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URBANIZATION, FLOOD FREQUENCY, AND SALMON ABUNDANCE IN PUGET LOWLAND STREAMS[1]

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ABSTRACT: Urbanization history and flood frequencies were determined in six low-order streams in the Puget Lowlands, Washington, for the period between the 1940/50s and the 1980/90s. Using discharge records from USGS gauging stations, each basin was separated into periods prior to and after urban expansion. Four of the study basins exhibited significant changes in urbanized area, whereas two of the study basins exhibited only limited change in urbanized area and effectively serve as control basins. Each of the basins that experienced a significant increase in urbanized area exhibited increased flood frequency; pre-urbanization 10-year recurrence interval discharges correspond to 1 to 4-year recurrence interval events in post-urbanization records. In contrast, no discernible shift in flood frequency was observed in either of the control basins. Spawner survey data available for three of the study basins reveal systematic declines in salmon abundance in two urbanizing basins and no evidence for decreases in a control basin. These data imply a link between ongoing salmon population declines and either increased flood frequency or associated changes in habitat structure.
(KEY TERMS: urban hydrology; watershed management; hydrobiology.)

INTRODUCTION

The construction of impervious surfaces during urbanization alters runoff generation mechanisms by reducing the effective permeability of the soil. The associated increase in rapid runoff by overland flow leads to increased flood flows (e.g., James, 1965; Hollis, 1975), which alter stream morphology through increased channel width or depth (e.g., Hammer, 1972; Leopold, 1973; Graf, 1975; Gregory and Park, 1976; Booth, 1990, 1991). Although such effects of urbanization on channel morphology are well known, significant changes in the discharge regime also affect other processes that influence stream ecology (Booth and Reinelt, 1993). For example, increased discharge associated with urbanization increases the frequency and depth of streambed scour (Booth, 1990), and alteration of riparian zones can influence stream shading and in-channel habitat structure. Significant changes in stream processes can particularly impact aquatic fauna maladapted to post-urbanization habitat characteristics or disturbance regimes.

The influence of dams, overfishing, and habitat loss are thought to have contributed to historic decimation of anadromous salmon runs in the Pacific Northwest (Nehlsen *et al.*, 1991). It has proven difficult, however, to isolate the relative impacts of these factors because of both geographic variability and insufficient data. Much attention focuses on the Columbia River runs because of the controversy over changes in dam management (e.g., Schwiebert, 1977), but runs in coastal areas and the Puget Lowlands, which lack dams, are also declining (Palmisano *et al.*, 1993). In these areas habitat loss and degradation, overfishing, and competition from hatchery stocks are among the factors influencing population declines. While much attention has focused on the impact of forest management (e.g, Meehan, 1991), the role of urbanization in habitat loss and hydrologic change has received relatively little attention. In notable exceptions, Booth (1990) modeled the effects of urbanization on flood frequency and predicted that urbanization could convert 10 year discharges to 2-5 year discharges in the Puget Sound region, and Lucchetti and Fuerstenberg (1992) related urbanization-driven hydrologic and habitat changes in the Puget Lowlands to adverse effects on fish populations. Here we examine evidence for changes in flood frequency in urbanizing drainage basins of the Puget Lowlands and find both changes in discharge recurrence intervals comparable to those predicted by

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Booth (1990), and evidence for associated declines in salmon abundance.

STUDY AREAS AND METHODS

Study areas were selected by examining U. S. Geological Survey (USGS) gauging station records to identify Puget lowland streams with hydrologic records extending from prior to until after substantial pulses of urbanization. Six basins with sufficient hydrologic records were located in the eastern Puget Sound area (Figure 1). Four streams lie within basins that became urbanized (Flett, Juanita, Mercer, and Swamp creeks) and two streams lie within basins that did not (Coal and May creeks), and therefore serve as a control group.

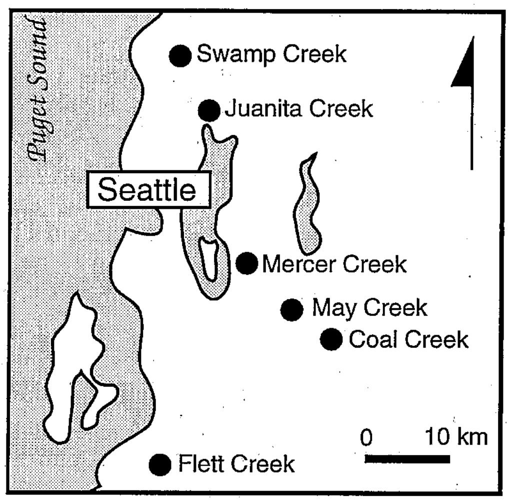

Figure 1. Location of the Study Basins Within the Puget Sound Region.

