HYDROLOGICAL EFFECTS OF LAND-USE CHANGE IN A ZERO-ORDER CATCHMENT

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ABSTRACT: Hydrologic modeling and relatively simple monitoring were used to estimate the hydrologic balance for two geographically close and, in the undisturbed state, hydrologically similar, zero-order basins: one undeveloped forest and the other suburban. Continuous precipitation and streamflow were measured in each basin; the model was used to estimate time series of evapotranspiration and ground-water recharge over a 40-yr period. The suburban catchment was denuded of forest cover, soil thickness was reduced, and 30% of the area was covered with impervious surfaces. The amount of annual precipitation that becomes runoff ranged from 12 to 30% in the forested catchment and 44 to 48% in the suburban catchment where runoff from pervious areas accounts for 40–60% of the annual total. The peak flow rate per unit area for an approximate 24-h, 50-yr rainfall was more than 10 times higher from the pervious area at the suburban site than at the forested site. These findings emphasize the need to consider surface flow from all sources in the catchment when considering mitigation measures.

INTRODUCTION

This work is an outgrowth of work started at the University of Washington 2 decades ago and is in the spirit of Beven (1989). It builds on the early work of Hardt and Burges (1976), Kemp and Burges (1978), and on the work from almost a decade ago when we started to incorporate field mappable spatial hydrologic zones directly into schemes for quantitative hydrologic descriptions of catchments before and after land-use change. That work was reported by Burges et al. (1989) and Wigmosta and Burges (1990). The present work includes both process zone descriptions and mapping in addition to measurements and model representations of relevant hydrologic fluxes for two small, zero-order catchments in the Puget Sound lowlands of Washington State. The larger of the two (37 ha), "Novelty Hill" catchment, is representative of glacial till-capped plateau region forested catchments. The smaller (16.7 ha), "Klahanie" catchment, is representative of a planned suburban housing development in the same geologic setting. The general location of the catchments is shown in Fig. 1.

Most engineering hydrologic designs for land-use change from forest, rangeland, pasture, or farmland to urban or suburban states are done without benefit of any direct hydrologic measurements. The availability of relatively inexpensive electronic recording devices has made it possible to combine hydrologic monitoring with appropriate hydrologic models as an integral part of design. Normally, there is sufficient lead time to make hydrologic measurements at the scale of a few tens of hectares to define the predevelopment hydrology of the land. Most governmental design ordinances are written in the hope that peak flow rates from the developed land will approximate those that would have occurred from the undeveloped land. Such ordinances focus typically on a few design storms and pay particular attention to the fraction of the land that will be covered with impervious surfaces. Here we show that the contribution to storm flow from the altered pervious portions of the land also must be considered if mitigative design measures are to be effective. We have written previously (Wigmosta and Burges 1990) of the importance of effecting designs using continuous hydrologic time series rather than particular infrequent events. The goal of this effort is to examine the utility of a combination of modeling and relatively simple hydrologic monitoring to estimate the hydrologic balance for one surburban and one undeveloped forested catchment.

The scale at which hydrologic measurements are made is important. The two small catchments we monitored and modeled are zero-order catchments. The larger has a central swale through which water flows for about one-half of each year. The smaller suburban catchment has an engineered drainage channel located in what was a swale in the natural state. The land area to be modeled is field mapped to identify hydrologic process zones at any desired scale, including the scale of an individual residence that is on the order of 0.05 ha or larger. Our subareas were assigned after field mapping of hydrologic process zones. By monitoring and modeling at this scale we capture the land phase of the hydrologic cycle at the incremental scale at which land-use change occurs.

The 37-ha Novelty Hill catchment was chosen for monitor-

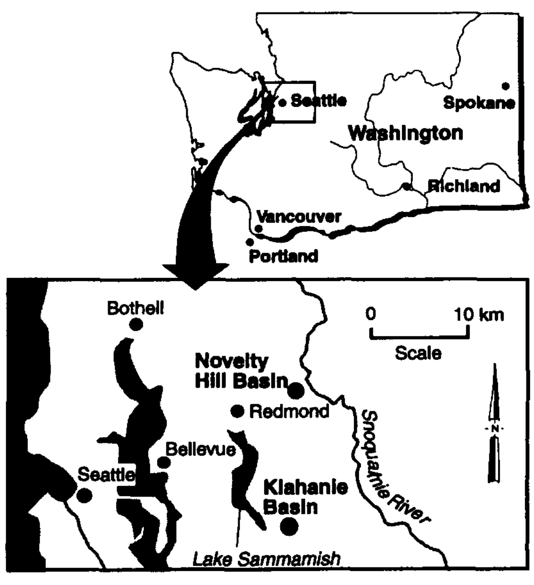

FIG. 1. Location of Novelty Hill and Klahanie Catchments, Puget Sound Lowlands, Washington

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ing because it is scheduled to be converted to a residential area starting in approximately 1998. We hope to monitor parts of it for several years after it has been developed fully. The 16.7-ha Klahanie catchment had been developed fully and contained lawns and other vegetated areas that had been established for at least 2 yr prior to the start of hydrologic monitoring. Because of the small area of this catchment we were able to demonstrate the effectiveness of using direct measurements of precipitation and catchment outflow to isolate the relative contributions of storm flow from pervious and impervious areas. Our emphasis in this paper is on the broad hydrologic budgets and particular hydrologic responses for several storms and not on model features or use. We use the model to estimate time series of actual evapotranspiration and recharge to the underlying formations.

We do not have pre- and postdevelopment hydrologic balances for a single catchment [see Langford and McGuinness (1976) on the uses of hydrologic modeling and paired watershed studies to evaluate hydrologic changes]. The hydrologic balance for the 16.7-ha suburban catchment is indicative of what likely is to be experienced by the 37-ha catchment when it is developed unless landscaping measures are taken to cause the catchment to behave hydrologically in a similar fashion to its predeveloped state. Insufficient attention has been given to landscaping designs where postdevelopment soil improvement is a part of mitigative designs. Ongoing work by the first writer on soil amendments (amending till with compost) and alternative landscape designs is directed toward developing approaches to cause the altered pervious parts of developed catchments to behave hydrologically in ways that do not differ markedly from their predevelopment state.

