Comparing the Changes in Hydrology due to Different Development Regulations using Sub-Daily SWAT

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Abstract

The City of Austin, Texas is in the process of updating its land development regulations and requested that the hydrologic impacts of the new regulations be compared to existing regulations. The authors increased the scope of the project in order to determine the overall effectiveness of land development regulations with respect to changes in hydrology. Four development scenarios were modeled using SWAT. These models represented conditions from pre-1970s through the proposed regulations and a baseline undeveloped scenario. Scenarios were compared based on impacts on flooding, erosion and aquatic life potential. Early regulations with narrow stream buffers and detention basins addressed infrequent flood events but increased the peak flows associated with return periods less than 25 years, increased excess shear and changed hydrologic metrics indicating a probable decrease in aquatic life potential. Later regulations, including the proposed regulation, which include more extensive creek buffers, detention and water quality controls, controlled the infrequent flood events and decreased the peaks flows for different return periods to near undeveloped conditions, reduced excess shear and maintained hydrologic metrics for aquatic life potential.

Keywords: Hydrology, development, flooding, erosion, aquatic life

Introduction

Over the past forty years the City of Austin (COA), Texas has implemented various rules and ordinances in order to protect the public, property and the natural environment from the changes in hydrology associated with urbanization. The initial ordinance, the Waterways Ordinance (WO) was passed in 1974 and focused primarily on flooding. The Comprehensive Watershed Ordinance (CWO) was passed in 1986 and included creek buffers and addressed water quality and erosion concerns in addition to flooding. The City is in the process of adopting the Watershed Protection Ordinance (WPO) which will build on the CWO. A rigorous evaluation of the effectiveness of these ordinances was not possible using field data due to multiple ordinances applied to a given watershed over time and the length of time for natural processes like erosion to occur.

This study evaluates effectiveness of these ordinances with respect to flooding, erosion and aquatic life potential using the sub-daily and urban BMP options in the latest version of AcrSWAT (2012.10.17) (Arnold et al, 2013).

Study Site and Model Development

The study site is a 4.99 km^2 tributary of Gilleland Creek located east of Austin, TX (30°17'45"N, 97°33'12"W) in the Blackland Prairie eco-region (Fig. 1). The watershed is currently undeveloped and dominated by unimproved pasture and scattered honey mesquite (*Prosopis glandulosa*) and eastern red cedar (*Juniperus viginiana*). In addition to modeling the undeveloped condition, four models were developed for this watershed based on the different regulations. All five models used the same SSURGO soils data and 3-m DEM developed from LIDAR data collected by COA in 2003.

The land use maps for the different development scenarios were created by the COA Watershed Protection Department's (WPD) Policy and Planning staff. Initially, a 'wallpaper' was created containing the various land uses in proportions found throughout the city. Buffers and easements were them applied to the stream in accordance to the different regulations. Prior to the implementation of WO, the only requirement was a limited easement of 9 m from the centerline of the creek along the channel with drainage areas >130 ha (320 ac). The WO required a wider easement (30 m) to the same extent. CWO required a wider buffer (45 m) which could include no development and an additional water quality transition zone of 60 m which could have limited development. The proposed WPO required a wider buffer (90m) but does away with the water quality transition zone. WPO also extends smaller buffers (30m) to areas with drainage >25 ha (64 ac). Precipitation was based 15-min rainfall from two gauges that are part of the COA Flood Early Warning System. Daily temperature data were from the NWS Robert Mueller Airport station. Other weather inputs were generated using the WGEN_US_COOP_1960_2010 database in ArcSWAT. Since the watershed is ungaged, model parameters were adjusted based on local knowledge and used for all scenarios. The adjusted parameters are in Table 1.

