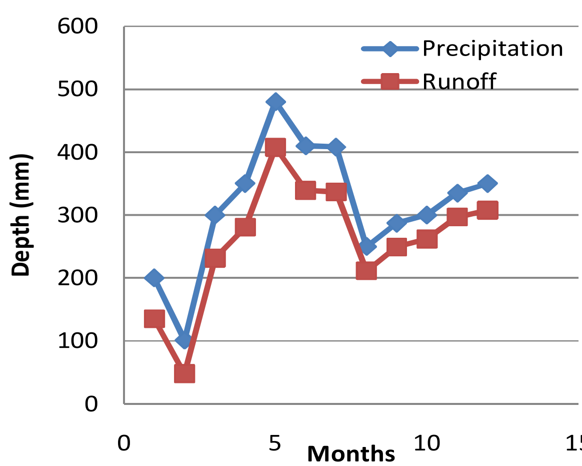

Figure 11. Monthly estimation of runoff for year 2009 for the study area.

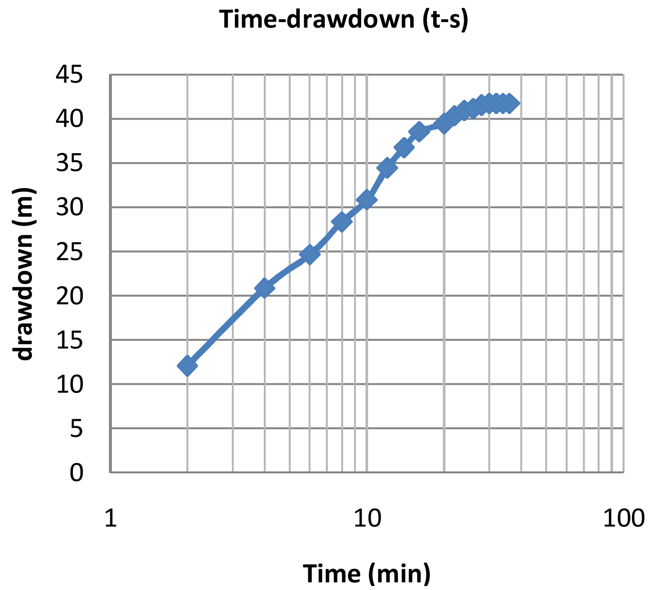

Figure 12. Time-drawdown (t-s) for single well pumping test.

and 'no-well' conditions; reduction in storm water of the system when a well was present in the physical model and the draining duration of the system for different experimental runs for both 'well' and 'no-well' conditions. From the single well pumping test performed on the actual site a transmissivity value of 136.3 m^2/day was obtained. Figure 10 is a graph representing the estimated recharge for the study area. The data obtained from the pumping test is graphically represented in Figure 12.

The result of the actual recharge carried out for three different rain events is contained in Table 2. The table showed that the actual rainfall has corresponding actual recharge volume. During these three events the volume of rainwater collected directly from the roof was injected into the ground by means of the recharge well installed at the site. The effectiveness of the recharge well system installed on the field was determined by calculating the amount of runoff that was successfully injected into the ground by means of the recharge well. An area of about 100,000 m^2 surrounding the recharge well was selected for the purpose of this research and only 92.7 m^2 of the total area (0.092%) is gauged for collecting rainwater for injection into the well. Figure 11 is a graphical representation of the monthly estimation of runoff for study area. The average precipitation for each month was obtained with the aid of a rain gauge placed on the site, using the data from the rain gauge a SCS runoff curve method was used to estimate the runoff for each month.

Conclusion

Although no direct proportionality can be said was attained from the experiment carried out on the physical model but a trend was noticed. And it can be concluded

Table 2. Data of amount of rain water recharged.

S/N	Parameters	Events		
		1	2	3
1	Rain starts at	3:00 pm	4:00 pm	10:45 am
2	Rain stops at	3:13 pm	4:31 pm	11:08 am
3	Date of event	9/04/2009	11/04/2009	30/04/2009
4	Water level before recharge	20 m *BGL	36 m BGL	34 m BGL
5	Water level after recharge	12 m BGL	10.3 m BGL	16.7 m BGL
6	Total volume of recharge (mm)	128.52 m^3	94 m^3	207 m^3
7	Rain duration (s)	780 s	1979 s	1380 s
8	Average rate of recharge (mm^3/s)	0.164 m^3/s	0.047 m^3/s	0.150 m^3/s
9	Constant pumping rate	1.67 l/s	1.67 l/s	1.67 l/s
10	Rainfall depth (mm)	96	51	112
11	Catchment area (m^2)	100,000	100,000	100,000
12	Depth of runoff (mm)	45	13	58
13	Generated runoff (m^3)	4,500	1,300	5,835.7
14	Runoff injected (%)	2.8	7.2	3.5
15	Roof compared to catchment (%)	0.092	0.092	0.092

that the 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 also be concluded that during the 'well' condition it takes lesser time for the rain water 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 involves 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. From these it can be concluded that the relationship between the rainfall characteristics and the draining duration of accumulated storm-water in terms of draining time is a function of the volume of accumulated storm-water, although a direct proportionality was not attained.

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