CONTINUOUS HYDROLOGICAL SIMULATION MODEL

The hydrologic model used in this study is of similar form to an earlier version reported by Wigmosta and Burges (1990); full details of the model are given in Wigmosta et al. (1994). The hydrologic model is operated continuously in time and can be calibrated with as little as 1 yr of hydrologic data. The data required are continuous precipitation (typically 5–15 min time increment), streamflow at the catchment outlet, and weather station data for estimating daily (or finer time increment) potential evapotranspiration. The model predicts spatial and temporal locations of Horton and saturated overland flow and local water table elevations, all of which can be compared directly with field observations (e.g., strategically placed piezometers with simple maximum water-depth recording) during model calibration and testing.

The catchment to be modeled is disaggregated into hillslope elements and channel reaches (Fig. 2). Hillslope elements contain areas with similar topography, vegetation, soil characteristics, and runoff mechanisms (as estimated from field mapping). Each hillslope element is modeled as a vertical two-dimensional section that is aligned with the predominant downhill flow path (Fig. 2). In plan view the hillslope segment consists of a quadrilateral, which extends from ridge crest to valley bottom. Each element may contain surface vegetation, a litter zone below the vegetation, and mineral soil beneath the litter. The mineral soil is assumed to overlie a less permeable layer.

Precipitation falling on a hillslope element may be intercepted by vegetation, with the excess (throughfall) landing on litter, soil, impervious surfaces, or dynamic zones of surface saturation. The amount of throughfall entering the soil is a function of throughfall intensity, the soil type, and antecedent moisture conditions. When the intensity of throughfall exceeds the current infiltration rate, Horton overland flow is generated once available surface detention is exhausted. When vertical unsaturated flow in the mineral soil exceeds the hydraulic conductivity of the layer below it, a perched water table forms. If this water table rises to intersect the ground surface, saturation overland flow and return flow may be generated.

The model is structured so its parameters can be determined from field measurements. Variations in the slope of the ground surface and the lower layer, as well as soil thickness, are included (Fig. 2). The soil saturated hydraulic conductivity can vary with depth below the ground surface and with downslope distance. The user specifies the flow path width, ground surface slope, and bed slope at the top and bottom of each hill-

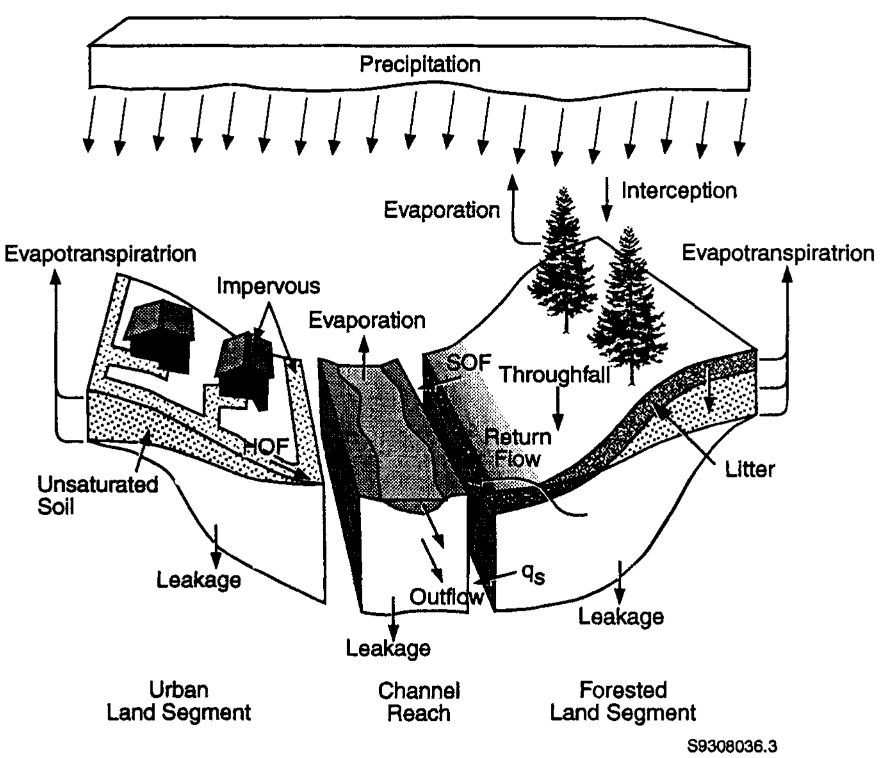

FIG. 2. Model Representation of Urban and Forest Hillslope Elements Draining to Channel Reach

slope segment. Ground surface elevation, soil depth, and upper soil lateral hydraulic conductivity must be supplied at selected downslope distances; the user determines the number and position of these locations. Cubic spline interpolations are used to estimate hillslope properties between input locations. The hillslope is subdivided into as many downslope computational increments as required with cross-sectional width, soil depth, hydraulic conductivity, and ground surface slope calculated at each location.

Each land segment drains to a stream reach that consists of a main channel and its associated floodplain. Hydraulic properties such as slope, cross-sectional geometry, and roughness are assumed constant within the reach. Reach discharge includes surface flow in the channel and floodplain, downstream flow through the channel bed, and downward leakage out of the channel bed. Channel reaches are linked to form the channel network.

STUDY AREA DESCRIPTION

Novelty Hill Catchment

The 37-ha Novelty Hill catchment is located within a broad, glacial till-capped plateau 6 km northeast of Redmond and 26 km northeast of Seattle in King County, Wash. (Fig. 1). The site was logged around the beginning of this century and now contains an extensive cover of second growth Douglas Fir (*Pseudotsuga menziesii*), Alder (*Alnus rubra*), Cottonwood (*Populus trichocarpa*), Western Red Cedar (*Thuja plicata*), Big Leaf Maple (*Acer macrophyllum*), and Vine Maple (*Acer cirinatum*). A typical soil profile consists of forest litter and an organic layer approximately 0.15 m thick, underlain by sand to silty sand with minor amounts of gravel and cobbles. The sandy layer generally extends to a depth of 0.6–1 m and overlies the dense glacial till. The saturated vertical hydraulic conductivity of the till is very low, from 0.15 to 0.3 m per year (Olmsted 1969). Plant roots extend to the till; however, the root network thins rapidly at a depth of 0.4–0.6 m below the ground surface.