We compared trends in discharge recurrence intervals through periods of urban growth to determine whether discharge regimes changed as a result of urbanization. We used USGS annual peak discharge data to compare pre- and post-urbanization hydrologic records for each basin by separating data into subrecords for the periods before and after significant increases in the density of urban development. The year of separation between these subrecords was determined based on the length of the hydrologic record and the sequence of development portrayed on topographic maps, as discussed below. Discharge recurrence intervals (RI) measure the probability that a given discharge will occur in any one year. Generation of a discharge recurrence interval relationship involves dividing the relative rank of each annual maximum discharge in the period of record by one more than the total years of record (e.g., Dunne and Leopold, 1978). We hypothesized that a correlation existed between increased urban area and discharge recurrence intervals. Conversely, flood frequency for basins that experienced little increase in urban area should either remain unchanged, or reveal systematic biases in storm size or longer-term changes in weather patterns for the periods under comparison.

For the purpose of this study, urbanized areas were considered as areas so identified on USGS topographic maps, which provided a surrogate measure of percent impervious area. More direct determinations of the proportion of impervious areas within urbanized zones (e.g., field calibration of mapping from aerial photographs) required resources beyond the scope of this project. The urbanized area within each basin was measured from depictions on USGS 7.5' topographic maps at intervals of every 5 to 18 years depending upon the frequency of map updating. Urban areas include dense residential (closely spaced single family homes and housing complexes), urban (commercial building complexes and city blocks), and industrial (airports and factories) land use. Dispersed dwellings were not considered urbanized because of their relatively small percentage of impervious area. Hence our depictions of urbanized areas provide a conservative portrayal of the change in impervious area in the study basins.

Trends in salmon populations were also examined for each basin using Washington State Department of Fisheries and Wildlife salmon spawning ground database. Each entry in the survey data base consists of the total number of fish observed during a visit to a stream reach; we combined data for chinook, coho, and sockeye salmon into an index of total salmon abundance. Because the number of visits per year varied widely both among streams and through successive years, we used the annually averaged number of fish observed per field visit as a metric for overall fish abundance. Also, only years when fish were observed were included in our analysis, which was limited to the three of the six study basins for which sufficient data existed to examine trends in salmon abundance. Two of these basins (Flett and Swamp creeks) experienced significant urbanization while the third (May Creek) did not.

RESULTS

The study basins exhibited a wide range in the extent of the changes in urbanized area between the pre- and post-urbanization periods. The four basins that experienced rapid urbanization showed significant changes in discharge recurrence intervals, whereas both basins that were only marginally urbanized showed little change. Although the spawner data are sparse, they support a link between altered flood frequency and salmon abundance.

Flett Creek

Urbanization of the Flett Creek basin occurred primarily by development of large tracts in the northern portion of the basin and progressively moved south. Flett Creek experienced a total change in urban area of 30 percent of the basin from 1960 to 1981 (Figure 2a). Basin development slowed between 1968 and 1973 and experienced only an additional 7 percent growth by 1981. The hydrologic record extended from 1960-1994, and we separated pre- and post-urbanization records by the interval between 1968-1973 (Table 1). Due to lack of earlier data, the period that we considered as the pre-urbanization discharge record actually records urbanizing conditions. The pre-urbanization 10-year discharge is anomalous and likely reflects the effect of a more than 50-year storm during a short period of record. Consequently, we have omitted this event from our analyses. Discharge recurrence intervals for Flett Creek changed dramatically between the two periods (Figure 3). A flood with an extrapolated recurrence interval of 10 years before 1968 increased in frequency to a 1.5-yr event after 1973.

TABLE 1. Division of the Hydrologic Record for Each Basin Into Periods Before and After Urbanization.

Drainage Basin	Before	After
Flett Creek	1960-1968	1973-1994
Juanita Creek	1964-1972	1973-1990
Mercer Creek	1956-1968	1974-1994
Swamp Creek	1964-1973	1981-1990
Coal Creek	1964-1970	1972-1979
May Creek	1946-1967*	1968-1979

*Incomplete record.

Juanita Creek

Dense urban development occurred in the Juanita Creek basin between 1950 and 1983. During this period, the drainage basin went from 5 percent to 42 percent urbanized, experiencing the most rapid urban growth between 1968 and 1973 (Figure 2b). The hydrologic record extended from 1964 to 1990. Because a hydrologic separation beginning in 1968, prior to the most dramatic increase in urban growth, would allow only five years of record to compare with the post urbanized record, we separated the hydrologic record between 1972 and 1973 (Table 1). The period from 1964-1972 represents pre-urbanization conditions and the period from 1973-1990 represents post-urbanization conditions. Discharge recurrence intervals for these two periods record that Juanita creek experienced a dramatic increase in flood frequency following urbanization (Figure 3). As for Flett Creek, a pre-urbanization discharge with a recurrence interval of 10 years had a post-urbanization recurrence interval of 1.5 years.

