Section 3 Functional Aspects of Freshwater Wetlands in the Central Puget Sound Basin

CHAPTER 8 EFFECTS OF WATERSHED DEVELOPMENT ON HYDROLOGY

by Lorin E. Reinelt and Brian L. Taylor

INTRODUCTION

In urbanizing areas, the quantity (peak flow rate and volume) of stormwater can change significantly as a result of developments in a watershed. Increases in stormwater may result from new impervious surfaces, removal of forest cover, and installation of constructed drainage systems. Watershed development can also cause reduced recharge of groundwater and baseflow to streams, and less evapotranspiration.

Changes in hydrology, whether brought about intentionally or incidentally, have an influence on wetland systems. Wetlands will likely have a positive effect on downstream areas by dampening stormflows before discharging to streams and lakes. However, wetlands may also be adversely impacted by these same higher peak flows and volumes. For cases where wetlands are the primary receiving water for urban stormwater from new developments, it is hypothesized that the effects of watershed changes will be manifested through changes in the hydrology of wetlands.

Wetland hydrology is often described in terms of its hydroperiod, the pattern of fluctuating water levels resulting from the balance between inflows and outflows of water, landscape topography, and subsurface soil, geology, and groundwater conditions (Mitsch and Gosselink, 1993). Hydroperiod alterations are the most common effect of watershed development on wetland hydrology. This usually involves increases in the *magnitude*, *frequency* and *duration* of wetland water levels. In other words, increased stormwater flows tend to cause higher wetland water levels, on more occasions during the wet season, and for longer periods of time. These changes in wetland hydroperiod then result in impacts to plant and animal communities that were adapted to the pre-existing hydrologic conditions.

Puget Sound Wetlands and Stormwater Management Research Program

Palustrine wetland hydrology was studied as part of both components of the research program: (1) the study of the long-term effects of urban stormwater on wetlands, and (2) the study of the water-quality benefits to downstream receiving waters as urban stormwater flows through wetlands. This chapter presents results from the statistical analysis of 19 study wetlands from the long-term effects study, and from the water balance of two wetlands from the water-quality benefit study.

Research Objectives

The primary objective of this portion of the research program was to examine the effects of urban stormwater on wetland hydrology. However, there were also a variety of specific hydrologic questions addressed throughout the research which developed into the following specific objectives:

1. Identify the wetland and watershed hydrologic processes, and the factors governing these processes.
2. Determine how urban catchments behave differently from forested catchments.
3. Determine the percent contribution of wetland hydrologic inputs and outputs.
4. Relate wetland hydrologic conditions to wetland/watershed characteristics.
5. Characterize wetland hydroperiods and develop a set of dependent variables for analysis.

DATA COLLECTION AND ANALYSIS METHODS

As noted in Chapter 1, a conceptual model was used to show the relationship between factors influencing wetland and watershed hydrologic processes and the wetland hydroperiod (Figure 1-4). In the conceptual model, some of the key factors thought to influence wetland water level fluctuation included: (1) forested area, (2) impervious area, (3) wetland morphology, (4) outlet constriction, (5) wetland-to-watershed area ratio, and (6) watershed soils. Statistical analyses were carried out to determine which factors were most important.

Statistical Analysis of Development Impacts on Wetland Hydrology

A variety of graphical and statistical techniques were used in identifying relationships between the watershed or wetland characteristics and wetland hydroperiod (Taylor, 1993). Microsoft EXCEL was used in processing the data and SYSTAT was used for statistical analyses.

Graphical Analysis

The objective of the graphical analysis was to identify trends and threshold levels that could then be statistically tested to determine which statistical methods (parametric or nonparametric) were appropriate. Graphical analysis provided insights into which factors correlated to specific aspects of the hydroperiod; however, it failed to show the effects of multiple factors or varying importance simultaneously.

Normality Testing

In order to determine which statistical tests were appropriate for a given hypothesis, the normality of the data was assessed. The Kolmogorov-Smirnoff test was used to compare the maximum difference between two cumulative distributions. The Lilliefors test was used when the mean and variance of the distribution were unknown, in order to automatically standardize the variables and test whether the standardized distributions were normally distributed (Wilkinson, 1990). The Lilliefors test was used to assess the distribution of water level fluctuation measurements. The significance level used in testing normality was alpha equal to 0.05.

Threshold Testing

Threshold testing was done when a scatterplot suggested one or more threshold levels in the response of wetland water level fluctuations to a specific watershed or wetland characteristic. The data were grouped categorically based on thresholds suggested in the scatterplots. These groups were compared in a test of the null hypothesis that all groups were from equivalent distributions.