A shallow seasonal wetland covering approximately 1.4 ha (4% of the total catchment area) exists within a well-defined swale that extends 800 m upstream from the basin outlet (Fig. 3). Detailed field mapping and observations during site visits indicated that the seasonal wetland was the only source of surface runoff generation. Discharge from the remainder of the site is in the form of subsurface flow to the swale. The wetland expanded to its largest areal extent during heavy rainfall in January 1990; when we estimate its areal extent was no more than 50% greater than the wet-season average. Discharge from the swale is measured at the outlet using a compound weir. A tipping-bucket rain gauge, with a bucket capacity of 0.254 mm has been recording at 15-min intervals since October 1, 1989. Rainfall data for the period from May 4, 1990 to June 13, 1990 were lost. The missing record was filled in using data from a 15-min gauge located at a similar elevation 1 km to the northeast. The locations of hydrological monitoring stations are shown in Fig. 3. Complete documentation of all instruments and instrument records is given in Wigmosta et al. (1994).

Klahanie Catchment

The 16.7-ha Klahanie catchment is located 14 km south of the Novelty Hill basin within a till-capped upland plateau similar to that found at Novelty Hill (Fig. 1). The Klahanie catchment was forested before development. Trees were cut and removed and stumps, roots, and the litter layer and natural topsoil were removed immediately prior to urban construction. In its natural state, apart from being steeper, the Klahanie catchment was similar to the Novelty Hill catchment. Geologic conditions, climate, and native soils at the two sites are generally the same and prior to development soil depths were nearly equal. Current soil thickness at Klahanie is from 0.08 to 0.15 m. Changes to the natural landscape at Klahanie have altered runoff mechanisms, resulting in a more rapid runoff response to rainfall.

Present land use at Klahanie is entirely residential, with 117 single-family homes, a tennis court, and a community center with a swimming pool and parking lot (Fig. 4). An air photograph of a cluster of residences immediately to the south of the catchment boundary is shown in Fig. 5. This layout of residences, sidewalks, and roads is typical of Klahanie housing and streets and other recently developed suburban areas in King County, Wash. The paved sidewalks show clearly as white borders separating lawns and driveways from the roads. The storm water conveyance system is associated almost entirely with the road network. Road runoff is routed through gutters to catch basins; roof drainage is also transmitted to the catch basins through closed conduits. The collected runoff discharges to a central engineered swale at several locations. The catchment outlet is located at the northern border where discharge from the swale is measured using separate v-notch and rectangular weirs. A tipping-bucket rain gauge, with a bucket capacity of 0.51 mm has been recording at 15-min intervals since October 16, 1990. Rainfall data for the period from December 24, 1990 to January 1, 1991 were lost. The missing record was filled in using data from a 15-min gauge located 3 km to the east. The locations of the hydrologic recording instruments are shown in Fig. 4.

As a result of the field mapping, we chose to model the catchment as 13 independent subcatchments based on existing topography, the road network, and the storm water conveyance system. Hydrologic process zones were mapped within each subcatchment. Horton overland flow is generated on roads, sidewalks, driveways, and roofs. Almost all of this flow is transmitted directly to the storm water conveyance system. Most residential lawns in the subdivision consist of a thin layer of imported topsoil overlain by sod. Lawns, flowerbeds, and gardens are well maintained and appear to infiltrate most, if not all, rainfall. Generally, low areas are drained with French drains and/or perforated pipe. Although there is little evidence of overland flow on lawns, saturation overland flow was observed on the western foot slopes of land segments 5 and 10, in the common area adjacent to the swale (Fig. 4). We report here on the integrated outflow from the catchment. The dynamic, or active, impervious area (that which is connected directly to drains or the engineered swale) is 4.8 ha (29%) and the pervious area is 11.9 ha (71%). The locations of the hydrologic recording instruments are shown in Fig. 4. A more complete description of the site and of the recording histories is given in Wigmosta et al. (1994).

HYDROLOGIC BALANCES

Novelty Hill Catchment

The data used for developing and calibrating the Novelty Hill hydrologic model start on October 1, 1989 and end on June 30, 1990. We use additional recorded precipitation, runoff, and climate data time series with the model to examine aspects of catchment behavior for drier conditions than experienced during calibration. The extended series for water years 1991, 1992, and 1993 (through the end of June 1993) include several successive seasons of below average rainfall depth.

Flow production from the catchment occurs after some soil water threshold volume is reached. All rainfall apart from that which falls directly on the saturated swale area and that which is intercepted by the vegetation enters the forest litter. Flow to

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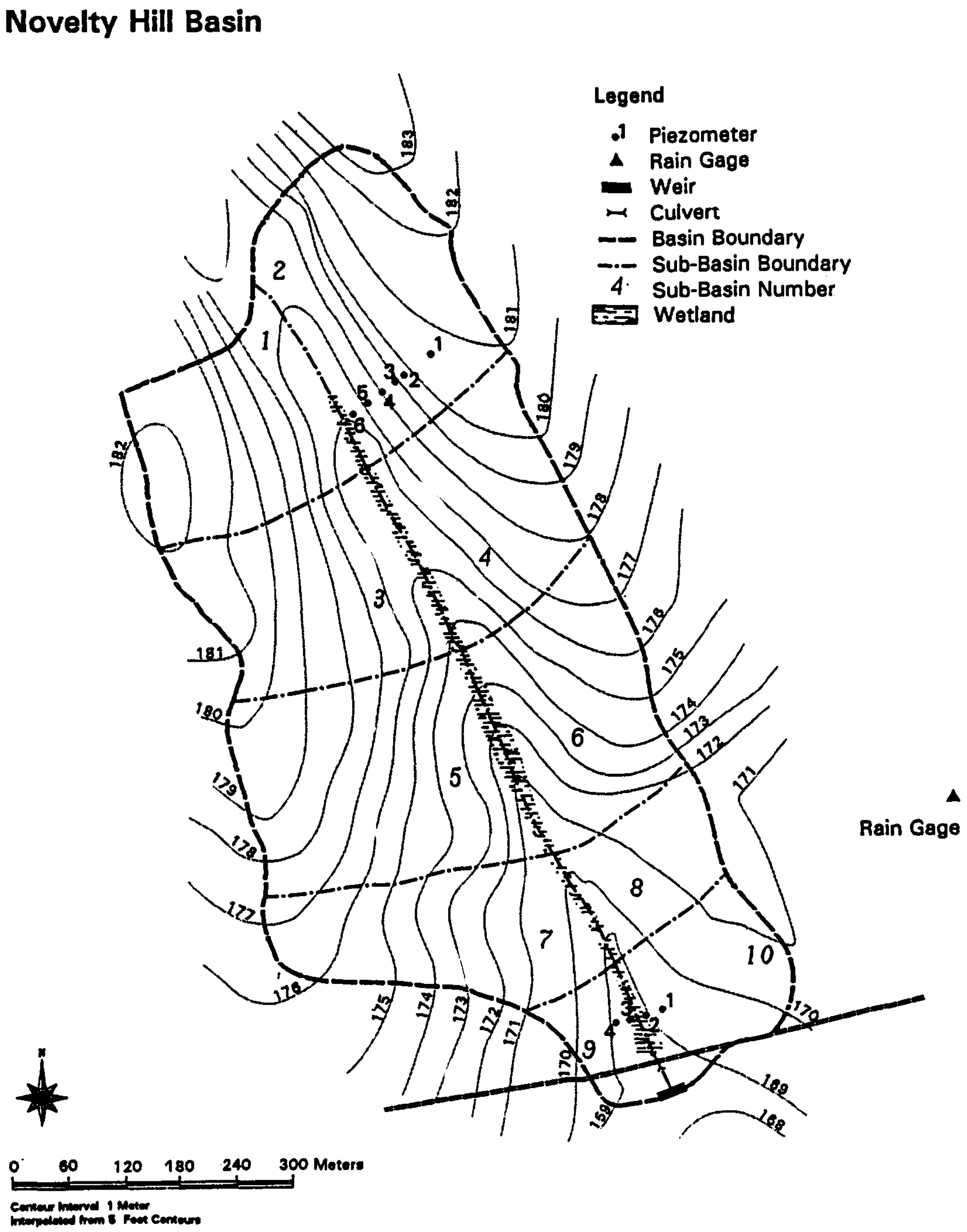