Mercer Creek

The Mercer Creek basin experienced the most dramatic urbanization of the six study areas, with a change from 1 percent urbanized area in 1950 to 65 percent in 1983. Steady urban growth in Mercer Creek during 1950-1973 accelerated between 1973-1983 (Figure 2c). The hydrologic record extends from 1950-1994. We considered the pre-urbanization period to be before 1969 and post-urbanization from 1974 to 1994 (Table 1). A pre-urbanization 20-yr recurrence interval discharge had a 1.1 yr recurrence interval for the period from 1974 to 1994 (Figure 3).

Swamp Creek

Urban areas in the Swamp Creek basin grew steadily from an initially small portion of the basin during 1953-1968. Growth decelerated during 1968-1973, and accelerated from 1973 to 1981 (Figure 2d). The hydrologic record spanned 1964 to 1990; we represented the pre-urbanized portion of the record as the period from 1964 to 1973 and the post-urbanization record as that from 1981 to 1990 (Table 1). The average of the total urbanized area in the basin changed by 15 percent between the pre- and post-urbanization periods. A flow with a 10-year recurrence interval between 1964-1973 became a 3.6-year event in the period between 1981-1990 (Figure 3).

Coal Creek

The basin of Coal Creek underwent relatively steady urbanization from < 1 percent to 14 percent of

