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Development of Hydrological Model for Effective Flood Control

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Abstract

The paper presents the application of storm water detention basins/ponds in urban catchments for the protection of the cities or parts from floods risks, and for the purpose of protecting the water resources from the pollutants running off with storm water flow. The simplified mathematical hydrologic relationships were derived in the research work aiming to determine volumes of rainfall detention basins/ponds based on patterns of rainfall charts (rainfall intensity versus rainfall duration and return period), applying this method for rainfall floods of return period (n) between 0.5 (probability of one flood per 2 years) and 0.2 (probability of one flood per 5 years) on case study of Lattakia city as an example for a Coastal Arab Region, and on case study of Damascus as an example for an Arid or Semi-Arid Region. The results came accurate besides being attained through simple application of this developed model, with the possibility to generalize this method to other climatic regions where rainfall charts or rainfall stations are available.

Keywords: Urban catchments; storm water detention basins / ponds; volume determination; coastal regions; arid / semi – arid regions.

Introduction

The discharge of the storm water flow in separated or combined sewerage networks will exhaust the sewers, due to the high density rain water flow that occure for short periods and are relatively rare, besides, the design of the sewers for such storm water flows requires employing large dimensions or diameters and consequently higher expenses [1, 2], therefore, through the introduction of storm water detention basins pr ponds, are able to reduce the costs of sanitary networks, and through the higher capacity for detention of the storm water flow, we insure a better protection of the water resources from the pollutants carried with storm water runoff, besides, these basins serve to prevent soil erosion, and protecting the residential centers from the hazards related to floods [3]. Storm water detention systems are considered as abatement strategies in urban watersheds [4].

According to the stipulated objectives, the storm water detention basins or ponds will discharge their detained water through little and constant flow in the sewers or the water resources, following to insuring that the runoff will not damage the water resource. As a general conception, the flash flood defined as a flood of short duration (not to exceed 6 hours) with relatively high peak discharge, that occur as result of exceptional rainfall intensities occurring at the site of flood and extend from the beginning of the runoff till the peak flow time. The runoff time (time of concentration) decreases with the decrease of the catchements.

The flash floods occur primarily at the catchments where runoff are collected due to the previous and consequent storm waters [5].

At the 1980s, property damage from flash floods in the United States amounted to about one billion dollars annually, and in most of the developing countries exposed to floods, several casualties are seen [6].

Based on the probability statistical study for rainfall storms recorded in coastal city of Lattakia in the period extending between years 1966 – 1997, it was determined the patterns of relationships among rainfall height h (m) with the rainfall duration (T) and return period (n) extending from 0.5 year till 40 years (Table 1), besides, the values of the Table (2) represent the results of study and analysis of rainfall storms recorded for the city of Damascus for the period ranges between years 1966 – 1997, which denotes as well the patterns of relationships among rainfall height h (m), the rainfall duration (T), and return periods (n), extended from 0.5 year till 40 years.

In the practiced examples, we were satisfied to consider the return period (n) between 2 year till 5 years, since this is mostly approved in the safety and feasibility studies against the floods risks in urban catchments [7,8].

Based on these patterns, the research work reached a method that relayed on deriving the simplified hydrological – mathematical relationships to determine volumes of storm – water detention basins / ponds for the aim of protecting urban areas from the floods risks, and in the same time to protect the water resources from pollutants flowing with the storm water runoff, through a simplified method instead of employing the complex relationships mostly based on the computer simulation models which are not always conforming to reality besides that it is not commonly applied and easily employed by hydrologists and environmental engineers.

Deriving Mathematical – Hydrologic Relationships

The curve that relates among rainfall height, rainfall duration and return period is represented in the following exponential function in general.

