Pergamon

Wat. Sci. Tech. Vol. 29, No. 1–2, pp. 155–161, 1994.

0273–1223/94 \$7·00 + 0·00

USE OF A TROPICAL BASIN MODEL TO ASSESS THE IMPORTANCE OF URBANIZED LAND CONDITION ON THE INCREASE OF FLOOD PEAK

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ABSTRACT

Using the computer model of the Upper Bukit Timah Basin of Singapore, the effect of urbanized land condition on the flood peak increase due to urbanization has been assessed. The model results are presented in isopleths, which are lines of equal ratio of flood peak after and before urbanization. The degree of urbanization is expressed in terms of the percentage of area developed and the percentage of area channelized. By subjecting the Basin to the Singapore 2-year rainfall, the results show that the transformations from a forest to a developed land with 30% imperviousness may cause a three-fold increase in the flood peak. If the imperviousness of the developed land were to increase to 100%, the flood peak increase could be as high as five times. Evaluation of flood peak increase is therefore highly dependent on the degree of imperviousness of the urbanized land.

KEYWORDS

Basin model; flood peak; imperviousness; land use; urbanization.

INTRODUCTION

Of all the land use changes affecting the hydrology of a drainage basin, urbanization is by far the most forceful. By physically replacing the rougher, more permeable land surface with a smoother, more impermeable surface, and replacing the unlined natural channel with lined canals, the result on the runoff hydrograph is an increase in peak discharge and runoff volume, and the shortening of the time to peak. Evaluation of the flood peak increase is commonly quantified by means of a peak flow ratio (Leopold, 1968; Rantz, 1971; Hollis, 1975; Sauer et al, 1983; Chen and Wong, 1989; Wong and Chen, 1993a, 1993b). The ratio is defined as the peak flow under the urbanized land use condition divided by the peak flow under the undisturbed land use condition. Based on Riordan et al's (1978) summary of 34 studies on the effect of urbanization on the hydrologic regime, Packman (1980) commented that the large differences in results may be caused by the different nature of the undisturbed land use condition among the studies. In fact, the importance of undisturbed land use condition on the evaluation of flood peak increase has been demonstrated by Chen and Wong (1989). By applying the kinematic wave method to an idealized drainage basin, they showed that while the increase in flood peak due to urbanization for a grass-based basin is about two times, the corresponding flood peak increase for a forest-based basin could be as high as six times. In this paper, using the computer model of the Upper Bukit Timah Basin of Singapore, the importance of urbanized land use condition on the evaluation of flood peak increase has been assessed.

THE UPPER BUKIT TIMAH DRAINAGE BASIN

Located in the central region of Singapore Island (latitude 1^{o} 20' N, longitude 103^{o} 47' E), the main climatic features for the Upper Bukit Timah Basin are the relatively uniform temperature, high humidity and abundant rainfall. As a result of urban development, the hill tops in the southwest corner of the Basin have been re-graded such that the drainage area of the Basin increased from 5.8 km^2 in 1924, to 6.2 km^2 in 1969, and then to 6.4 km^2 in 1988. The highest hill in Singapore, the Bukit Timah Hill is situated in the northwest sector of the Basin. Its summit is at an elevation of 165 m above mean sea level. The downstream outlet point is situated in the Bukit Timah Canal, at an elevation of 5 m above mean sea level. The flow in the Basin is not subject to tidal influence.

Rainfall and Runoff Data

There are two autographic rain gauges inside the Basin (Murnane Reservoir and Bukit Batok Boys' Hostel) and three just outside the Basin (Dairy Farm, Turf Club and Singapore Boys' Home). Installed in 1968, the hydrometric station is situated near the intersection of Maple Avenue and Bukit Timah Road in the Bukit Timah Canal.

The rainfall and runoff records have been processed by various authorities and are presented on an hourly basis. The data used in this study essentially covered two periods, i.e. 1968-1974 and 1978-1988. For the first period, rainfall data are only available from Dairy Farm, Turf Club and Singapore Boys' Home. For the second period, rainfall data are available from all five stations. In addition to the above data, Taylor (1934) reported one rainfall-runoff event that occurred in 1932 for a 24.3 km^2 drainage basin at Newton Bridge. The most upper portion of the Newton Bridge Basin is the Upper Bukit Timah Basin.