FIG. 3. Contour Map of Novelty Hill Catchment Showing Principal Features, Subcatchments, and Locations of Hydrologic Measuring Stations

the swale occurs only after a series of storms in October and November deliver sufficient rain to feed the soil column to some level beyond field capacity. Soon thereafter flow is observable at the catchment outlet where it is measured. Rainfall depth and time between storms are important to flow response. The pattern of rain delivery is more important here for flow production than for a shallower soil, as is the case in the Klahanie catchment.

Daily Time Series

Fig. 6 shows recorded daily precipitation depth, modeled 10-day average evapotranspiration, the recorded daily average streamflow rate, and the residual (recorded minus simulated) average daily flow rate. It is evident from Fig. 6 that the model does not simulate well the measured short-duration, higher flow rates that follow dry periods. The most obvious examples of this are the storms in February 1992 and January 1993. The differences between the simulated and recorded flow time series (the residuals) in these cases equal more than 75% of the recorded values. After a period of rainfall whose cumulative volume exceeds cumulative evapotranspiration, the soil moisture level increases and the model again provides an accurate simulation. We have no independent check to know if the limitations in "dry soil" model response result from inaccurate estimates of potential evapotranspiration or if the soil water dynamics are not well represented for dryer soil conditions.

There were substantial storms in November 1989, January 1990, November 1990, and April 1991. The largest 24-h depths for the January and November 1990 storms were in excess of the estimated 50-yr return period (0.02 annual exceedance probability) storm for the region. The April 1991 storm was of approximately the same magnitude. The automatic weir recording equipment was not operational up to and

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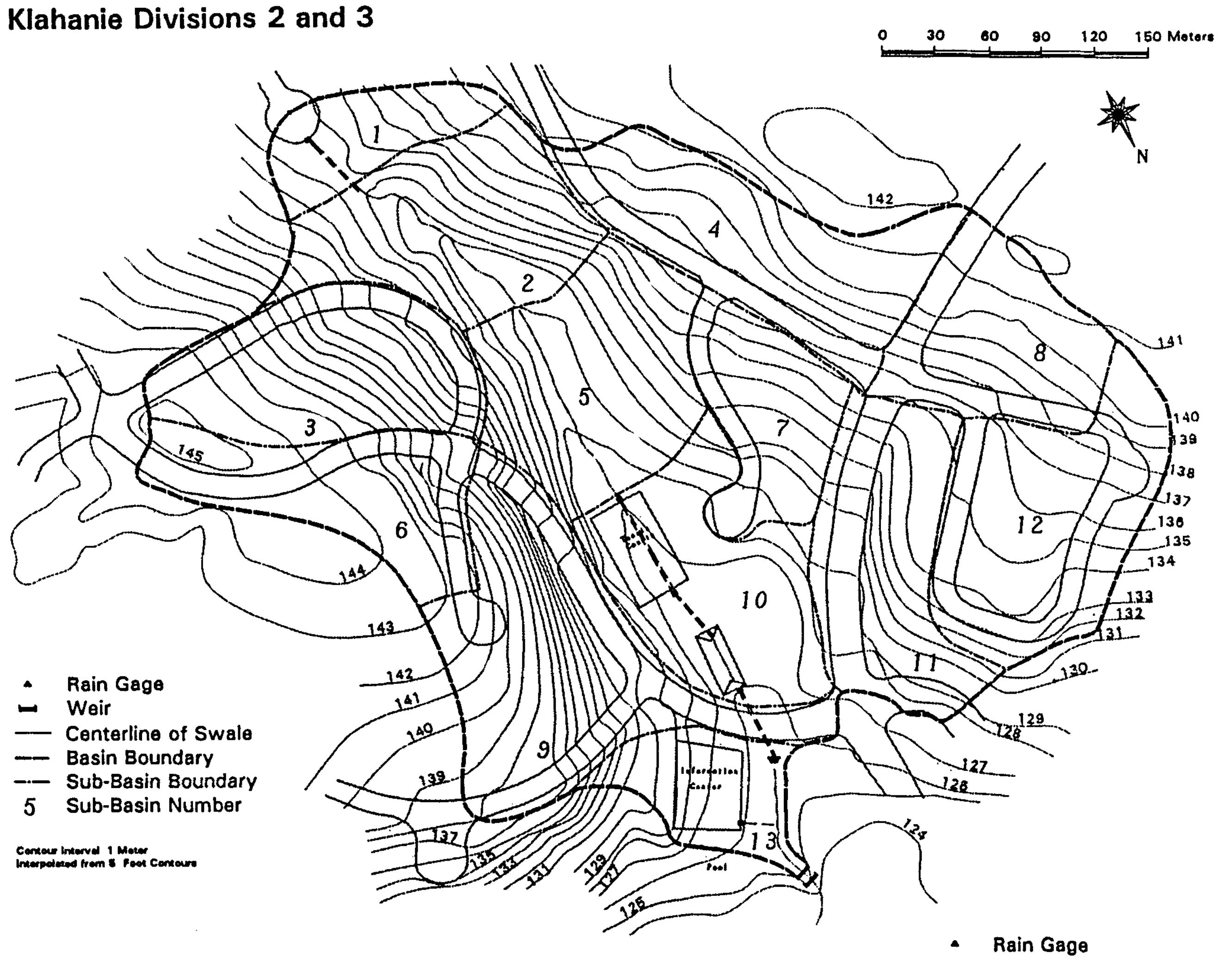

FIG. 4. Contour Map of Klahanie Catchment Showing Principal Features, Subcatchments, and Locations of Roads and Hydrologic Measuring Stations

FIG. 5. Air Photograph of Typical Residential Layout in Klahanie Region

including the January 1990 storm. During that storm, weir pool depths were measured manually, but the corresponding flow rates are not shown in Fig. 6. The hydrograph of outflow in water year 1991 shows the catchment at its most responsive state for the 4 yr of observation. Here the patterns of storm depth, duration, and time between storms show that the response is relatively rapid and relatively short lived. There are distinct recessions following storm-induced peak hydrograph responses.