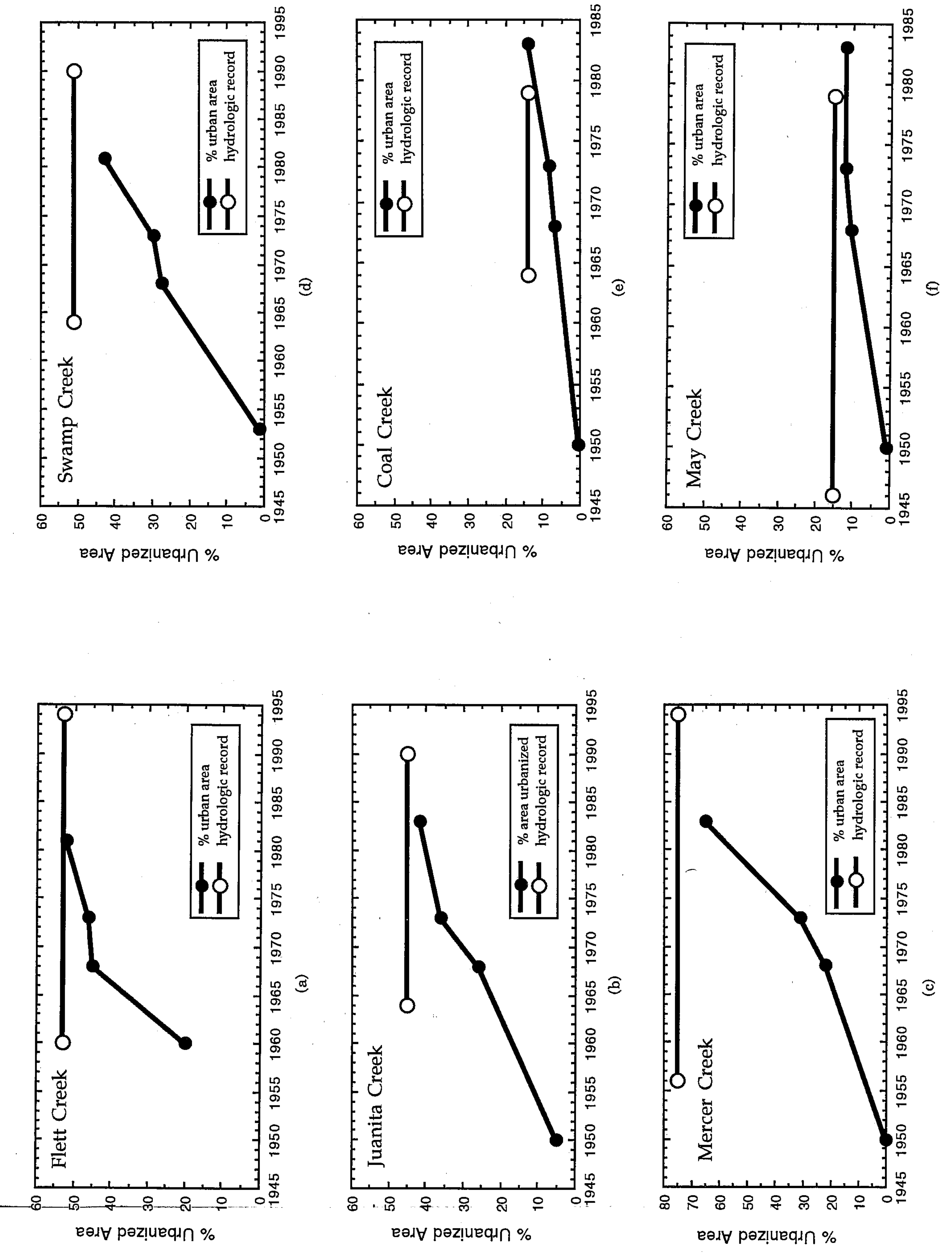

Figure 2. Percentage of Urbanized Area Through Time and the Duration of the Hydrologic Record for the Study Basins.

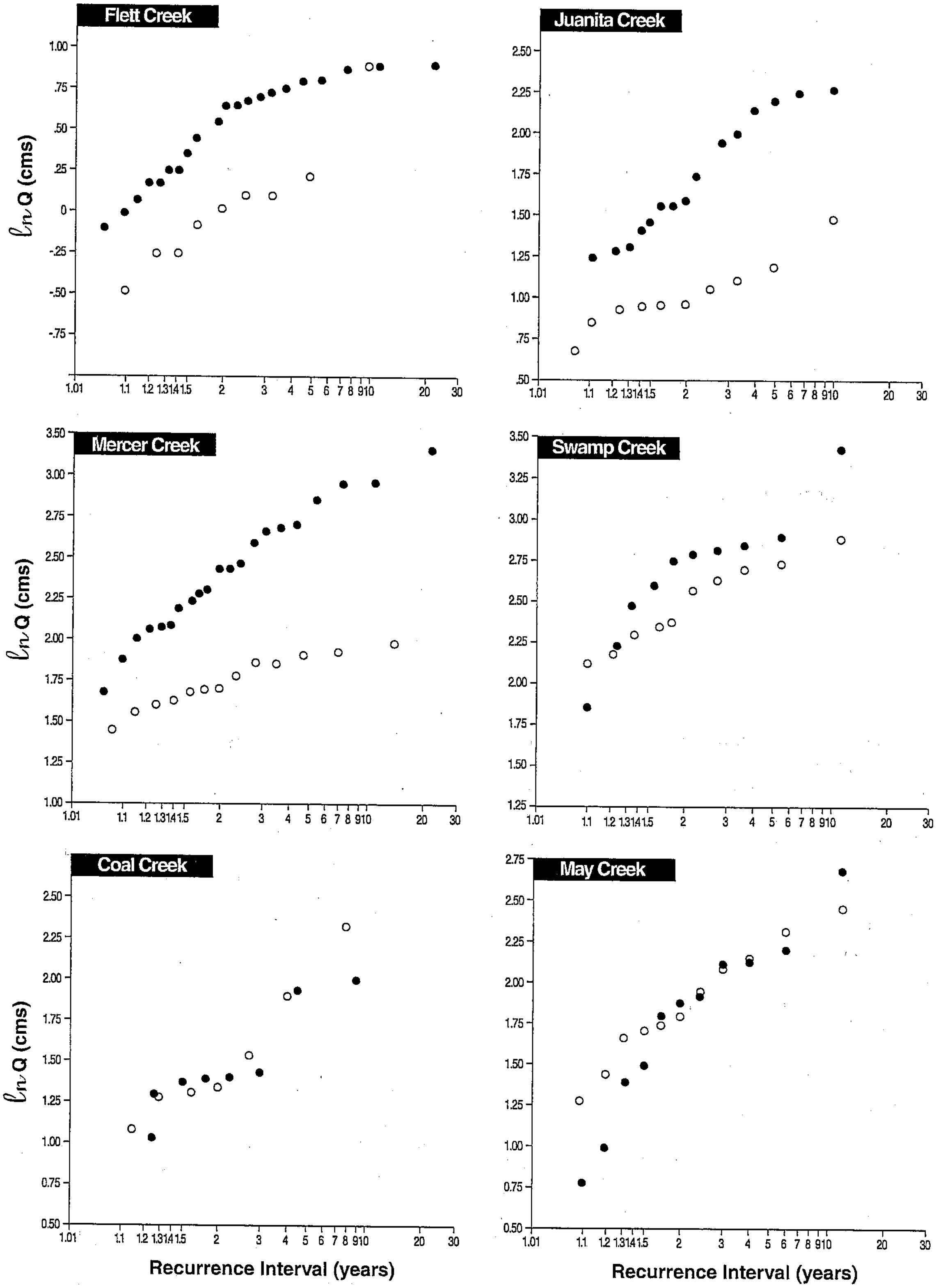

Figure 3. Pre- and Post-Urbanization Discharge Recurrence Interval Relations for the Study Basins.

the basin from 1950-1983. The hydrologic record extends from 1964-1979 (Figure 2e). Because of the limited hydrologic record and little change in urban area between 1950-1983, the hydrologic break was imposed in the middle of the record in 1971, which was discounted from the record (Table 1). Coal creek shows no measurable increase in the return frequency of flood flows for the periods 1964-1970 and 1972-1979 (Figure 3).