Because the water level fluctuation measurements were not normally distributed for all of the study sites, nonparametric tests were used: the Mann-Whitney test for two groups and the Kruskal-Wallis test for more than two groups. These two tests are analogous to the independent groups t-test for normally distributed data, but are based on data ranks rather than the data values (Zar, 1984; Wilkinson, 1990). The Kruskal-Wallis test will reject the null hypothesis if *any* of the groups are significantly different; nonparametric multiple comparisons were done to identify *which* groups were significantly different (Zar, 1984). The significance level used in evaluating thresholds was alpha equal to 0.05.

Multivariate Regression Models

Multivariate, least squares, linear regression models were calibrated to the study data to show how various wetland and watershed factors combine to effect wetland hydroperiod (Taylor, 1993). Models were developed by: (1) using step regression to identify factors important to the aspect of wetland hydroperiod being investigated, (2) determining the best way to quantify or express this factor, (3) evaluating model fit, and (4) examining the sensitivity to the predictor variables. The data for each wetland were weighted by sample size when appropriate; mean water level fluctuation was weighted by the total number of observations used in its calculation while the length of the dry period and seasonal water level fluctuations were weighted by the number of years used in their calculation.

The fit of the regression models was evaluated through various methods: the coefficient of determination (r^2) and the F-ratio, which compares the explanation provided by each predictor to the residual associated with each observation. The final step in the generation of the multiregression models was to examine the sensitivity of each predictor variable. The standardized coefficient of each predictor variable provides a way to compare the significance of the variables (Wilkinson, 1990). Additionally, variables were removed from the final model one at a time to determine their effect on the model r^2 and the standard error of the estimate.

Data Collection and Analysis for the Wetland Water Balance

In the detailed study of two wetlands (Bellevue 3I and Patterson Creek 12), a complete water balance was performed (Reinelt et al., 1993). This consisted of independent measurements of the following components: precipitation, evapotranspiration, surface inflow, surface outflow, groundwater exchange, and change in wetland storage. Precipitation was measured using an event recorder connected to a tipping-bucket gauge that recorded each 0.25 mm of rainfall. Continuous water flow measurements were taken at the inlet and outlet of the two wetlands using a variety of different techniques (Reinelt et al., 1990).

Shallow (1.2 to 4 m) and deep (6 to 18 m) piezometers were installed at both wetlands to aid in the estimation of groundwater flow using Darcy's Law (see Chapter 1). The hydraulic conductivity (K) of the underlying aquifer at both wetlands was determined using variable head pump and slug tests as described by Cedergren (1978) and Chapuis (1989). Piezometric head measurements were taken regularly to determine the hydraulic gradient (Surowiec, 1989). Control volumes were defined around each wetland to facilitate estimation of the horizontal and vertical components of groundwater flow.

Evapotranspiration was estimated from pan evaporation data from the Washington State University Extension Service Puyallup station representing the Puget Sound Lowlands region. Adjustments were made for differences between pan evaporation, open-water evaporation, and evapotranspiration by plants. Daily changes in wetland water depth (and corresponding storage volume) were estimated by correlating daily outflow data with regular gauge (water depth) readings. Storage volumes were determined for different water levels by multiplying the areal water coverage by water depth.

Identifying and describing seasonal differences in the hydrologic balance of the two wetlands was one objective of the study. Seasons were defined and analyzed by two classification methods. The first method included simply wet (October - March) and dry (April - September) seasons. The second method defined four seasons based on the climate of the Puget Sound region: wet (November-February), dry (June-September) and two transition (March-May; October) seasons. The division of data by season allowed for comparison of changes in the relative contributions of different inputs and outputs.

RESULTS AND DISCUSSION

Wetland Hydrology and Water Level Fluctuation

Three parameters were used to examine hydrologic conditions in the wetlands: water depth, water level fluctuation (WLF), and length of summer dry period. The minimum, maximum and range of water depths at the gauges are given in Table 8-1. Also given are the mean (according to equation 4 of Chapter 1) and maximum WLF, and days of summer drying in the wetland. Water depth and WLF varied widely for the 19 wetlands.

Table 8-1 Wetland watershed, outlet and hydrologic characteristics.