The influence of antecedent catchment moisture is clear when the second largest response for water year 1991 is considered. Relatively benign rain depth caused this response. Comparable rain depth falling in January 1992 with a noticeable time between storms produced almost no response. The measured hydrograph between November 1990 and May 1991 (Fig. 6) demonstrates the need for continuous hydrological modeling representation of a catchment of this type if the preurbanization hydrologic state is to be characterized adequately.

Annual Water Balance

The annual water balance for Novelty Hill is presented in Table 1. Model simulated catchment outflow was used for the period October 1, 1989 to January 14, 1990 and for the period April 1, 1993 to May 13, 1993 when the weir recording equipment was not operating correctly. The annual net change in soil water storage is neglected and losses through a combination of evapotranspiration and ground-water recharge through the till layer are taken as the difference between precipitation and catchment outflow. All quantities are expressed as average depth over the catchment. The vast majority of annual precipitation leaves the basin through evapotranspiration and ground-water recharge through the till layer, ranging from 69% in a wet year (1991) to 88% in a dry year (1992).

Approximate Seasonal Mass Balances

Wet and dry season–measured precipitation and modeled catchment outflow (runoff), evapotranspiration, and recharge

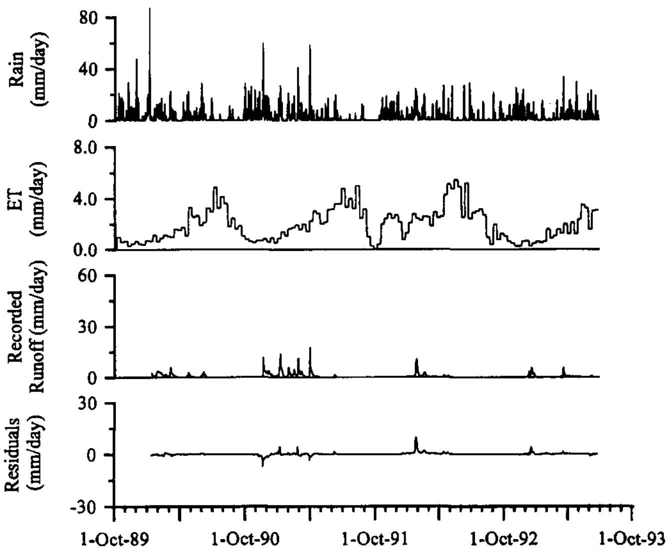

FIG. 6. Novelty Hill Recorded Average Daily Flow Rate and Daily Precipitation Depth, Modeled 10-Day Average Evapotranspiration Depth, and Recorded Minus Modeled Average Daily Flow Rate (Residual)

TABLE 1. Annual Water Balance for Novelty Hill

Water year (1)	Precipitation (mm) (2)	Discharge (mm) (3)	Evapotranspiration and till recharge (mm) (4)
1990[a]	1,210	356	854
1991	1,331	407	924
1992	998	123	875
1993[b]	914	182	731
Total	4,453	1,068	3,384

[a]Simulated discharge totaling 175 mm was used for October 1, 1989–January 14, 1990.

[b]October 1, 1992–June 30, 1993. Simulated discharge totaling 84 mm was used for April 1–May 13, 1993.

to the till (till leakage) are given in Fig. 7 to show the major hydrologic fluxes by wet and dry season. All quantities are expressed as average depth over the catchment. The wet season was chosen to encompass the period of swale discharge, normally between October 1 and April 30; 70–85% of annual precipitation falls during this period. The dry season was from May 1 to September 30. If initial and ending season–modeled soil and interception water storages were included in Fig. 7, they would contain all information for complete mass balance to be effected at annual time increments. The differences in modeled moisture zone storage are less than 2% of the annual precipitation in all years and are not shown in Fig. 7.

The four quantities displayed in Fig. 7 show the relative distributions by wet and dry seasons of the inputs to and outputs from the catchment. Some of the water stored in the soil and swale during the wet season evaporates and recharges the till while some of the water added to the soil column during the wet season also recharges the till during the dry season. The net addition to soil water storage during the wet season results in modeled evapotranspiration greater than precipitation during the following dry season. The catchment is approximately at the same (relatively dry) moisture state at the start and end of each year.

With reduced precipitation in dry years, the fraction of rainfall that becomes simulated catchment outflow is small. During the water years of relatively normal precipitation, 1990 and 1991, approximately 33 and 40%, respectively, of the precipitation delivered during the wet season became simulated runoff. In contrast, during the dry water year of 1992, most of the precipitation that reached the litter layer was stored in the soil column. This water left the basin primarily in the form of (modeled) evapotranspiration; modeled till leakage and measured runoff was small during the wet season and negligible during the dry season. The timing of the rainfall in water year 1993 differed from 1992 although the annual totals were similar. In water year 1993, the measured runoff and modeled till leakage were approximately equal in both the wet and dry seasons. The summation of the runoff and till leakage was slightly less than the modeled evapotranspiration depth.

The modeled amount of water lost to till leakage decreases when periods of below average precipitation occur. For these conditions, the water stored in the soil column is less than the field capacity of the soil for much of the year and is not available to infiltrate into the till. Whenever the soil water content is above field capacity, simulated vertical gravity drainage delivers water to the soil-till interface and provides till recharge supply.