(Figure 1): $h_N = a.t^x$ (1)

Parameters a and x for each rainfall station and rainfall frequency are determined as follows:

$$\frac{dh_N}{dt} = x.a.t^{x-1} \tag{2}$$

$$x = \frac{Log\left(\frac{h_{N1}}{h_{N2}}\right)}{Log\left(\frac{t_1}{t_2}\right)} = \frac{Log\left(\frac{h_{N2}}{h_{N1}}\right)}{Log(t_2)} \tag{3}$$

where: t_1 = 60 min = 1h

$$a = \frac{h_{Ni}}{t_i^{\ x}}$$

when: i = 1h

then: a = h_{N1} (4)

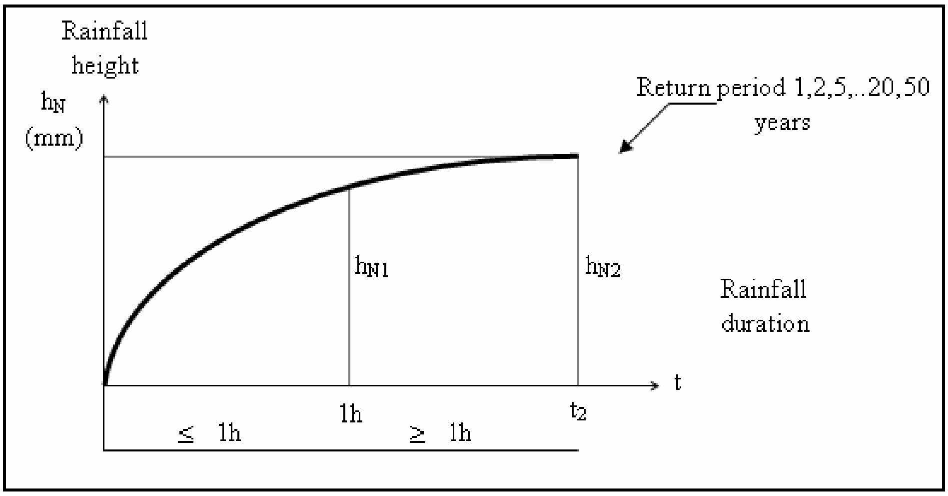

Figure 1. A curve represents: rainfall height – duration – return period

1. Volume determination of storm water detention basins / ponds

$$\forall_{infl.} = A_{red.}\, h_N \,.\, 10 \qquad (5)$$

where: h_N = rainfall height (mn)
$A_{red.}$ = impermeable area (hectare)
$\forall_{influent}$ = inflow volume during rainfall (m3)

substituting Eq. (1) into Eq.(5):

$$\forall_{infl.} = 10.\, A_{red.}\, a.\, t^x \qquad (6)$$

The outflow volume in constant condition:

$$\forall_{effl.} = Q_{effl.}\, t \,.\, f_t \qquad (7)$$

where $Q_{effl.}$ = outflow from basin (l/s)

t = empting / discharge duration from basin (min. or hr)

f_t = transfer factor = 0.06 (when duration in minutes) = 3.6 (when duration in hours)

Detention volume of runoff:

$$\forall = \forall_{infl.} - \forall_{effl.} \qquad (8)$$

Detention volume is maximum when: $\dfrac{d(\forall)}{dt} = o$

$$d\,\frac{(\forall_{infl.} - \forall_{effl.})}{dt} = o \qquad (9)$$

$$10.A_{red}\,.a.x.t_o^{x-1} - f_t.Q_{effl.} = o$$

Then maximum duration considered for design:

$$t_o^{x-1} = \frac{f_t.Q_{effl.}}{10.A_{red}\,.a.x}$$

Design rainfall considred for storage basin / pond:

$$t_o = \left(\frac{f_t .Q_{effl.}}{10.A_{red} .a.x} \right)^{\frac{1}{x-1}}$$
$$t_o = \left(\frac{10.A_{red} .a.x}{f_t .Q_{effl.}} \right)^{\frac{1}{1-x}} \qquad (10)$$

where t_o = design rainfall duration (hr).
substituting Eq. (10) into Equations (6) and (7) gives the required design volume (without considering runoff duration volume).

$$\forall = \forall_{infl.(to)} - \forall_{effl.(to)} \qquad (11)$$
$$\forall = 10.\ A_{red.} .\ a.\ t_o^x - f_t .\ Q_{effl.} .\ t_o$$

Considering the runoff duration (time of concentration) (t_f) leads naturally to continual increase in flow from watershed, and outflow from basin / pond (Q_{ab} or $Q_{effl.}$) will be full when inflow ($Q_{infl.}$) is equal to (Q_{ab}).