In addition to different land use requirements, the ordinances also had different requirements for stormwater control measures (SCMs). The WO was focused primarily on flooding generated by larger storm events and only required detention to control the peak flow from the 2-, 10-, 25- and 100-yr 24-hr design rainfall (Type III) (COA, 2013a). This was accomplished by placing an on-

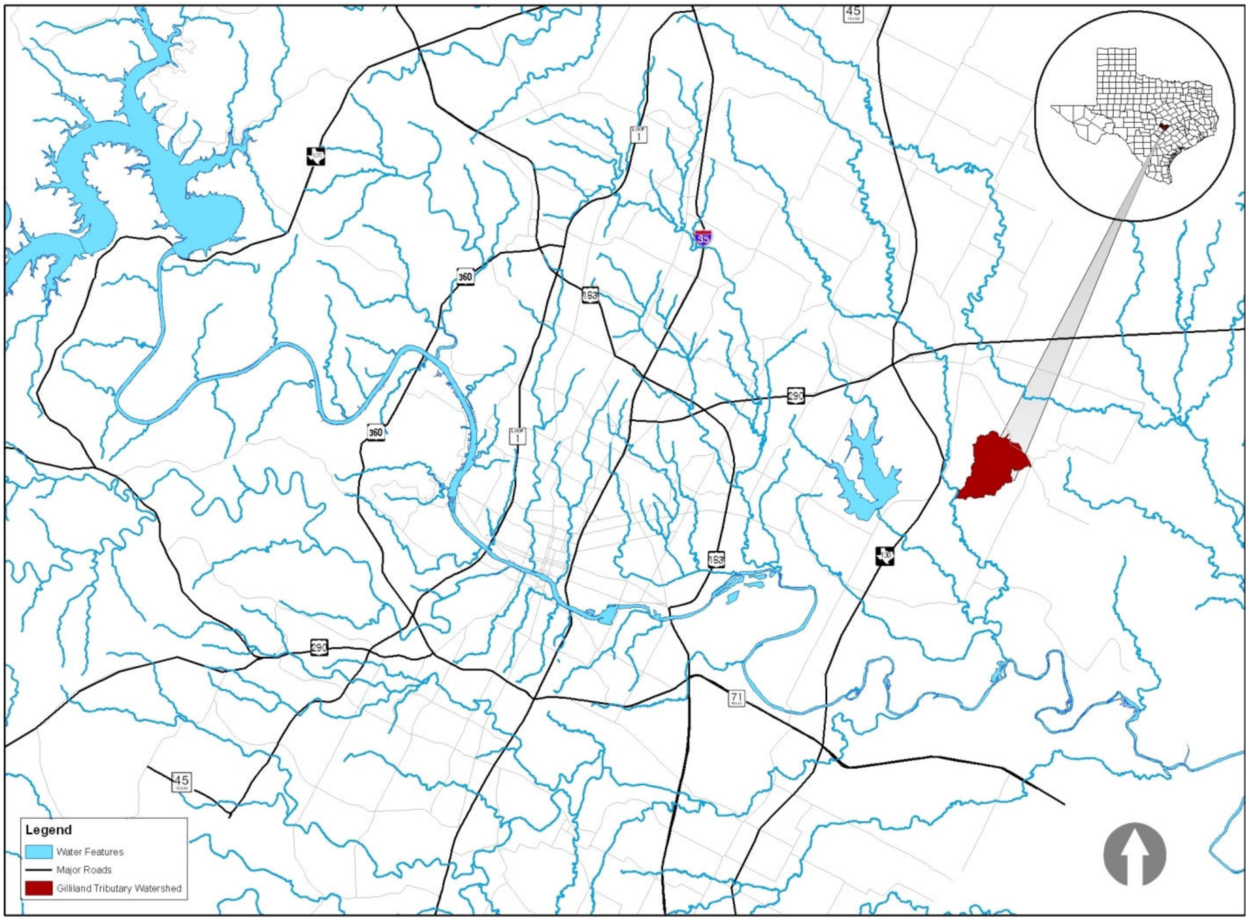


Figure 1. Gilleland tributary study area.

line detention basin at the outlet of reach 9 (see Figure 2). The peak discharges from the developed conditions for the design rainfalls matched the undeveloped peaks after passing through the detention basin. This detention basin design was also used for the CWO and WPO models.