Summary

Field measurements show that the vast majority of annual precipitation falling on Novelty Hill leaves the basin through evapotranspiration and ground-water recharge through the glacial till (Table 1). The Novelty Hill drainage basin acts in two distinctive fashions depending on the timing of storms and the amount of rain the basin receives. In a wet year (1991) where there are distinct periods when a significant depth of the soil column becomes saturated, approximately 69% of the precipitation leaves the area through evapotranspiration and ground-water recharge. During a dry year (1992) when the timing of storms is such that only a small depth of the soil column saturates and does so infrequently, combined losses through evapotranspiration and ground-water recharge account for 88% of the precipitation. However, in either type of year there is a cumulative threshold amount of precipitation, minus evapotranspiration and additions to soil moisture storage, that occurs before flow to the swale is produced.

Klahanie Catchment

The data used to calibrate the model and make preliminary assessments of the hydrological characteristics of the Klahanie basin included the period of November 20, 1990–May 15, 1991. This was a wetter year than normal. The following 2 yr were noticeably drier. The data time series discussed here include water years 1991, 1992, and 1993 (through the end of June 1993). Seven of the 10 largest 1-day storm depths for this record occurred during the period of November 1990–May 1991. The storm patterns included in the longer data set make it possible to explore the effectiveness of the calibrated model for a range of hydrologic conditions not experienced during calibration.

Daily Time Series

Fig. 8 contains information for Klahanie similar to that shown in Fig. 6 for Novelty Hill. Because of faster dynamic response than at Novelty Hill the modeled evapotranspiration is shown as the average value for a 2-day period. Fig. 8 shows that the model simulates catchment flow production equally well for both wet and dry years. The model oversimulates flow response to rain falling on the pervious portion of the catchment when the catchment is relatively dry. Errors in estimating the amount of and vertical distribution of soil moisture and evapotranspiration fluxes at Klahanie have much less influence on modeled outflow than such errors for the deeper Novelty Hill soil.

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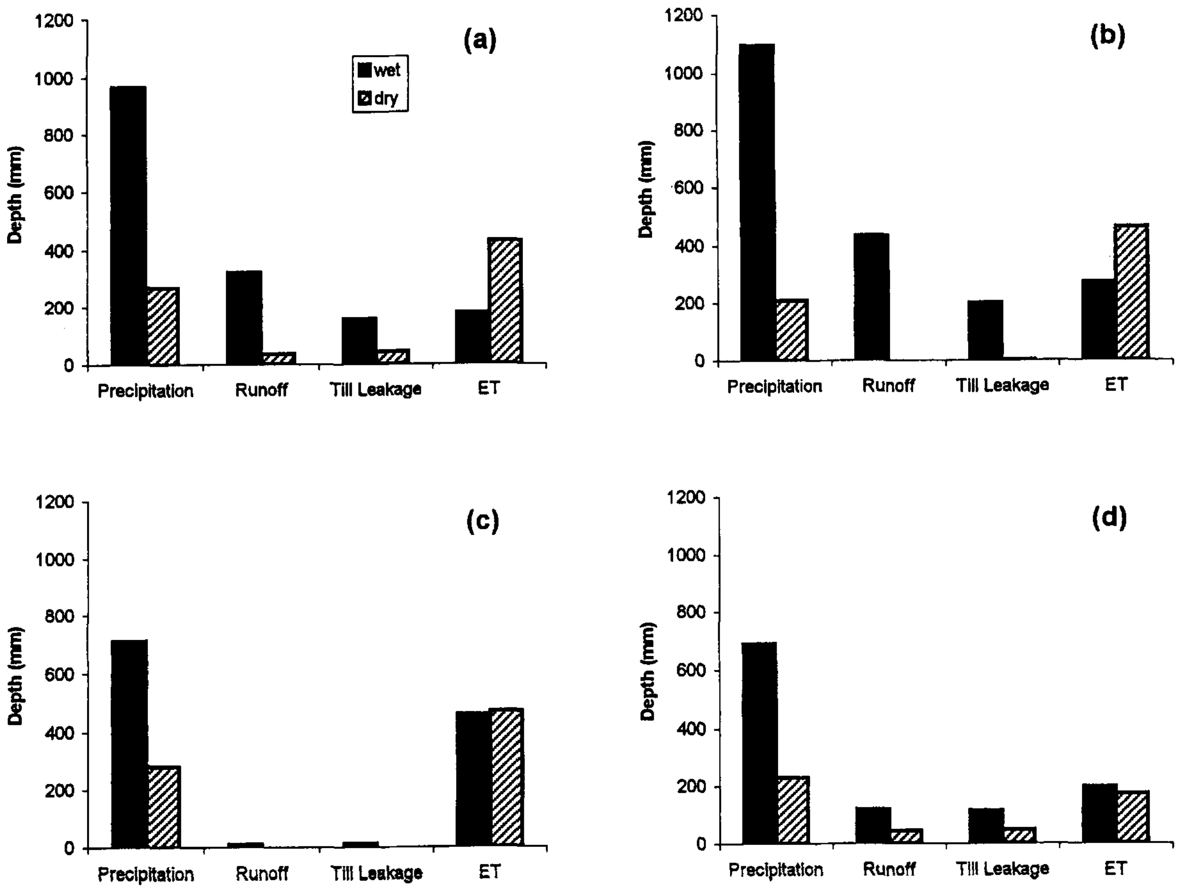

FIG. 7. Wet (October 1–April 30) and Dry (May 1–September 30) Season Novelty Hill Measured Precipitation and Calculated Runoff, Till Leakage, and Evapotranspiration for Water Years: (a) 1990; (b) 1991; (c) 1992; (d) 1993

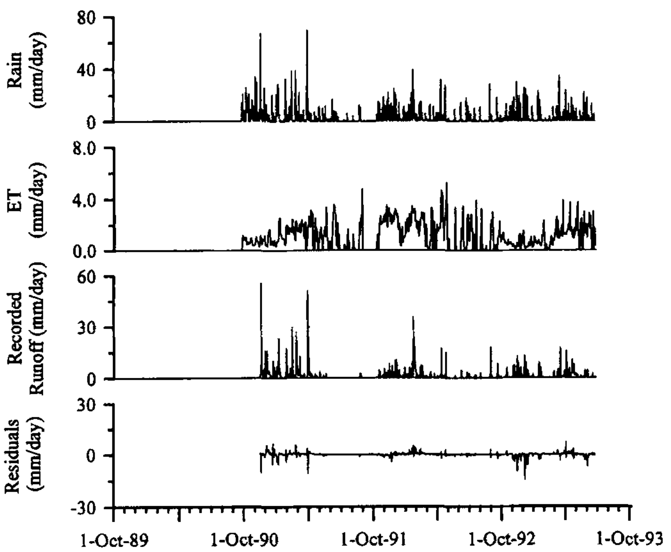

FIG. 8. Klahanie Recorded Average Daily Flow Rate and Daily Precipitation Depth, Modeled 2-Day Average Evapotranspiration Depth, and Recorded Minus Modeled Average Daily Flow Rate (Residual)