At the end of runoff duration (time of concentration) (t_f) (rainfall is considered as a box model) inflow becomes full. Also outflow becomes full directly just at start of discharging duration or operating the basin / pond.

In case of box – rainfall model and constant flow we can write the following:

$$\frac{Q_{effl.}}{Q_{\inf l.}} = \frac{\forall_{effl.}}{\forall_{\inf l.}}$$

thus:

$$\frac{t_a}{t_f} = \frac{Q_{effl.}}{Q_{\inf l.}} = \frac{\forall_{effl.}}{\forall_{\inf l.}}$$

then:

$$t_a = t_f .\frac{\forall_{effl.}}{\forall_{\inf l.}}$$

Outflow volume during the initial period (t_a) considering regular increase of ($Q_{effl.}$) during the same period:

$$\forall_a = \frac{1}{2}.t_a .Q_{effl.}$$
$$\forall_a = \frac{1}{2}.t_f .f_t .Q_{effl.} \frac{\forall_{effl.}(t_o)}{\forall_{\inf l.}(t_o)} \qquad (12)$$

Thus design volume, with considering runoff duration (time of concentration) will be:

$$\forall_B = \forall_{\inf l.}(t_o) - \forall_{effl.}(t_o) - \frac{1}{2}.t_f \cdot f_t .Q_{effl.} \frac{\forall_{effl.}}{\forall_{\inf l.}} \qquad (13)$$

according to Eq. (11): $\forall_{\text{infl.(to)}} = 10.\ A_{\text{red.}}\ .a.\ t_o^x$

$\forall_{\text{effl.(to)}} = f_t.\ Q_{\text{effl.}}\ .\ t_o$

substituting it into Eq. (13) gives the final design volume:

$$\boxed{\forall_B = 10\ .A_{red}\ a\,(1 - x).t_o^x - \frac{1}{2}.t_f \cdot f_t .Q_{effl.}.x} \qquad (14)$$

where: t_f = runoff duration (time of concentration) (min.)

$A_{red.}$ = impermeable area (hectare)
$Q_{effl.}$ = storm water flow or runoff (l/s)
$\forall_{B.}$ = volume (m^3)
f_t = 0.06 (when a and t in min.)
f_t = 3.6 (when a and t in hr.)

2. Flow determination ($Q_{effl.}$)

In detention basins / ponds where outflow is not regulated and fixed, but depends on water level at outlet, this outflow increases with the rise of water level. Then it would be important to find a relation between design ($Q_{effl.}$) and maximum flow ($Q_{effl.\ max}$).

- In basins / ponds with vertical walls (rectangular basins) and when the outflow ($Q_{effl.}$) is little in comparison with the inflow ($Q_{infl.}$), that leads to filling the detention basin with constant speed approximately, then the actual flow will be calculated with the following formula that represents storm overflow: $Q = \mu.A.\sqrt{2gh}$

Since the height of the raised water level (h) is directly proportional to the inflow period so:

$$Q_{effl.} = \frac{2}{3}.Q_{effl.\max} \qquad (15)$$

This applies when (Q = 0) at initial flow. In case of initial or minimum outflow at start of water accumulation at outlet, design flow will be [2]:

$$Q_{effl.} = \frac{2}{3}.\frac{Q^3{}_{\max} - Q^3{}_{\min}}{Q^2{}_{\max} - Q^2{}_{\min}} \qquad (16)$$

where Q_{max} represents maximum flow. and Q_{min} represents minimum flow.

- In basins / ponds with inclined walls, outflow increases with the rise of water in basin, but in slower degree. This also applies, when the outflow (Q_{ab} or $Q_{effl.}$) is not little in comparison with the inflow ($Q_{infl.}$). Thus its value will be:

$$Q_{effl.} > \frac{2}{3} Q_{effl.\max}$$

We should refer in this respect that depending on two Equations (15 and 16) keeps within the design safety.