Wetland Name	Forest (%)	Imperv. Area (%)	Outlet Constr.	Range of Water Depth (m)	Mean WLF (m)	Max. WLF (m)	Mean Dry Period (days)	Calculated Mean WLF (m) Using Multiple Regression
AL3	73.9	3.4	1	0.00-0.62	0.07	0.31	101	0.21
MGR36	88.8	2.7	0	0.13-0.74	0.07	0.26	0	0.08
JC28	34.4	19.3	0	0.00-0.32	0.08	0.17	74	0.14
RR5	62.4	3.2	0	0.02-0.52	0.09	0.24	0	0.11
SC4	46.1	11.8	0	0.00-0.30	0.10	0.15	125	0.13
SR24	100.0	2.0	0	0.00-0.67	0.11	0.23	32	0.07
NFIC12	100.0	2.0	1	0.00-0.53	0.13	0.30	189	0.17
ELS61	0.0	3.9	0	0.05-0.84	0.14	0.33	0	0.19
PC12	75.2	3.9	1	0.20-1.19	0.14	0.84	0	0.20
BBC24	89.5	2.8	0	0.07-0.60	0.14	0.20	0	0.08
TC13	100.0	2.0	0	0.00-0.72	0.16	0.31	156	0.07
ELW1	0.0	19.9	0	0.00-0.66	0.22	0.44	19	0.19
HC13	76.6	3.6	1	0.09-1.56	0.24	0.41	0	0.20
SC84	20.1	15.9	0	0.00-1.08	0.26	0.53	62	0.16
FC1	14.7	30.8	0	0.11-1.01	0.28	0.62	0	0.38
LCR93	44.1	3.9	1	0.00-0.81	0.28	0.57	61	0.24
ELS39	0.0	28.0	1	0.00-1.61	0.46	1.29	151	0.51
B3I	0.0	54.9	1	0.63-2.37	0.57	1.54	0	0.51
LPS9	0.0	21.8	1	0.00-1.72	0.60	1.47	85	0.51

The largest range of water levels, as well as mean and maximum WLFs were found at B3I and LPS9, where the basins have among the highest percent of impervious area of any of the study sites and the wetland outlets are constricted (see B3I and LPS9 in Figure 8-1). Those wetlands with 90 percent or more forested cover and less than 3 percent impervious surfaces generally exhibited lower water ranges and low WLFs (see BBC24 and SR24 in Figure 8-1). As can be seen from Figure 8-1, these trends of low or high WLF are independent of whether the base level condition in the wetland is stable or fluctuating. Wetland JC28 was an exception to the normal relationship between high impervious area and high WLF; this was because the watershed soils are predominantly glacial outwash (highly permeable soils), thus reducing runoff volumes.