Land Use Changes

The developments within the Basin comprise residential and industrial buildings, roads, reservoir and quarries. The residential and industrial buildings are essentially distributed along the main canal and the downstream reaches of the tributaries. There are numerous major and minor roads and two expressways within the Basin. There are also one service reservoir and two quarries in the Basin. As the quarries trapped all the rain water that fell within their individual drainage basins, in the estimation of the Upper Bukit Timah Basin area, the quarry drainage areas were excluded. Table 1 contains the percentage of area developed for various years, estimated from topographic maps. The rate of increase in developed area is approximately linear (Chen and Wong, 1991). Further, for typical developed areas within the Basin, the proportion of paved area was estimated to be around 30%. This percentage has been used to represent the degree of imperviousness of the developed areas in the Basin. According to the U.S. Department of Agriculture (1985), the 30% imperviousness corresponds to the medium density residential land use condition and for a business district, the degree of imperviousness can be as high as 90%.

TABLE 1 Land Use Changes in the Upper Bukit Timah Basin

Year	Developed Land (%)	Grassland (%)	Forest Land (%)
1924	14	unknown	unknown
1969	51	41	8
1988	64	28	8

As part of the Bukit Timah Flood Alleviation Scheme (Phase I), the Bukit Timah Canal was enlarged and concrete lined between 1970 and 1972. Prior to this scheme, all the channels were unlined. Other flood alleviation schemes, in which most of the major tributaries were also enlarged and concrete lined, were implemented between 1979 to 1985.

COMPUTER MODEL OF THE UPPER BUKIT TIMAH BASIN

In order to evaluate the flood peak increase due to urbanization at the Basin, a computer model of the Basin has been developed using the HEC-1 program (Wong and Chen, 1993a). Details of the program can be found in U.S. Army Corps of Engineers (1987). Essentially, the program is designed to simulate single event, surface runoff response of a drainage basin to precipitation. For the Upper Bukit Timah Basin model, the exponential loss model was used to simulate the rainfall abstractions, and the kinematic wave option was used to convert the rainfall excess to runoff.

Basin Model Calibration

As the developed area in the Basin was not a constant but increased over the years, the Basin model was developed for three land use conditions (i.e. 1932, 1969 and 1988). In the model, the Basin has been divided into sub-basins. Each sub-basin is represented by one or two overland planes, and one channel segment. The physical characteristics of a plane are defined by the length of the overland plane, the overland slope, the Manning's resistance coefficient, the percentage of the sub-basin area represented by the plane, and the percentage of impervious area within the plane. According to the dominant surface type in that particular plane, the plane was classified into primarily developed land, primarily grassland, or primarily forest land.

For the channel segments, the physical characteristics are defined by the channel length, the channel slope, the Manning's resistance coefficient, the channel cross-section, the base width, and the side slope. The physical characteristics of the channel segments were obtained from the design drawings of the flood alleviation schemes as well as on-site inspections. In the model, two types of channel surface (i.e. earth and concrete), and three types of cross-sections (i.e. triangular, rectangular, and trapezoidal) were used.

The Basin model was calibrated by entering the observed rainfall, and adjusting the loss rates in the exponential loss model, such that the observed and the simulated runoff hydrographs were in reasonable agreement. Since for each event rainfall records are available from more than one rainfall station, the rainfall record actually applied to each sub-basin was determined based on the Thiessen polygons method. All available records from the three rainfall stations were used for the model with the 1969 land use condition. For the model with the 1988 land use condition, four out of the five available rainfall records were used, as the polygon for Dairy Farm did not cover the Basin. For each land use condition, a total of six events were used in the calibration.

In addition to the above, the model was also developed for the 1932 land use condition. In this model, the 1924 channel network was used. Further, based on linear interpolation of the developed area in 1924 and 1969 (Table 1), a 20% developed area was estimated for 1932. Since the exact areal extent of forest land could not be ascertained, those planes with less than 30% developed land were classified as primarily forest land. Based on this classification, the extent of primarily forest land is 60%. The rainfall of the 1932 event was entered into the model, and the simulated flood peak was then adjusted to the drainage area of Newton Bridge Basin, using the Creager flood peak-drainage area relationship (Creager et al. 1944). The simulated flood peak is in close agreement with that of the observed.

Figures 1 and 2 show the Basin model with the 1932 and 1988 land use conditions.