Applied Examples

1. Coastal region (Lattakia as an example) With the assumption of the following data:

studied drainage area A = 50 hectare

impermeable area $A_{red.}$ = 25 hectare

maximum flow $Q_{effl.max}$ = 750 l/s

minimum flow $Q_{effl.min}$ = 0 l/s

Time of concentration t_f = 25 min

Design outflow:

$$Q_{ab} = Q_{effl.} = \frac{2}{3}.Q_{effl.\max} = \frac{2}{3}.750 = 500 l/s$$

- Rainfall data: return period n = 2 years (Table 1):

T(h)	1	1.5	2	3	4	6	12
h_N(mm)	30.24	34.9	39.96	48.06	55.03	66.34	91.33

The expected storm water duration range in the relevant catchments is between 1 hr and 6 hrs.

from Eq. (1): $h_N = a\,t^x$

from Eq. (3): $$x = \frac{Log\left(\frac{66.34}{30.24}\right)}{Log 6} = 0{,}44; \frac{1}{1-x} = \frac{1}{0{,}56} = 1{,}8$$

$$a = h_{N(1h)} = 30{,}24$$

Design rainfall:

from Eq. (10):

$$t_o = \left(\frac{10.A_{red.}.a.x}{3{,}6.Q_{ef.}}\right)^{\frac{1}{1-x}}$$

$$t_o = \left(\frac{10.25.30{,}24.0{,}44}{3{,}6.500}\right)^{1{,}8} = 3{,}0h$$

Design volume:

from Eq. (14):

$$\forall_B = 10.A_{red}\,a(1-x).t_o^x - \frac{1}{2}.t_f \cdot f_t.Q_{ef.}.x$$

$$\forall_B = 10.25.30{,}24(1-0{,}44).3^{0{,}44} - \frac{1}{2}.25.0{,}06.500.0{,}44$$

$$\forall_B = 6865 - 165 = 6700m^3$$

- Rainfall data: return period n = 5 years (Table 1):

T(h)	1	1.5	2	3	4	6	12
h_N(mm)	35.90	41.76	47.76	57.96	66.5	80.5	111.85

$$x = \frac{Log\left(\frac{80.5}{35.9}\right)}{Log 6} = 0{,}45; \frac{1}{1-x} = \frac{1}{0{,}55} = 1{,}82$$

$$a = h_{N(1h)} = 35{,}9$$

$$t_o = \left(\frac{10.25.35{,}9.0{,}45}{3{,}6.500}\right)^{1{,}82} = 4{,}353h$$

$$\forall_B = 10.25.35{,}9(1-0{,}45).4{,}353^{0{,}45} - \frac{1}{2}.25.0{,}06.500.0{,}45$$

$$= 9576 - 169 = 9407m^3$$

It is noticeable here that with the increase of safety condition against flood risks from return period n = 2 years to n = 5 years, volume of required detention basin / pond increases accordingly at a rate of 40%.

2. Arid or Semi – Arid region (Damascus as an example)

- Rainfall data: return period n = 2 years (Table 2):

T(h)	1	1.5	2	3	4	6	12
h_N(mm)	8.34	9.54	10.92	13.32	15.8	19.43	27.7

The expected storm water duration range in the relevant catchments is between 1 hr and 6 hrs.

from Eq. (1)