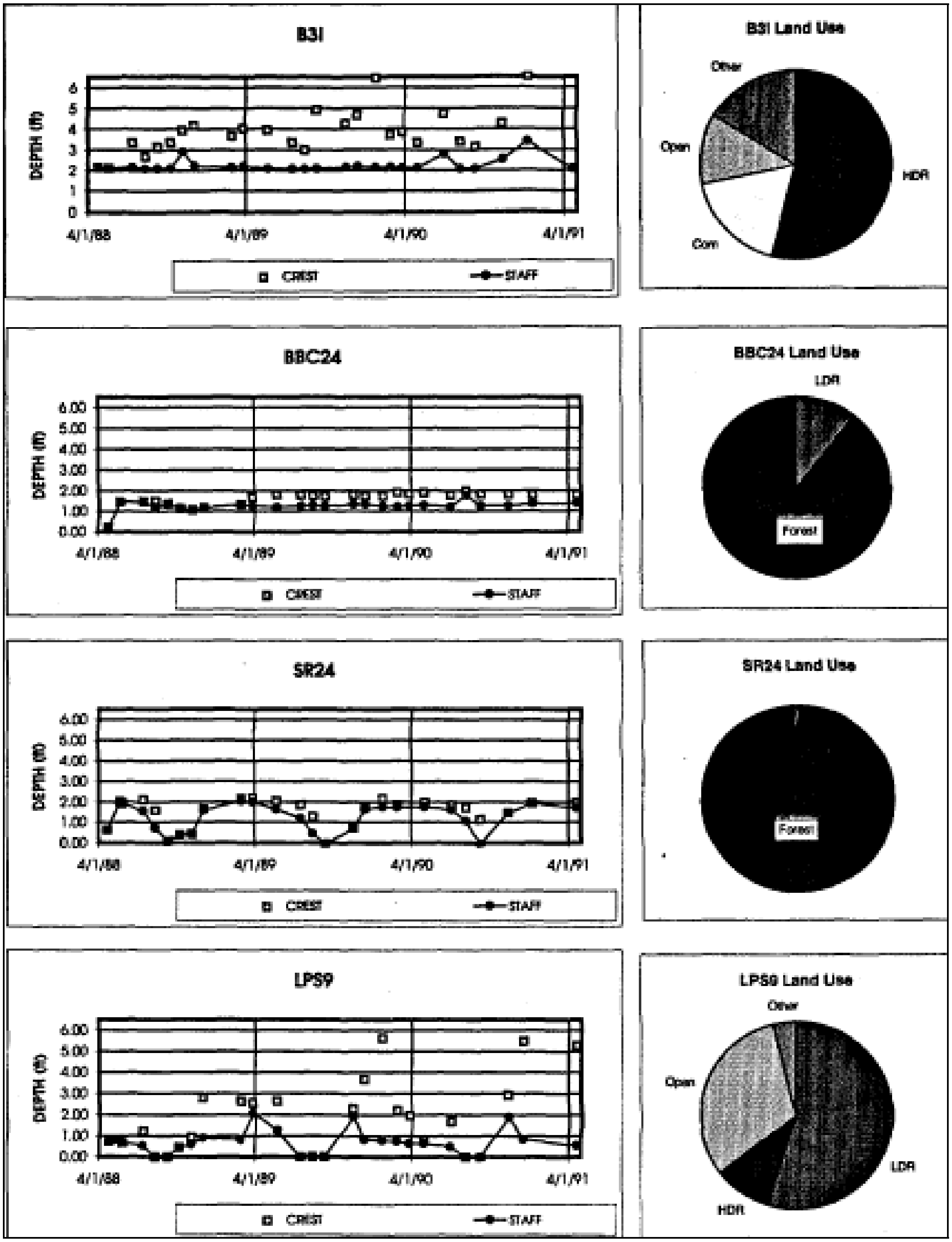

Figure 8-1. Wetland hydrographs (base and crest levels) and land use.

Threshold Level Analysis

Scatterplots of the event water level fluctuation data were plotted against the various wetland and watershed morphological parameters. Some of these plots showed apparent thresholds that signify a range of the hydrologic parameter where the event fluctuation data are similarly distributed. Within these ranges, characteristics such as the mean and variance of the data were approximately equal. Table 8-2 shows significant threshold levels (P < 0.05 for all thresholds) and characterizes the water level fluctuation data within each range.

Table 8-2 Parameters significant to wetland water level fluctuation.

Parameter	Range (a)	Mean WLF (m)	Std. Dev. (m)	n
Forested area	forest = 0%	0.384	0.338	97
	forest ≥ 14.7%	0.151	0.138	224
Total impervious area	2.0 ≤ TIA ≤ 3.5%	0.105	0.072	105
	3.5 < TIA ≤ 20%	0.176	0.151	143
	21.8 < TIA ≤ 54.9%	0.478	0.348	73
Outlet constriction	low to moderate	0.148	0.119	198
	high	0.34	0.33	123
Wetland-to-watershed area ratio	0.005 ≤ W/Ws ≤ 0.04	0.304	0.301	169
	0.05 < W/Ws ≤ 0.44	0.129	0.091	152
Watershed soils index	3.9 ≤ WSI ≤ 4.1	0.247	0.279	209
	4.2 < WSI ≤ 5.8	0.174	0.143	112

(a) The upper and lower bounds are the maximum and minimum values of the parameter within the range.

A key index relating urbanization to WLF was basin imperviousness. Two thresholds were identified in the relationship between event WLF and impervious area (Figure 8-2). The first threshold (3.5% impervious area) may represent the level of urbanization where scattered clearing of forests is added to by larger developments, and storm drainage systems that route runoff to the wetland are developed. Development within the first range was usually below 15% low density residential (LDR), whereas the second range begins around 24% LDR. Wetlands HC13 and LCR93 (in the second range) were exceptions to this tendency, because of the large proportion of their watersheds that were clear-cut. The second threshold (20% impervious area) may represent the point that changes in storm runoff caused by urbanization (e.g., flow volumes, flashiness) become dominant over the other factors that influence wetland hydroperiod.

The amount of forested area in a watershed was expected to be inversely related to event WLF. Forests store rainwater in the canopy, return water to the atmosphere through evapotranspiration, and typically have a highly permeable litter zone on the soil surface, all of which act to reduce storm runoff volumes and reduce the delivery rate to receiving waters. Furthermore, in an area such as the Puget Sound lowlands which are primarily forested until urbanization begins, forested coverage is an index of urban development. The expected relationship was observed (Figure 8-2). Sites with highly constricted outlets were expected to exhibit higher event WLF than those with less constricted outlets due to backwater effects. Figure 8-2 shows that this trend was observed, particularly in the maximum levels of event WLF.