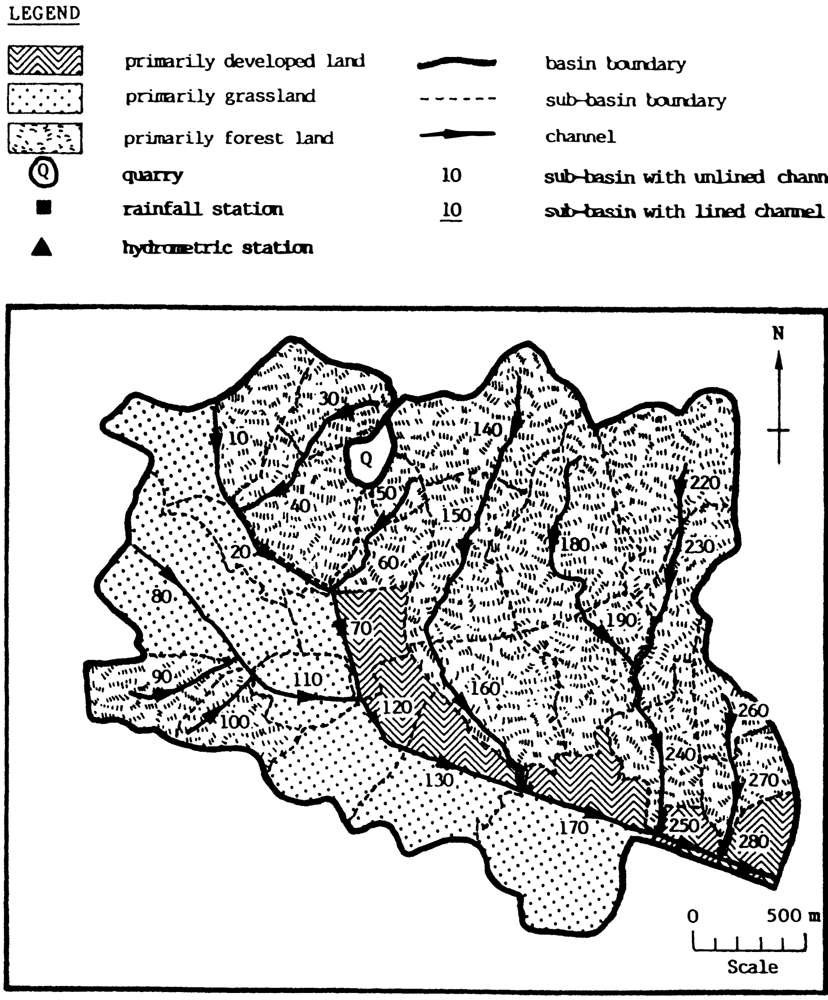

Fig. 1. Upper Bukit Timah Basin Model: 1932 land use

EFFECT OF URBANIZED LAND CONDITION ON FLOOD PEAK INCREASE

Since the dominant land use in 1932 was judged to be forest land, the assessment was carried out by simulating forest land as the undisturbed land use condition. The flood peak increase was evaluated for two fully urbanized land use conditions (i.e. developed land with 30% imperviousness, and developed land with 100% imperviousness). For each case, following the historical urbanization pattern, a total of 12 urbanization conditions were simulated. Further, for each of the 12 urbanization conditions, an individual storm in accordance with the Singapore 2-year rainfall intensity-duration curve (Figure 3) was entered into the Basin model. The largest resultant discharge was taken as the peak discharge for that particular urbanization condition.