In addition to detention, CWO and WPO require water quality controls, typically accomplished with sedimentation-filtration basins (SF). The typical COA SF is designed to capture a specified volume of upland runoff from urban areas in a sedimentation basin. The outlet of the sedimentation basin is usually controlled by an orifice designed to allow water to pass to the sand filter basin at a rate that would allow the entire volume to be drained in 48 hours. Effluent from the sand filter is discharged into the creek. The volume of the sedimentation basin is determined by the impervious cover of the contributing area: for 20% impervious cover, the volume is 1.27 cm; for every additional 10% of impervious cover, the capture volume increases by 0.254 cm. If the volume of the sedimentation basin is exceeded, additional flow bypasses the system and is discharged into the creek (COA, 2013b). In ArcSWAT 2012.10.7 SF basins are applied to runoff from specified urban HRUs, the runoff is then combined with runoff from other HRUs before being routed through the reach.

The five models were run for twenty-five years 1987-2012 based on the valid 15-minute rainfall dataset. The first two years were used as a warm up period and not used for analyses.

Table 1. Calibration parameters for Gilleland scenarios

Parameter	Value	File
CH_N2	0.035	.RTE
CH_K2	5	.RTE
ALPHA_BNK	0.25	.RTE
ALPHA_BF	0.1	.GW
GW-DELAY	10	.GW
BFLO_DIST	0.25	.BSN
IUH	2	.BSN
UHALPHA	4	.BSN
SURLAG	1	.BSN
IRTE	1	.BSN
CH_N1*	0.035	.SUB
CH_K1*	5	.SUB
CN for PAST*	-4	MGT

* for undeveloped case only

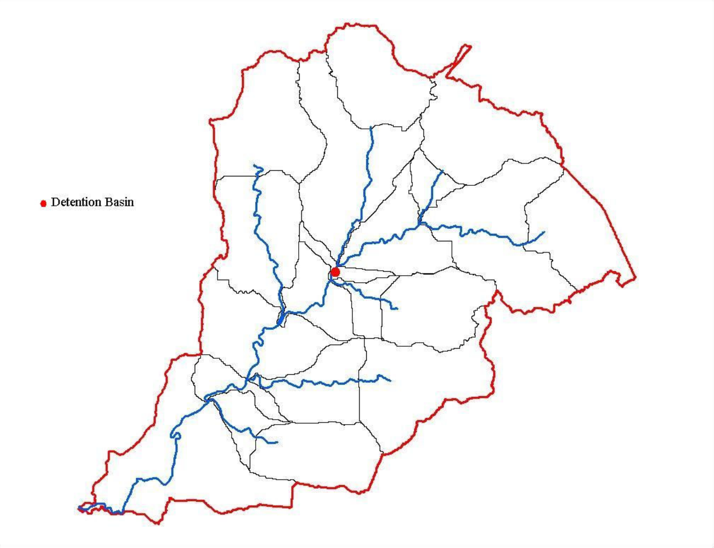


Figure 2. Detention basin location in WO, CWO and WPO models.

Data Analyses

Data from each scenario were analyzed based on the three different missions for WPD, flooding erosion and water quality & aquatic health. Flooding was assessed through peak flow rates for different return periods. Erosion was assessed by an evaluation of annual average cumulative excess shear. Water quality was not addressed in this study but the potential impacts of hydrologic modification on aquatic life were assessed.

Table 2. Peak flow rate recurrence intervals for development scenarios on Gilleland tributary.

Recurrence Interval (yr)	UND (cms)	PRE (cms)	WO (cms)	CWO (cms)	WPO (cms)
24.00	39.4	65.2	50.7	39.3	39.7
12.00	37.8	62.7	47.6	32.9	38.6
8.00	36.1	52.7	43.1	31.2	32.8
6.00	34.8	50.1	41.2	31.1	31.9
4.00	32.1	49.3	39.3	29.1	29.9
3.00	30.6	45.9	37.5	26.4	29.7
2.00	25.7	40.7	33.1	22.8	25.3
1.50	21.7	38.3	29.9	18.4	22.2
1.00	18.8	32.8	27.9	12.6	15.2
0.75	16.4	29.5	24.2	10.4	12.8
0.50	11.4	23.8	20.3	3.87	4.96
0.25	5.59	17.6	14.4	0.616	0.681

Flood Impacts

Typical flood analyses examine large and infrequent flood events based on design rainfall events to protect lives and property. However, less frequent events may also cause problems with low water crossings or inundation of the floodplain. While detention basins may limit peak discharge, the recurrence of that discharge may be more frequent than previously experienced. Frequent flood peaks were assessed in this study by comparing the peaks at given return periods to the same return period peaks. This was accomplished by ranking the storm peaks in descending order for the 23 year period of analysis. Then, assuming a Weibull distribution, average recurrence interval was determined by,

$$T = \frac{N+1}{m} \quad [1]$$

where T is the average recurrence interval in years, N is the number of years in the record and m is the rank of the event (Gordon, et al., 1994). Recurrence events for the five development scenarios on Gilleland are presented in Table 2.