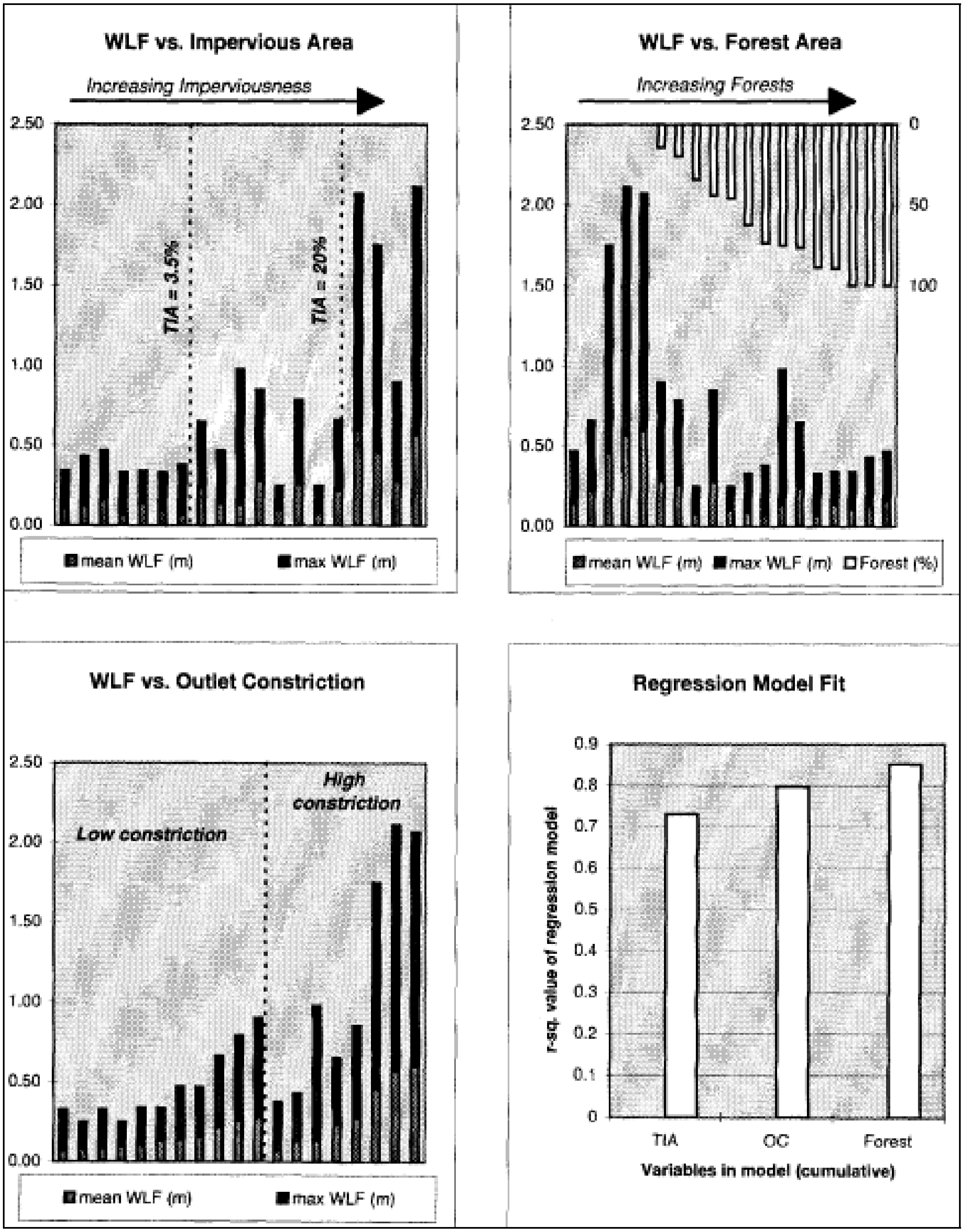

Figure 8-2. Relationships between water level fluctuations and imperviousness, forest area, and outlet constriction.

As shown in Table 8.2, there were two other variables that exhibited trends with wetland WLF: wetland-to-watershed area ratio and watershed soil index (WSI). The wetland-to-watershed ratio can be thought of as a "loading" term. The lower the ratio, the less area available to store storm runoff, resulting in higher event WLF. The threshold observed (ratio = 0.045) corresponds with the recommended ratio for stormwater detention ponds, which is five percent (KCSWM, 1990). The WSI was developed to quantify the soil drainage characteristics; since higher values indicate soils with high infiltration capacity, these values were expected and found to be associated with low event WLF.

Multiple Regression Analyses

Multiple regression analyses were done on the mean event WLF data from 1988 through 1991. The mean WLF data were weighted by the sample size, with the size of the weighted data set consisting of 321 observations. The best model fit was found using three variables: impervious area, outlet constriction, and forested area (see Figure 8-2). The following equation produced the best fit when using percent impervious and forested areas as continuous variables, and outlet constriction as a binary variable (0 or 1):

$$\text{Mean WLF (m)} = 0.145 + 0.0052*(\text{Impervious}) + 0.141*(\text{OC}) - 0.0011*(\text{Forest})$$
$$\text{where } R^2 = 0.790 \text{ and SE} = 0.08 \text{ m.}$$

The model fit explained 79% of the variation in mean event WLF between sites. Residual analysis showed no deviations from the model assumptions. All the parameter coefficients were of the sign (positive or negative) expected. This model was tested in later years using data from 1993 through 1995 and not confirmed (Chinn 1996), however there were some significant differences in the assumptions guiding the selection of data between the two analyses which likely account for the different results.

Dry Period

The length of the summer dry period for the study sites ranged from zero for the sites with stable base flow to nearly 200 days (Table 8-1). A variety of approaches were used to evaluate which factors are important in determining the permanence of a site and the length of the dry period for those sites that dry in the summer. Spearman rank correlations were used to investigate the relation between the mean length of the summer dry periods and morphologic parameters at sites that dry during the summer. Significant negative correlation was found between the length of the dry period and the area of the wetland. The significance of the wetland area is attributable to two factors of the hydrologic balance, evapotranspiration and groundwater exchange. Because the correlation is negative, however, it is assumed that groundwater discharge to the wetlands is driving the relationship.