$h_N = a\ t^x$

from Eq. (3) $$x = \frac{Log\left(\frac{19.43}{8.34}\right)}{Log 6} = 0{,}472; \frac{1}{1-x} = \frac{1}{1-0{,}472} = \frac{1}{0{,}528} = 1{,}9$$

$$a = h_{N(1h)} = 8{,}34$$

Design rainfall:

from Eq. (10)

$$t_o = \left(\frac{10.A_{red.}.a.x}{3{,}6.Q_{ef.}}\right)^{\frac{1}{1-x}}$$

$$t_o = \left(\frac{10.25.8{,}34.0{,}472}{3{,}6.500}\right)^{1{,}9} = 0{,}32h$$

Design volume:

from Eq. (14)

$$\forall_B = 10.A_{red}\, a(1-x).t_o^x - \frac{1}{2}.t_f.f_t.Q_{ef.}.x$$

$$\forall_B = 10.25.8{,}34(1-0{,}472).0{,}32^{0{,}472} - \frac{1}{2}.25.0{,}06.500.0{,}472$$

$$= 643{,}0 - 177 = 466m^3$$

- Rainfall data: return period n = 5 years (Table 2):

T(h)	1	1.5	2	3	4	6	12
H_N(mm)	9.66	10.44	12	14.22	16.83	20.36	28.2

$$x = \frac{Log\left(\frac{20.36}{9.66}\right)}{Log 6} = 0,42; \frac{1}{1-x} = \frac{1}{1-0,42} = \frac{1}{0,58} = 1,724$$

$$a = h_{N(1h)} = 9,66$$

$$t_o = \left(\frac{10.25.9,66.0,42}{3,6.500}\right)^{1,724} = 0,372h$$

$$\forall_B = 10.25.9,66(1-0,42).0.372^{0,42} - \frac{1}{2}.25.0,06.500.0,42$$

$$= 925 - 158 = 767m^3$$

It has been found out that Damascus region does not need detention basins / ponds with volumes more than 7% to 8% from those needed for Lattakia region, within the design return period (n) of 2 to 5 years. This big difference in the detention basin volumes between the two regions (arid and coastal) is due to the different meteorological data such as rainfall intensity, frequency, duration, season and run off pattern.

Conclusions

The developed hydrological method is characterized with its simplicity and accuracy, which enables the environmental engineer or hydrologist to design basins / ponds for storm water detention directly based on the patterns of rainfall charts known or pre-determined for any studied site aiming to protect from floods risks, which enables generalizing and apply this method in any climatic region wherever it be provided to have the rainfall charts or rainfall stations. It was clearly seen that this method is distinquished from the tradititional design method employed in some countries, where the differences were plain in the detention volumes at the same selected rainfall return period (n). In addition to the large variation in the volumes of detention basins / ponds between the arid and coastal regions due the wide variation in the nature of climatic / rainfall data regarding rainfall intensities, durations, return periods and runoff patterns.

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Table 1. Rainfall height h_N(mm) versus rainfall duration T(min) and return period n (years) for Lattakia city [9 , 10]

N (year)	0.5	1	2	5	10	20	40
T(min)	h_N(mm)	h_N(mm)	h_N(mm)	h_N(mm)	h_N(mm)	h_N(mm)	h_N(mm)
5	6.51	8.19	9.66	11.485	12.835	14.065	15.235
10	9.48	10.68	11.88	13.49	14.75	15.83	16.79
15	10.2	13.68	15.39	17.455	19.155	20.505	21.855
20	10.8	15.6	17.4	20.38	22.78	24.34	26.14
25	13.65	17.7	19.8	23.075	25.775	27.725	29.525
30	14.4	19.08	21.6	24.63	27.15	29.13	30.93
40	14.88	21.36	22.36	28.04	30.92	33.56	35.96
50	15.3	23.4	27	31.75	35.35	38.35	40.75
60	15.6	26.28	30.24	35.90	39.54	41.7	43.86
70	16.8	26.97	31.15	37.03	40.95	43.75	46.27
80	18.6	27.52	33.12	39.44	43.6	46.56	49.2
90	20.4	28.89	34.92	41.76	46.08	49.14	51.93
100	22.3	30.2	36.7	43.8	48.5	51.6	54.5
110	23.7	31.46	38.39	45.87	51.37	54.01	56.98
120	24.9	32.64	39.96	47.76	52.8	56.28	59.28
130	26.2	33.8	41.47	49.66	54.86	58.37	61.49
140	27.1	34.86	42.84	51.38	56.84	60.34	63.56
150	29.0	36.031	44.25	53.1	58.65	62.4	65.7
160	30.12	37.04	45.6	54.72	60.48	64.32	67.68
170	31.24	38.015	46.92	56.44	62.22	66.13	69.53
180	31.85	38.956	48.06	57.96	63.9	67.86	71.46
240	36.12	44.06	55.025	66.465	73.376	77.767	81.585
360	45.32	52.418	66.34	80.542	88.877	93.959	98.3
720	59.04	70.532	91.33	111.854	123.335	129.829	135.189