Based on the modeling study, pre-ordinance development (PRE) exhibited much higher peaks for every recurrence interval. The 1-yr recurrence for undeveloped (UND) would be expected approximately every 3 months while the UND 24-yr recurrence would occur approximately every 18 months. Adding the detention basin at the end of Reach 9 in the WO scenario had some impact but not as much as planned. It was hoped that by placing the detention basin in this location the downstream flood peak would pass before the upstream peak arrived. This worked to some extent but all of the peak flows were higher for every recurrence interval. This was more pronounced at the more frequent events (<2-yr) because the smallest storm the detention basin was designed to control was the 2-yr rainfall event. The addition of SF controls in the CWO and WPO scenarios significantly reduced the peak discharges across all recurrence intervals, nearly matching the undeveloped condition for recurrence intervals between 2 and 24 years. For more frequent recurrence intervals the SF controls removed almost the entire peak, such that the 3-month peak was almost non-existent.

Erosion Impacts

The impacts of development on erosion potential were assessed using average annual excess shear (ES). Excess shear occurs when the shear stress exceeds the critical shear for the stream bed and bank. When the flow exceeds the channel capacity and spills into the floodplain, average velocities drop and total shear decreases while shear in the channel will continue to increase. To account for this, this study only examined shear in the main channel.

Shear and critical shear were computed using the following equations:

$$\tau = \gamma_w \cdot D_H \cdot S_w \qquad [2]$$

and

$$\tau_c = \Theta_c(S_g - 1) \cdot \gamma_w \cdot d_{50} \qquad [3]$$

where,

τ = shear (Pa)
τ_c = critical shear (Pa)
γ_w = density of water (kg/m^3)
D_H = depth of water (m)
S_w = channel slope (m/m)
S_g = specific gravity of soil, 2.65
d_{50} = median particle diameter (m)
θ_c = critical Shield's parameter, 0.047

ES was defined as:

$$ES = \sum(\tau - \tau_c) \text{ for all } \tau > \tau_c \qquad [4]$$

Hydraulic properties at the watershed outlet were estimated using WinXSPRO 3.0 (Hardy, et al., 2005). This program uses the channel cross-section and slope (estimated from the DEM) to develop a stage-discharge relationship based on Manning's equation. The program allows the user to treat the floodplain differently than the main channel to separate total flow from flow in the main channel. A Manning's n of 0.035 was used in the channel while 0.1 was used in the floodplain. WinXSPRO computed shear discharge as a function of stage for both the total cross-section and the main channel. A table relating channel ES to discharge, assuming a 19 mm median particle diameter, was developed and loaded into Hydstra version 10.3.2 (Kisters, 2011). The HYCRSUM routine in Hydstra was used to compute cumulative excess shear for the 23 year study period based on flow generated by the sub-daily SWAT models. Average annual excess shear for the five scenarios is presented in Figure 3.

With the 19 mm median particle diameter, ES increased by 181% without any regulations compared to the undeveloped scenario. When detention was added as part of the WO scenario ES increased by 196%. The increase in ES with the added detention is a result of the detention basin maintaining flows above the flow associated with τ_c for a longer period of time. The CWO