The Klahanie basin responds more rapidly to rainfall than Novelty Hill, with higher peak flows and more frequent periods of storm discharge, especially during the summer months (Figs. 6 and 8). The difference in runoff response results from not only the introduction of impervious surfaces at Klahanie, but also the changes to pervious areas of the catchment. The small soil water storage capacity of the permeable parts of the basin requires less precipitation to saturate the soil than is the case at Novelty Hill with its deeper soil, resulting in a more rapid response to rainfall. Left unmitigated, the resulting changes in catchment outflow may alter streamside ecology and the sediment transport characteristics of receiving channels. In the case of Klahanie, a short distance below the measurement weirs water from the site discharges into a lake with sufficient volume to attenuate flow peaks. Impacts to the lake ecology resulting from changes to the runoff regime are unknown at this time.

Annual Water Balance

Table 2 contains information for Klahanie similar to that shown in Table 1 for Novelty Hill. A much larger percentage of the annual precipitation leaves Klahanie through catchment outflow than at Novelty Hill. There is appreciable runoff in all three water years in contrast to the reduced runoff production at Novelty Hill in the 2 dry water years, 1992, and 1993. Water year 1992 provides the best means of comparison, because there were no gaps in the measurement record for either basin during the year. In 1992, 44% of the annual precipitation left Klahanie as catchment outflow versus 12% at Novelty Hill.

TABLE 2. Annual Water Balance for Klahanie

Water year (1)	Precipitation (mm) (2)	Discharge (mm) (3)	Evapotranspiration and till recharge (mm) (4)
1991[a]	1,028	650	378
1992	1,066	467	599
1993[b]	959	378	581
Total	3,053	1,495	1,555

[a]November 20, 1990–September 30, 1991.
[b]October 1, 1992–June 30, 1993.

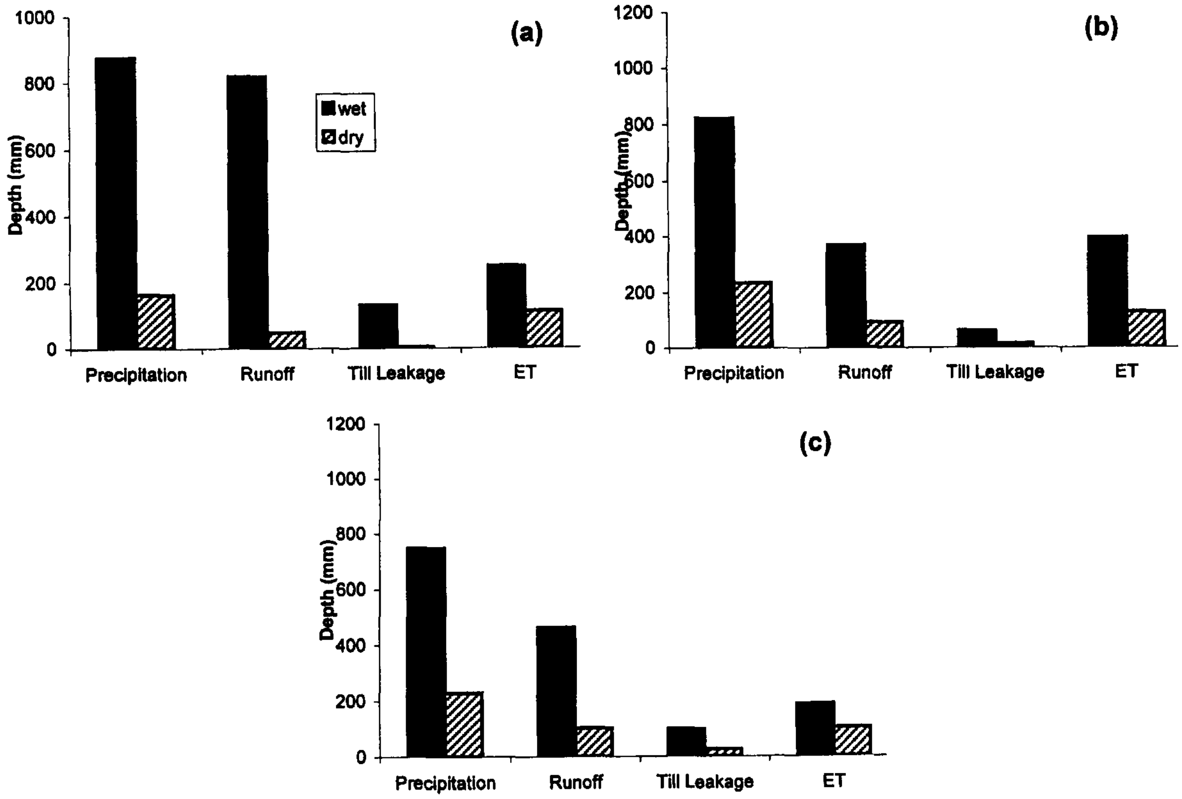

FIG. 9. Wet (October 1 – April 30) and Dry (May 1 – September 30) Season Klahanie Measured Precipitation and Calculated Runoff, Till Leakage, and Evapotranspiration for Water Years: (a) 1991 (starting November 20, 1990); (b) 1992; (c) 1993 (through June 30, 1993)

Approximate Seasonal Mass Balances

The extension of the data to include the additional 2 yr of information beyond the part year of data used to calibrate it allows the Klahanie runoff model to be evaluated in times of drought. This model does not account for supplemental lawn and garden irrigation water that is supplied typically between late April and early October during our "dry season." Lawn-watering restrictions were in force from May to September 1992 during a regional drought; little if any supplemental irrigation was applied during this period. We do not have any records or ways to estimate the amount of supplemental irrigation but believe that the hydrologic effects of any supplied irrigation would have been small in the other 2 yr.

Wet and dry season–measured precipitation and –modeled catchment outflow (runoff), evapotranspiration, and till leakage are shown in Fig. 9. The wet season was defined as it was for Novelty Hill, from October 1 to April 30 and accounts for the bulk of rainfall. The dry season is from May 1 to September 30. All quantities are expressed as average depth over the catchment and include simulated runoff and modeled evapotranspiration for both pervious and impervious areas. All modeled till recharge occurred beneath pervious areas, and the catchment till recharge is the amount for the pervious areas expressed as a depth over the 16.7-ha basin. (The reported till leakage depth is the actual leakage from the pervious area multiplied by 11.9/16.7.)