Hydrologic Characteristics of Two Intensively Studied Wetlands

A summary of the natural and hydrologic characteristics during the study period (1988-90) for the B3I and PC12 wetlands is given in Table 8-3. The hydrologic reactions to storms exhibited by the two wetlands are typical of the respective watershed land uses. The reaction of B3I inlet flows to storms is fast and dramatic. Flows increase almost immediately because of the large impervious land area and piped storm drain system. Similarly, when storms end, the flow recedes quickly to near baseflow conditions. The PC12 inlet flow, on the other hand, reacts relatively slowly to storms, with the receding limb of the hydrograph extending much longer than at B3I. Significant inflows occurred at PC12 only from October to June; however, there was water in the wetland year round.

Table 8-3. Natural and hydrologic characteristics of two wetlands.

Variable (unit)	B3I Wetland	PC12 Wetland
Dominant land type	Urban	Forest
Watershed area (ha)	187	87
Wetland area (ha)	2	1.5
Wetland-to-watershed ratio	0.011	0.017
Total precipitation (mm)	1,813	1,934
Precip. volume (m^3) in drainage area	3.4×10^6	1.7×10^6
Mean daily inlet flow (m^3/s)	0.042	0.021
Maximum daily inlet flow (m^3/s)	0.75	0.22
Days with measurable flow during study	730	493
Total flow during study (m^3)	2.7×10^6	0.9×10^6
Wetland storage volume (m^3)[a]	400-5,000	600-7,000
Runoff/precipitation ratio	0.80	0.53

[a] Wetland storage volume varies depending on season and flow conditions.
(Note: Study period was two years for B3I and 20 months for PC12).

Nearly 80 % of the annual precipitation occurred between October and March. The maximum daily precipitation occurred on January 9, 1990 (approximately 80 mm at both sites). Pan evaporation data from the Puyallup station were used for ET estimates at the wetlands. The measured pan evaporation was greatest from May to August (exceeding 100 mm per month) and least from November to March. The maximum monthly and daily evaporation rates during the study were 160 mm (July 1989) and 16 mm (July 30, 1989), respectively.

Water storage volumes varied from 400 to 5,000 m^3 at B3I and from 600 to 7000 m^3 at PC12. Generally, changes in storage volume at B3I were short-term (on the order of hours) and directly related to storm events. Baseflow rates and water storage were comparable during the wet and dry seasons. At PC12, on the other hand, storage volumes changed during storm events and by season. Water volumes were greatest during large storms or groups of storms during the late wet season.

The results of the groundwater investigation indicate that both wetlands are discharge zones under most conditions meaning that groundwater discharges to the wetland and becomes surface water. Recharge wetlands, in contrast, replenish groundwater through infiltration of surface water. This was determined by the piezometric head measurements, and given the fact that groundwater flows from areas of high to low head. The head measurements in both wetlands generally increase with depth below the water table (as measured by the deep piezometer clusters) and distance from the wetland, indicating the groundwater flows both vertically and laterally to each wetland. Discharging wetlands have also been documented by other authors (Wilcox et al., 1986; Siegel and Glaser, 1987).

Wetland Hydrology by Season and Wetland

Table 8-4 summarizes the hydrologic inputs and outputs by season for the two wetlands. For both wetlands, surface water outflow accounted for greater than 99 % of the outputs during the study period. Thus, groundwater recharge and ET, the other potential sources of output, were insignificant on an annual basis. This is typical for wetlands that have a low wetland-to-watershed area ratio (1.1 and 1.7 % for B3I and PC12, respectively) and for wetlands that lie in a groundwater discharge area. For wetlands with low wetland-to-watershed ratios, inputs from the larger watershed (i.e., surface water flows) often dwarf the contributions from "in-wetland" components, such as groundwater and ET, because of the relatively small wetland area. Also, if groundwater exhibits mostly a discharge pattern as a result of topography and wetland location, then groundwater recharge is likely a minimal source of water output.

Table 8-4. Summary of hydrologic inputs and outputs by season (all values are in 1000 m^3; percent of total input or output in parentheses).