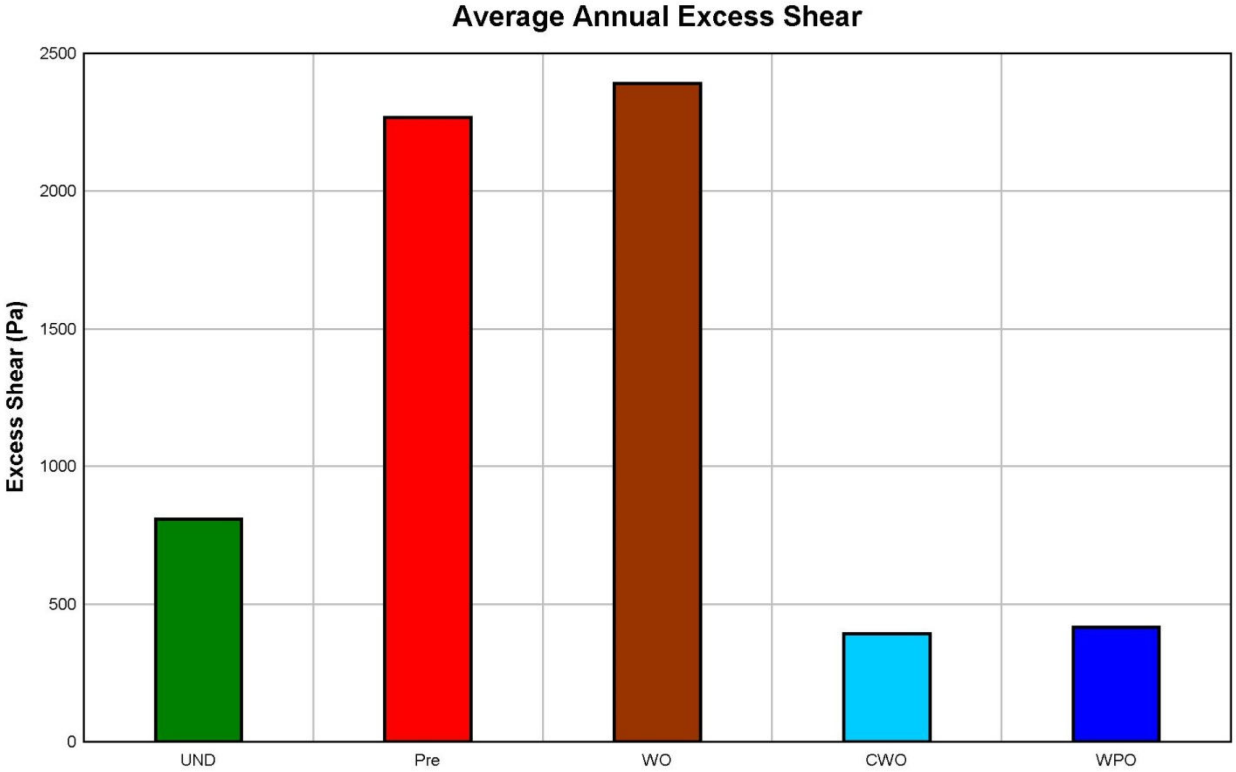


Figure 3. Average annual excess shear for five different development scenarios in the Gilliland tributary assuming a 19 mm median particle diameter.

and WPO scenarios resulted in a reduction of ES by approximately 50% compared to undeveloped. This may result in some aggrading of the stream under this condition until equilibrium is reached with a new median particle size is reached.

Another study by COA (Glick and Gosselink, 2013) indicates that these trends hold for other particle sizes. However, for median particle diameters less than 19 mm, there will be degradation of the channels even with the inclusion of SF basins given this channel cross-section. This is due to the long drawdown time of the SF basins resulting flows above the critical flow associated with τ_c for smaller particle sizes. This will be of most concern in areas like the one where the study watershed is located with deep clay soils. While the increased buffers associated with the proposed WPO may not address this directly, the wider buffer will provide an area for the processes to occur without threatening structures.

Aquatic Life

The potential impacts on aquatic life were evaluated based on various hydrologic metrics identified by Glick and Gosselink (2009; 2011; 2012) and Glick, et al. (2010) which correlated well with COA Environmental Integrity Index (EII) aquatic life scores. These metrics measure the presence/absence of flow, the ratio of baseflow to total flow and the variability of the flow regime. These metrics are not absolute; some changes in the metrics might indicate a ‘better’ flow regime. However, it would be a change to regime in which the naturally occurring organisms developed. Use of these metrics should be based on local background conditions.