May Creek

The extent of urbanized areas in the May Creek basin increased from 1 percent in 1950 to 11 percent in 1968, with little or no increase until the latest map edition of 1983 (Figure 2f). We therefore divided the hydrologic record into a pre-urbanization period from 1946 to 1967 and a post-urbanization period of 1968-1979 (Table 1). May Creek also showed no discernible hydrologic change between the earlier and later records (Figure 3).

Hydrologic Change

The ratio of pre- to post-urbanization discharges exhibited a systematic decrease with increasing urbanized area (Figure 4). Although based on a limited sample size, least squares linear regression indicates that the change in urbanized area can explain 83 percent and 95 percent of the variance in the 2-year and 10-year discharge recurrence intervals in the study basins. These trends confirm that the magnitude of hydrologic change scales with the extent of drainage basin urbanization. Although there is no clear threshold in the extent of urbanization necessary to trigger hydrologic change, no detectable change is evident in the two watersheds that experienced a less than 14 percent increase in urbanized area.

We also examined temporal variation in annual rainfall in order to account for the varying time periods included in the pre-and post-urbanization hydrologic records for each drainage basin. The lack of post-1980 data for the control basins could mask systematic temporal differences in rainfall that may explain the observed shift in flood frequency in the urbanized drainage basins. Two lines of evidence, however, suggest that this is not the case: (1) the annual rainfall record at the Seattle-Tacoma rain gauge reveals a weak declining trend rather than any systematic post-1980 increase (Figure 5); and (2) the mean annual rainfall was greater in the period before urbanization than in the post-urbanization period for each drainage basin (Table 2). Hence, the observed changes in discharge recurrence intervals are likely attributable to basin urbanization.

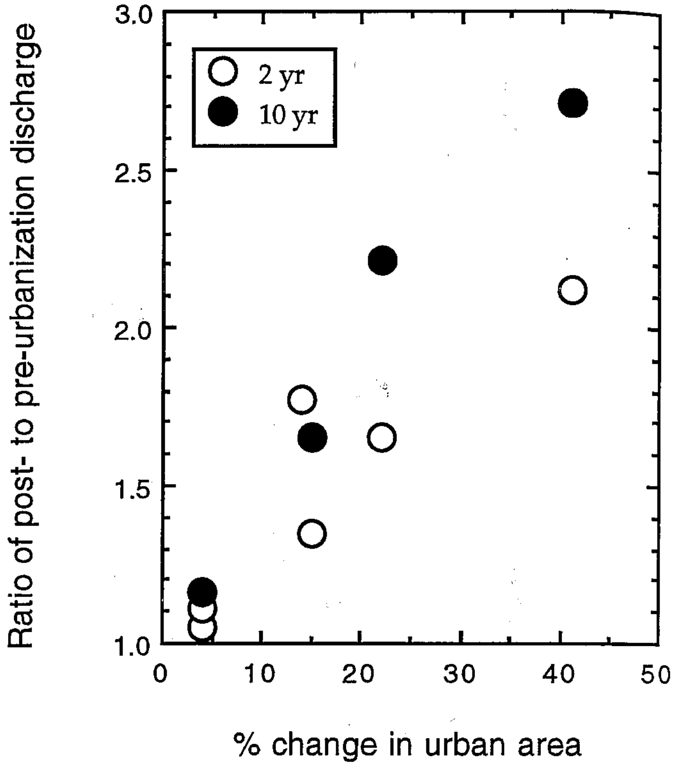

Figure 4. Ratio of the Post-Urbanization to Pre-Urbanization Discharge for 2 and 10-Year Recurrence Interval Flows Versus the Percentage Change in Average Urbanized Area. Least squares linear regression of the data yields $y = 1.052 + .027x$ ($R^2 = 0.83$) for the 2-year discharge and $y = 1.066 + .042x$ ($R^2 = 0.95$) for the 10-year discharge.