Wetland/ Season[a]	Precip- itation	Inputs Inflow	Ground- water[b]	Outputs Outflow	Evapo- ration	Error
B3I[c]						
Dry 88	2 (0.6)	289 (80.8)	66 (18.6)	319 (97.0)	10 (3.0)	28 (8.8)
Wet 88-89	12 (1.6)	639 (85.4)	99 (13.2)	762 (99.9)	1 (0.1)	-12 (-1.6)
Dry 89	6 (0.7)	668 (84.5)	116 (14.8)	627 (98.1)	12 (1.9)	150 (23.5)
Wet 89-90	14 (1.4)	863 (90.0)	82 (8.6)	989 (99.9)	0 (0.1)	-29 (-3.0)
Dry 90	2 (0.7)	239 (87.1)	33 (12.1)	231 (99.2)	2 (0.8)	40 (17.5)
Total	36 (1.2)	2,697 (86.1)	398 (12.7)	2,928 (99.2)	25 (0.8)	178 (6.0)
PC12[d]						
Wet 88-89	12 (2.1)	445 (79.5)	103 (18.4)	535 (99.9)	0 (0.1)	23 (4.4)
Dry 89	5 (3.9)	97 (72.4)	32 (23.8)	136 (93.6)	9 (6.4)	-9 (-6.4)
Wet 89-90	11 (2.5)	312 (74.1)	99 (23.4)	373 (99.9)	0 (0.1)	48 (13.0)
Dry 90	1 (2.5)	49 (82.3)	9 (15.2)	62 (97.7)	1 (2.3)	-4 (-6.4)
Total	29 (2.5)	904 (76.9)	243 (20.7)	1,105 (99.0)	11 (1.0)	58 (5.2)

[a] Dry season = April-September; wet season = October-March

[b] Positive groundwater values indicate groundwater discharge to wetlands.

[c] B3I study period: June 1988 - May 1990

[d] PC12 study period: October 1988 - May 1990

Surface water inflows accounted for 86 and 77% of the inputs for B3I and PC12, respectively, on an annual basis. Groundwater discharge to the wetlands accounted for most of the remaining input (13 and 21% for B3I and PC12, respectively). Direct precipitation inputs were quite small in the overall balance. During individual months or groups of months, however, groundwater and precipitation contributed substantially more to the wetland water inputs, particularly at PC12.

Differences also existed in the magnitudes of inputs and outputs for the wet and dry seasons. This was particularly true for precipitation, with 75 to 80% occurring during the wet season, and ET, with approximately 90% occurring during the dry season. At B3I, 60% of annual surface water flow occurred during the wet season, whereas at PC12 this component totaled approximately 80%. At PC12, ET accounted for greater than 50% of the output from July to September 1989 when baseflows were minimal. During the same period, ET at B3I was less than 5% of the output, because of the stable and relatively high baseflow. The direct groundwater input to B3I was fairly steady throughout the year. However, at PC12, nearly 83% of the groundwater contribution to the wetland occurred during the wet season.

Urbanization and Other Factors Affecting Wetland Hydrology

The dynamics of wetland hydrology are governed by factors that may change seasonally or slowly over time. Seasonal changes result from variation in climate (e.g., precipitation, solar radiation), plant growth and groundwater recharge. Longer-term changes result from human activities, including watershed development, groundwater withdrawal, wetland outlet modification or drainage activities. Although this study was not designed to investigate change over time, some general conclusions can be drawn from comparisons between urbanized and nonurbanized catchments.

The runoff-to-precipitation ratios were 0.80 and 0.53 for B3I and PC12 wetland watersheds, respectively. Thus, more water is captured in the nonurbanized catchment, resulting in less runoff to the wetland. Potential pathways for the difference in water reflected in these numbers are ET, regional groundwater recharge and withdrawal in the watershed itself. The ET in the forested nonurbanized catchment of PC12 is undoubtedly greater than in the developed urbanized catchment of B3I. Regional or deep groundwater recharge within the PC12 watershed is also likely greater than in the case of B3I, because of milder topography and less impervious surface. Finally, groundwater withdrawal to meet local water needs is likely more significant in the PC12 watershed.

Water level fluctuation is perhaps the best single indicator of wetland hydrology, because it integrates nearly all hydrologic factors. The mean WLFs were 0.15 and 0.49 m for the PC12 and B3I wetlands, respectively. The higher mean occasion WLF at B3I reflects the effect of many factors, including its urbanized catchment, piped storm drain system and constricted outlet. The maximum study period WLFs were quite similar. This apparent discrepancy occurred because of the evaporation and lowered water level in PC12 during the summer. In summary, both wetlands experienced similar long-term fluctuations; however, the urban wetland was exposed to much more frequent and greater WLFs.

Hydrologic Components Error Analysis

By measuring all components of the water balance shown in Equation 1 (Chapter 1), it was possible to determine error estimates for the seasonal balances. The seasonal errors (Table 8-4) ranged from -6.4 to +23.5% of the total hydrologic outputs. For the entire study period, the errors were 6.0 and 5.2% for B3I and PC12, respectively. This reduction reflects the cancellation effect of positive and negative errors when summed over a longer time period. Generally, the larger percentage errors occurred during the dry seasons, reflecting the increased importance of groundwater inputs and ET in the overall balance at that time.

The type and magnitude of the errors associated with hydrologic or water balances may be characterized in several ways. These include errors associated with the: (1) equipment (e.g., inaccurate calibration), (2) measurements (e.g., representativeness of measurement), (3) calculations (e.g., weak stage-discharge correlations, groundwater calculations), and (4) summation of balance components. It is important to note that these errors can improve or degrade the apparent accuracy of a water balance depending on the interaction between errors.