Table 2- Rainfall height h_N(mm) versus rainfall duration T(min) and return period n (years) for Damascus city [9 , 10]

(year)	0.5	1	2	5	10	20	40
T(min)	h_N(mm)	h_N(mm)	h_N(mm)	h_N(mm)	h_N(mm)	h_N(mm)	h_N(mm)
10	2.5	3.08	3.74	4.58	4.71	6.34	7.13
15	3.24	3.915	4.74	5.865	6.12	7.03	7.78
20	3.66	4.66	5.32	6.32	6.92	7.73	8.33
25	4.075	5.35	5.825	7.075	7.61	8.33	9.46
30	4.47	5.49	6.69	7.62	8.06	9.52	11.93
40	4.96	5.96	7.16	8.44	9.04	10.52	13.67
50	5.65	6.65	7.45	8.75	10.47	11.33	15.82
60	6	6.78	8.34	9.66	12.21	13.96	18.54
70	6.3	7.56	8.68	9.87	13.24	14.62	19.58
80	6.88	8.24	9.04	10.08	13.87	15.94	21.13
90	7.29	8.46	9.54	10.44	15.06	17.44	23.20
100	7.4	9.3	10	10.9	16.11	17.93	24.12
120	8.4	9.96	10.92	12	17.79	19.84	26.00
180	10.44	12.78	13.32	14.22	22.57	24.67	30.12
190	10.907	12.936	14.009	15.083	23.21	25.17	30.18
200	11.225	13.303	14.382	15.451	24.05	25.91	31.45
210	11.536	13.662	14.746	15.809	24.80	26.74	32.10
220	11.84	14.013	15.101	16.158	25.47	27.68	32.80
230	12.139	14.358	15.44	16.489	26.01	28.12	33.10
240	12.431	14.695	15.788	16.831	26.74	28.85	33.94
360	15.6	18.335	19.429	20.36	34.22	36.34	38
480	18.326	21.453	22.51	23.304	38.32	40.52	44.70
600	20.765	24.231	25.233	25.877	43.76	46.35	45.00
720	22.997	26.766	27.7	28.189	47.00	52.66	55.73

تطوير نموذج هيدرولوجي للتحكم الفعال بمياه الفيضانات

عادل عوض
قسم الهندسة البيئية – كلية الهندسة المدنية – جامعة تشرين — للاذقية

الملخص تعرض الورقة هذه موضوع استخدام نظم التخزين المطرية في أحواض التصريف (الأحواض الصبابة للمدن (urban watersheds) من أجل حماية هذه المدن أو أجزائها من كوارث الفيضانات المطرية، وبغرض حماية المصادر المائية من الملوثات المساقة مع مياه السيول. جرى في البحث استنباط العلاقات الهيدرولوجية – الرياضية المبسطة لتحديد حجوم أحواض / برك التخزين المطرية انطلاقاً من أنماط المنحنيات المطرية الفعلية التي تربط بين ارتفاع الهطول المطري وفترة الهطول وتواتره مطبقين ذلك على دراسة حالة مدينة اللاذقية كمثال عن منطقة عربية ساحلية ودراسة حالة مدينة دمشق كمثال عن منطقة عربية جافة أو شبه جافة وذلك لفيضانات مطرية تواترها (n) كل 2 أو 5 سنوات. لقد برهنت النتائج الحاصلة على دقة النموذج المطور هذا إلى جانب بساطة تطبيقه وإمكانية تعميمه للتطبيق على مناطق مناخية أخرى تتوفر لها أنماط المنحنيات المطرية أو محطات القياس المطرية.