Salmon Abundance

Salmon abundance decreased through time for both Swamp Creek and Flett Creek, whereas no clear trend is apparent in data from May Creek (Figure 6). Excluding data from years with ≤ 2 field visits in a year does not alter these general trends. Least squares linear regression of the log of fish abundance versus time yields weakly correlated, but significant trends for Swamp and Flett Creeks, and an insignificant trend for May Creek. Note that the systematic curvature in the regression residuals apparent from examination of the data from Swamp Creek (Figure 6a) reveal systematic deviations from a simple semi-log linear population decline. Although great annual variation in salmon abundance is to be expected, these systematic trends provide evidence of declining

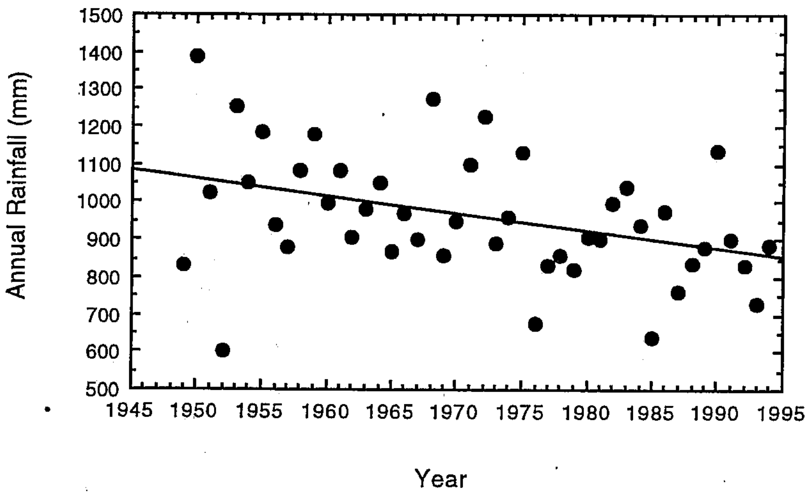

Figure 5. Annual Rainfall Record for the Sea-Tac raingauge (ID No. 7473). Least squares linear regression yields y = 0.0001 - 4.5868 x (R^2 = 0.14).

trends in the two urbanized drainage basins and do not suggest comparable declines in a marginally urbanized catchment.

TABLE 2. Mean and Standard Deviation of Annual Rainfall for Each Basin in the Periods Classified as Before and After Urbanization.

Drainage Basin	Before (mm)	After (mm)
Flett Creek	1,004 ± 122	888 ± 126
Juanita Creek	1,022 ± 152	898 ± 134
Mercer Creek	1,009 ± 121	889 ± 129
Swamp Creek	1,009 ± 149	911 ± 143
Coal Creek	982 ± 145	925 ± 178
May Creek	1,009 ± 173	965 ± 181

DISCUSSION

The systematic relation of increased urban area to changes in flood frequency implies a causal relation through increased runoff from impervious areas. The unchanged flood frequency in the two control basins supports this interpretation. Also, the record of annual rainfall for Seattle shows no systematic increase in precipitation that might explain the increased runoff from the four urbanized basins. Actually, the record shows the contrary; annual rainfall generally decreased from the 1940s through 1980s. The period from the 1970s through 1990s, when discharge recurrence intervals were higher, correspond to the post-urbanization category for most basins. As the trend in runoff expected to result from this is the opposite of that observed, we can reject systematic climatic fluctuations for the post-urbanization increase in flood frequency. We suggest that these lines of evidence leave little doubt that the observed changes in flood frequency arose from urbanization of the study watersheds.

Data on fish abundance in the Puget Lowlands are sparse and incomplete. Spawner surveys, executed mostly on foot, are usually conducted in late autumn, during the period of highest fish density. Nonetheless, our data imply a link between increased urbanization and decreased salmon abundance.If overfishing at sea were primarily responsible for the declining salmon runs in these streams, then the control basins should show trends comparable to the urbanizing basins. Although based on minimal data, declines in salmon populations in these Puget Lowland drainage basins appear related to hydrological or habitat changes that accompany urbanization.

The impact on fish populations associated with urbanization and increased flood frequency could be either direct or indirect and several possible mechanisms could result in the apparent correlation between urbanization and subsequent decreases in salmon abundance. Changes in channel size, morphology, or bed scour can directly impact fish (e.g., Booth and Reinelt, 1993; Montgomery *et al.*, 1996). Increased flow depths can alter velocity refugia and increased streambed scour can disturb developing embryos. Indirect effects of urbanization and changes in flood frequency include the removal of large woody debris by both human intervention and more effective transport by higher peak flows. These indirect effects on habitat characteristics can significantly alter habitat suitability for different species. Lucchetti and Fuerstenberg (1992) documented changes from salmon-dominated to trout-dominated communities in urbanizing Puget Sound basins and attributed the change to indirect effects associated with altered habitat characteristics.