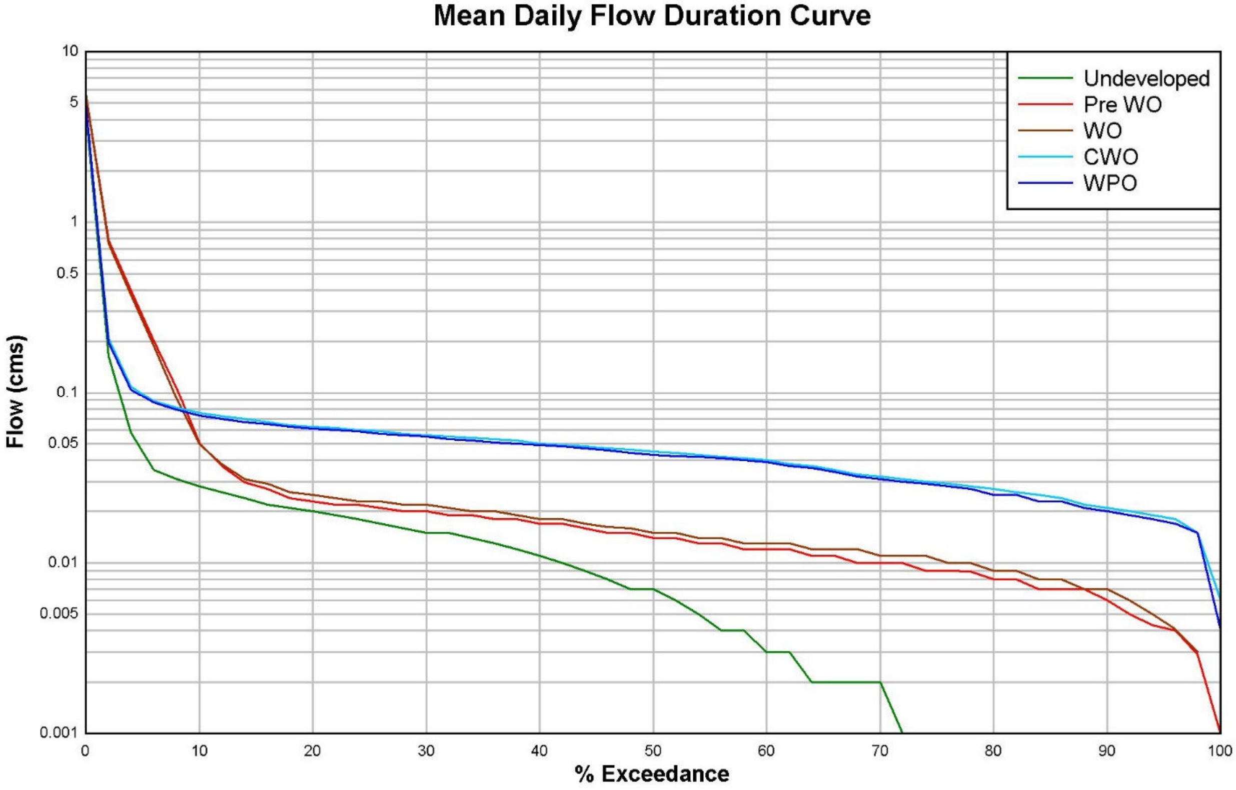
Table 3. Hydrologic flow metrics associated with aquatic life potential in the Austin, TX area for different development scenarios.

	UND	PRE	WO	CWO	WPO
T_{dry}	0.524	0.244	0.256	0.010	0.099
BFR	0.3734	0.1491	0.1534	0.6382	0.6328
F_{Ln}	15.78	27.04	28.83	10.87	8.65
F_{Ld} (day)	16.41	4.88	4.63	4.13	4.39
Q_{Peak} (cms)	39.4	65.2	50.7	39.3	39.1
SD	0.391	0.713	0.658	0.322	0.332
F_{Hn}	16.83	84.09	79.22	26.65	23.91
F_{Hn} (day)	2.30	0.16	0.19	4.61	5.19
$+_{mean}$ (cms)	0.100	0.246	0.244	0.113	0.106
$-_{mean}$ (cms)	0.047	0.076	0.077	0.026	0.026