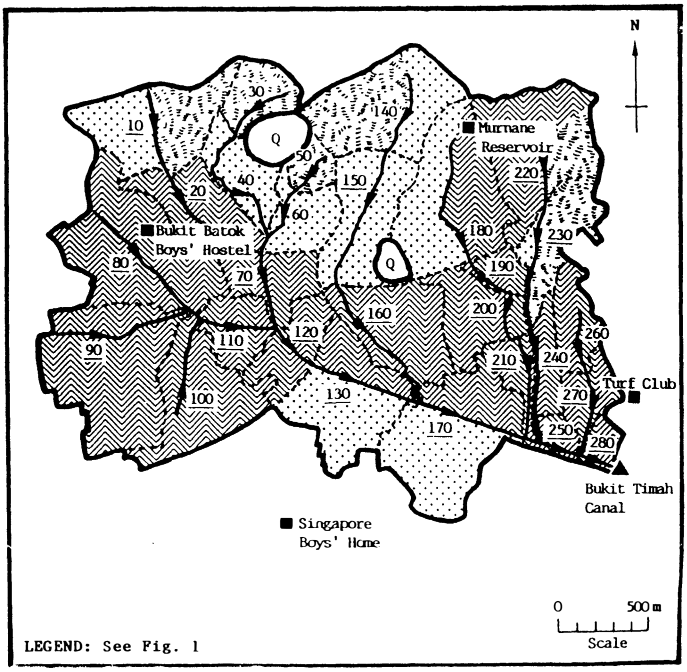

Fig. 2. Upper Bukit Timah Basin Model: 1988 land use

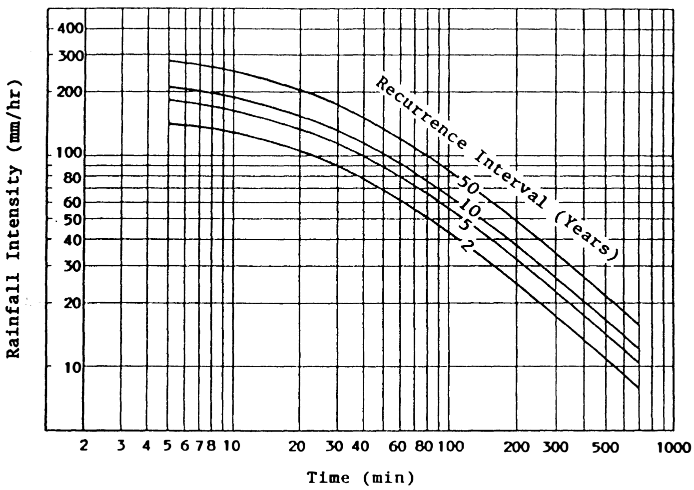

Fig. 3. Rainfall intensity-duration-frequency curves for Singapore Island (Ministry of the Environment, 1991)

As shown in Figure 4, the flood peak increase is presented in isopleths, which are lines of equal ratio of peak flow after and before urbanization. The degree of urbanization is expressed as a function of the two parameters which quantify the major physical changes of a basin as a result of urbanization, i.e. the percentage of basin area developed and the percentage of basin area channelized. The developed areas are the areas devoted to urban use. The channelized areas are the areas drained by concrete lined channels. The urbanization conditions in the years 1924, 1969 and 1988 are highlighted in Figure 4a, and the figure shows a three fold increase in the flood peak for the Basin to transform from a forest to a developed land with 30% imperviousness. If the imperviousness of the developed land were to increase to 100%, Figure 4b shows that the flood peak increase could be as high as five times. Further, for the same degree of imperviousness, Figure 4a shows a higher peak flow ratio than Figure 4b. The additional increase in peak flow for Figure 4a is due to the change of forest land to grassland which is the pervious portion of the developed land. A comparison of Figure 4a to 4b shows that, given identical undisturbed land use condition, the flood peak increase is highly dependent on the degree of imperviousness of the developed land.

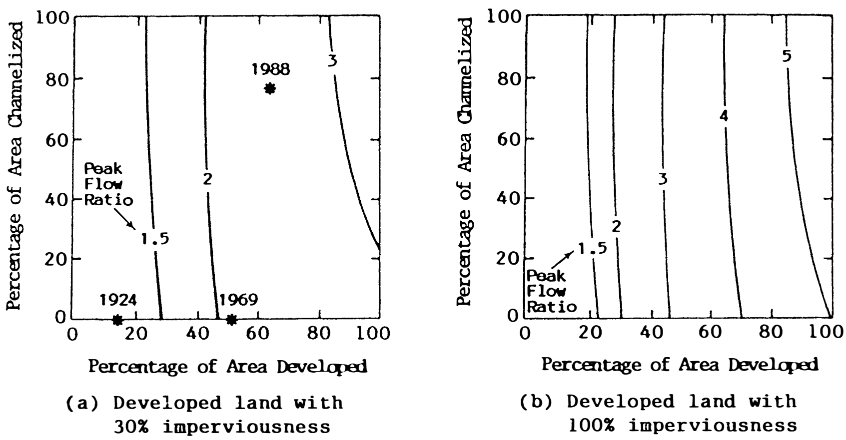

Fig. 4. Flood peak increase at the Upper Bukit Timah Basin subject to the Singapore 2-year rainfall (Wong and Chen, 1993a)

CONCLUSIONS

The effect of urbanized land use condition on the flood peak increase due to urbanization has been assessed using the Upper Bukit Timah Basin model. The results show that transforming the Basin from a forest to a developed land with 30% imperviousness may cause a three-fold increase in the flood peak. If the imperviousness of the developed land were to increase to 100%, the flood peak increase could be as high as five times. Evaluation of flood peak increase is therefore highly dependent on the degree of imperviousness of the urbanized land.

ACKNOWLEDGEMENTS

The authors are grateful to the Meteorological Service, the Ministry of the Environment and the Public Utilities Board for the provision of the rainfall and runoff data, and to the Ministry of Defence and the National Archives for the provision of the topographic maps.

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