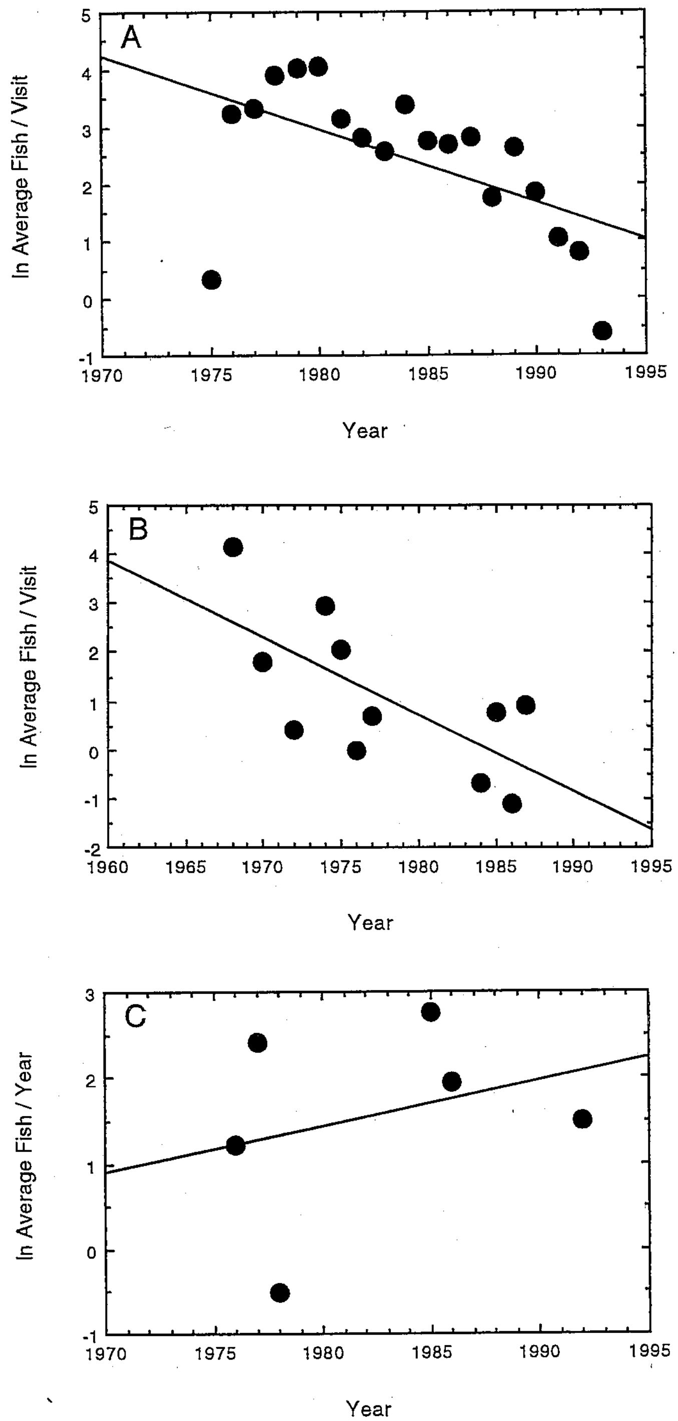

Figure 6. Semi-Logarithmic Plots of Trends in Salmon Abundance Revealed in Spawner Surveys for (A) Swamp Creek [$y = 258.2 - 0.1291x$ (R^2=0.32)]; (B) Flett Creek [$y = 311.1 - 0.1568x$ ($R^2 = 0.47$)]; and (C) May Creek [$y = -104.67 + 0.0538x$ ($R^2 = 0.09$)].

Another mechanism for fish loss from increased discharge is the scour of embryos from the streambed gravel. Scour-chain studies at Kennedy Creek at the southern end of Puget Sound revealed that chum salmon buried their eggs just deeper than the scour depth during an approximately bankfull (i.e., ≈ 1.5 year recurrence interval) flow (Montgomery *et al.*, 1996). Increased flood frequency will increase annual bed scour and, depending upon the timing, may increase egg loss due to scour. Dramatic increases in flood frequency would likely lead to steep declines in species for which embryos develop in streambeds during seasons likely to experience high flows. In rainfall-dominated Puget Lowland streams, salmon spawn in the fall, immediately prior to high winter discharges. In contrast, cutthroat trout spawn in the spring when high flows are much less likely. We suspect that the decline in salmon abundance and change to trout-dominated fish communities in urbanizing Puget Lowland streams arose from both structural habitat change associated with urbanization (Lucchetti and Fuerstenberg, 1992), such as loss of woody debris, and more frequent disturbance of egg-bearing gravel accompanying conversion of infrequent high flows into annual or common events.