Ten hydrologic metrics which correlate well with EII aquatic life score were computed for the different scenarios (Table 3). These metrics fall into two broad categories: stream flow and flow variability. The first four metrics, T_{dry} (dry fraction, >0.003 cms), BFR (baseflow ratio), F_{Ld} (average length of low flow/dry events, >0.003 cms), and F_{Ln} (annual number of low flow/dry events), are indicators of flow, primarily non-storm flows. As watersheds urbanize, creeks in arid and semi-arid areas tend to be dry more frequently; the ratio of baseflow to stream flow decreases; and the number of wet-dry cycles increases. Alteration of these may affect life cycles of the naturally occurring aquatic species. Of particular concern may be F_{Ln}; as the number of low-flow cycles increases the species may not be able to complete their life cycle, reducing species diversity. The stream flow metrics in Table 3 indicate that the aquatic life potential would tend to decline without regulations (PRE) and if detention alone is the only SCM strategy employed. The stream would be dry more often and BFR is reduced by more than 50%. In addition, the number of dry cycles increased (F_{Ln}) where increases indicate the potential interruption of the normal life cycles for some of the aquatic species. These numbers correspond well to other Austin area creeks with measured flow that were developed under these regulations (Glick, et al., 2010). With the addition of SF as an SCM in the CWO and WPO scenarios the stream appears to have more baseflow and be dry less frequently than in the undeveloped condition. This would be beneficial to the aquatic community but may shift the biological community composition from its natural state. As yet there are no gauged watersheds fully developed under CWO regulations so it is difficult to assess if this would actually be the case but it does appear that the addition of SF is beneficial to aquatic health with respect to low flow conditions.

The remaining metrics measure flow variability. These are more important to habitat stability. Q_{peak} (peak flow rate) and SD (standard deviation) provide an indication of the overall peak and variability. The combination of detention and SF used in the CWO and WPO scenarios appear to produce flows that are similar to the undeveloped condition while PRE and WO scenarios have higher peaks and more variability. This can also be seen in the mean daily flow duration curve (Figure 4) and the flood analyses in Table 2. F_{Hd} (duration of high-pulse events) and F_{Hn} (number of high-pulse events) are indicators of flow in excess of the 75th percentile of the undeveloped condition; typically duration of high pulses decrease with development but the

Figure 4. Mean daily flow duration curves for different development scenarios of the Gilliland tributary.



numbers increases. The change in these metrics without SCMs and detention only is dramatic, indicating a very flashy stream. The addition of SFs to the system under the CWO and WPO scenarios mitigate these changes to some extent, however the long drawdown of the SF controls results in extended high flow condition based on the undeveloped 75th percentile flow rate. Since the 75th percentile flow for the undeveloped condition was low, the increase in F_{Hd} may be outweighed by extending baseflow. The final measures of flow variability, $+_{mean}$ and $-_{mean}$, are the average rates of rise and fall in the daily mean flow rate. These typically increase with development. The use of detention alone has little impact on these variables but it appears the use of SF will address the changes in average rise to a large extent but reduces the average fall, once again due to the long drawdown times associated with SF.

There appears to be a slight improvement in the hydrologic metrics comparing CWO and WPO which may be a result of the increased buffers. This improvement is modest compared to the incorporation of SF as SCMs in the CWO.

Conclusions

Four scenarios based on different development regulations and an undeveloped condition were simulated for twenty-three years using the sub-hourly version of SWAT and urban BMP routines. The scenarios represented pre regulation development, development under the Waterways Ordinance in the 1970s, the Comprehensive Watershed Ordinance of the 1980s and a proposed Watershed Protection Ordinance. These scenarios were compared to the undeveloped condition and the changes in hydrology were evaluated on impacts on flooding, erosion and aquatic life potential.

Changes in hydrology associated with development prior to regulations indicated increased flood frequencies, increased erosion and degradation of aquatic life potential. The Waterways Ordinance focused primarily on flooding from larger rainfall events by incorporating detention basins. The changes in hydrology still indicated more frequent high flow events, increased erosion and degradation of aquatic life potential. The Comprehensive Watershed Ordinance included requirements for water quality control in addition to wider stream buffers and detention. The CWO reduced flood frequencies and erosion to near the undeveloped condition and maintained flow metrics in ranges associated with good aquatic life potential. The primary difference between the CWO and the proposed Watershed Protection Ordinance is extending stream buffer into the headwaters of creeks. The SWAT model was not able to significantly differentiate these changes; however, the WPO, like the CWO, significantly reduced the hydrologic impact of development.

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