If precautions are taken to minimize the errors associated with the equipment, measurements and calculations, and if all components are included in a water balance, it is possible to reduce potential errors greatly. An assessment of the importance of the different components of a balance is a critical task in this process. Because of the above-noted errors, it is recommended that no components of a balance be estimated by difference. Using this technique simply masked the errors in the unknown or unmeasured component (usually ET, groundwater, or both).

CONCLUSIONS

The quantity of stormwater entering many palustrine wetlands in the Puget Sound region has changed as a result of rapid development in urbanizing areas. The purpose of this chapter has been to characterize the hydrology of wetlands affected by urban stormwater, in comparison to unaffected or forested systems. This information, then, may help to explain observed changes in wetland soils, plants and animals over time. Additionally, if observed effects of stormwater on wetlands can be documented, it may be possible to mitigate these effects through watershed controls and stormwater management efforts.

The hydrology of wetlands as measured by water level fluctuation was highly variable. Differences in water level fluctuation were attributed to level of watershed imperviousness, forested cover, and wetland outlet constriction. A multivariate model using these three parameters, calibrated to the study sites, was found to predict water level fluctuations relatively accurately. This model should be verified and tested further using similar data sets from all years of collection in future research efforts.

For the two study wetlands, surface water inflow and outflow were the dominant components in the water balance on an annual basis. It was concluded that this is typical for wetlands with low wetland-to-watershed ratios. The ET was insignificant in the overall water budget on an annual basis; however, it was the major source of water output from the PC12 wetland from July to September, when outflows were minimal. Both wetlands were identified as primarily groundwater discharge zones, with groundwater contributing significant inputs. Like ET, the influence of groundwater was greatest at PC12 during the summer months.

Differences were also identified in the hydrology of both wetlands because of the level of watershed urbanization. In the urbanized watershed, a greater proportion of the precipitation was realized as surface inflow to the wetland. Storm runoff was delivered more quickly and in greater short-term volumes to the urban wetland. The result of these conditions was greater and more rapid water level fluctuations in the urban wetland. This characteristic would probably be replicated in most wetlands where development occurs in the watershed.

REFERENCES

Cedergren, H.R. 1978. Seepage, Drainage and Flow Nets. John Wiley and Sons, Inc., New York, N.Y.

Chapuis, R.P. 1989. Shape factors for permeability tests in boreholes and piezometers. Ground Water, 27(5):647-654.

Chin, N. T. 1996. Watershed Urbanization Effects on Palustrine Wetlands: A Study of the Hydrologic, Vegetative, and Amphibian Community Response During Eight Years. M.S.C.E. thesis, University of Washington, Department of Civil Engineering, Environmental Engineering and Science Program, Seattle, WA.

King County Surface Water Management. 1990. King County Surface Water Design Manual. King County Department of Public Works, Seattle, WA.

Mitsch, W.J. and Gosselink, J.G. 1993. Wetlands, 2nd Ed.. Van Nostrand Reinhold Co., New York.

Reinelt, L.E. and Horner, R.R. 1990. Characterization of the Hydrology and Water Quality of Palustrine Wetlands Affected by Urban Stormwater. King County Resource Planning, King County, WA.

Reinelt, L.E., Horner, R.R., and Wittgren, H.B. 1990. Removal of sediment and nutrients in palustrine wetlands receiving runoff from urban and nonurban watersheds. In Reinelt, L. Nonpoint Source Water Pollution Management, Linköping Studies in Arts and Sciences 57, ISBN 91-7870-708-0.

Reinelt, L.E., Surowiec, M.S., and Horner, R.R. 1993. Urbanization effects on palustrine wetland hydrology as determined by a comprehensive water balance. (Manuscript).

Siegel, D.I. and Glaser, P.H. 1987. Groundwater flow in a bog-fen complex, Lost River Peatland, Northern Minnesota. J. of Ecology, 75:743-754.

Surowiec, M.S. 1989. An Hydrogeologic and Chemical Characterization of an Urban and Nonurban Wetland. M.S.E. Thesis. Department of Civil Engineering, University of Washington.

Taylor, B.L. 1993. The Influence of Wetland and Watershed Morphological Characteristics on Wetland Hydrology and Relationships to Wetland Vegetation Communities. M.S.C.E. Thesis. Department of Civil Engineering, University of Washington.

Wilcox, D.A., Shedlock, R.J. and Hendrickson, W.H. 1986. Hydrology, water chemistry and ecological relations in the raised mound of Cowles Bog. J. of Ecology, 74:1103-1117.

Wilkinson, L. 1990. SYSTAT: The System for Statistics. SYSTAT, Inc., Evanston, IL.

Zar, J.H. 1984. Biostatistical Analysis. Prentice Hall, Englewood Cliffs, N.J.