Implications

The relation between watershed urbanization and changes in flood frequency holds distinct implications for management of human population growth in the Puget Sound region. This study supports Booth's (1990) prediction of a direct correlation between urban growth and an increase in flood frequency. Although changes of 14 percent or more in total urbanized area result in increased flood frequency, smaller changes in urbanized area appear to yield no resolvable change in discharge recurrence intervals. The changes we report are comparable to those predicted by Booth (1990) based on simulations of runoff generation in response to increasing impervious area accompanying urbanization. The rapid urbanization of many Puget Lowland drainage basins in the 1970s and 1980s likely altered discharge recurrence intervals throughout the region [see Booth (1990, 1991) for an excellent discussion of associated changes in channel morphology]. The apparent influence of urbanization on salmon abundance poses important policy questions, as failure to restrain changes in flood frequency after development may ensure that salmon populations remain depressed or declining.

SUMMARY

The profound alteration of stream flow characteristics in small, rapidly urbanizing drainage basins in the Puget Lowlands provides a good example of a spatially distributed and cumulative effect. Discharge recurrence intervals in basins in which the total urbanized area expanded by more than 14 percent of the basin area changed such that the pre-urbanization 10-year discharge became a 1 to 4-year discharge after urbanization, with the degree of hydrologic change proportional to the degree of urbanization. During the same period, discharge recurrence intervals did not measurably change for discharges in catchments that experienced minor increases in urbanized area. Of the three basins with adequate spawner survey data, the two urbanized basins show decreased salmon abundance, whereas the unurbanized basin shows no discernible trend in fish abundance. Our analysis suggests that rapid urbanization partially explains the ongoing decline in salmon abundance in Puget Lowland streams.

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LITERATURE CITED

Booth, D., 1990. Stream Channel Incision Following Drainage Basin Urbanization. Water Resources Bulletin 26:407-417.

Booth, D., 1991. Urbanization and the Natural Drainage System Impacts, Solutions, and Prognoses. The Northwest Environmental Journal 7:93-118.

Booth, D. and Reinelt, L. E., 1993. Consequences of Urbanization on Aquatic Systems – Measured Effects, Degradation Thresholds, and Corrective Strategies. Watershed '93, American Water Resources Association, pp. 545-550.

Dunne, T. and L. Leopold, 1978. Water in Environmental Planning. W. H. Freeman & Co., New York, New York, 818 pp.

Graf, W. L., 1975. The Impact of Suburbanization on Fluvial Morphology. Water Resources Research 11:690-692.

Gregory, K. J. and C. C. Park, 1976. Stream Channel Morphology in Northwest Yorkshire. Revue de Geomorphologie Dynamique 25: 63-72.

Hammer, T. R., 1972. Stream Channel Enlargement Due to Urbanization. Water Resources Research 8:1530-1546.

Hollis, G. E., 1975. The Effect of Urbanization on Floods of Different Recurrence Interval. Water Resources Research 11:431-435.

James, L. D., 1965. Using a Digital Computer to Estimate the Effects of Urban Development on Flood Peaks. Water Resources Research 1:223-234.

Leopold, L. B., 1973. River Channel Change with Time: An Example. Geological Society of America Bulletin 84:1845-1860.

Lucchetti, G. and R. Fuerstenberg, 1992. Urbanization, Habitat Conditions and Fish Communities in Small Streams of West King County, Washington, USA, With Implications for Wild Management of Wild Coho Salmon. Paper presented at 1992 Coho Salmon Workshop in Nanaimo, Canada.

Meehan, W. R. (Editor), 1991. Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. Special Publication No. 19, American Fisheries Society, Bethesda, Maryland, 751 pp.

Montgomery, D. R., J. M. Buffington, N. P. Peterson, D. Schuett-Hames, and T. P. Quinn, 1996. Streambed Scour, Egg Burial Depths and the Influence of Salmonid Spawning on Bed Surface Mobility and Embryo Survival. Canadian Journal of Fisheries and Aquatic Sciences 53:1061-1070.

Nehlsen, W., J. E. Williams, and J. A. Lichatowich, 1991. Pacific Salmon at the Crossroads: Stocks at Risk from California, Oregon, Idaho, and Washington. Fisheries 16(2):4-21.

Palmisano, J. F., R. H. Ellis, and V. W. Kaczynski, 1993. The Impact of Environmental and Management Factors on Washington's Wild Anadromous Salmon and Trout. Report prepared for Washington Forest Protection Association and The State of Washington Department of Natural Resources, Olympia, Washington, 371 pp.

Schwiebert, E. (Editor), 1977. Columbia River Salmon and Steelhead. Special Publication No. 10, American Fisheries Society, Washington, D. C., 214 pp.