The pervious area moisture storage zones are small relative to the rainfall depth. Fig. 9 shows the dominant components of the catchment mass balance. With the low soil water storage capacity of the relatively thin soils, the difference between the modeled starting and ending soil water storage for each year is nearly zero and is not shown. The runoff shown in Fig. 9 consists of both pervious and impervious area flows. A breakdown of the two components is shown in Fig. 10; the runoff produced from the pervious areas comprises at least 39% (1993) and as much as 60% (1991) of total runoff.

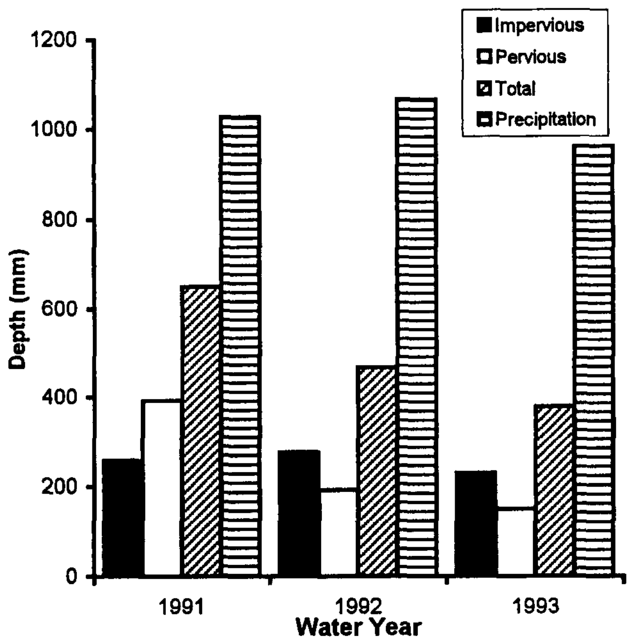

FIG. 10. Klahanie Calculated Impervious, Pervious, and Measured Total Surface Runoff Depths, and Measured Precipitation Depths for Water Years 1991 (starting November 20, 1990), 1992, and 1993 (through June 30, 1993).

Flow Production from Impervious and Pervious Areas

Runoff rates from impervious and pervious areas were estimated using the measured rainfall depth and channel flow rate and indicate how much can be gained in understanding hydrologic response of small urban catchments by simple analysis of measured fluxes. The method used to partition runoff into pervious and impervious components was based on the assumption that when flow is recorded at the gauge the im-

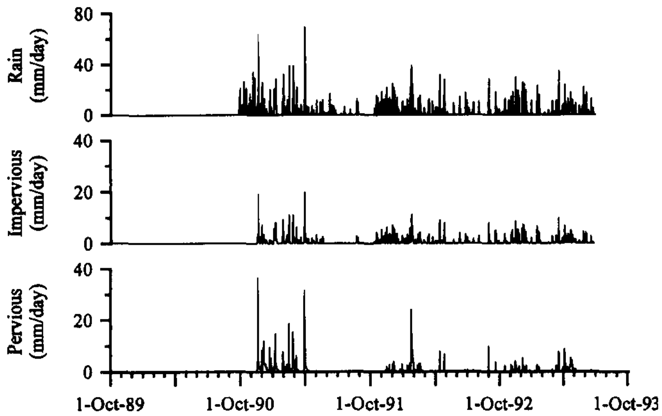

FIG. 11. Klahanie Measured Daily Precipitation Depth and Estimated Average Daily Flow Rate Produced from Impervious and Pervious Land

pervious areas produce a runoff depth less than or equal to the measured runoff. The estimated impervious area runoff response is slightly larger than actual because no explicit account was taken in this simple analysis of the effects of depression storage and evaporation from impervious surfaces on the resulting runoff. Whenever there was no measured basin outflow and rain was recorded we set impervious surface runoff to zero. When the measured daily runoff volume exceeds the daily precipitation depth multiplied by the impervious surface area, the difference is assumed to be the flow volume generated from the pervious area. It is unlikely that we have overestimated impervious surface runoff contributions for light rainfall falling on a dry surface. For heavier rain falling on an initially wet surface, the estimation scheme is close to the actual response.

Fig. 10 gives the division by water year of the areally averaged depth of runoff produced on impervious and pervious areas, total catchment runoff, and catchment precipitation. Runoff from pervious and impervious areas is nearly equal during the period of study (760 and 734 mm, respectively). Fig. 11 shows daily average precipitation depth and daily average estimated impervious and pervious area runoff production rates. As can be seen, pervious area runoff exceeds impervious area runoff during most large storms. The data presented in Figs. 10 and 11 demonstrate that runoff from urban pervious areas such as those associated with Klahanie is significant and must be considered in alternative urban design and mitigation strategies.

Summary

The value of concurrent precipitation and catchment outflow measurements for describing the hydrological response of a small urbanized catchment where channel influences have negligible effects on the outflow hydrograph is evident from the analysis presented in Figs. 10 and 11. Much can be learned about the apportionment of volumetric and peak flow production rates from pervious and impervious surfaces by relatively simple analysis of the measured time series of precipitation and basin outflow for a small catchment where the measured flow rates are for practical purposes unaffected by channels. Such analyses depend on the quality of the measured time series. There are many difficulties unique to streamflow data collection in urban environments. These issues are discussed in Appendix I.

Considerable insights into catchment hydrologic behavior can be gained by direct analysis of the measured and derived time series and by employing a calibrated model that uses measured precipitation and estimated potential evaporation as input for estimating unmeasurable quantities (evapotranspiration and till leakage). The relatively thin soil column of the pervious zone was modeled well for storm patterns that differed substantially from those that occurred in the record that was used to calibrate the model. Any inability of the model to represent soil moisture profiles and evapotranspiration precisely had only slight effects on model predictions of basin runoff production.

COMPARISON OF HYDROLOGIC BALANCES

Catchment Physical Differences

The most noticeable differences between the Novelty Hill and the Klahanie catchments are the land surface slopes, the impermeable surfaces that cover approximately 30% of the Klahanie basin, and the forms of the permeable surfaces. The Novelty Hill catchment has a steady longitudinal slope of approximately 1% and lateral slopes from 3 to 5% in the upper catchment and 1 to 2% in the lower catchment. The lateral land slopes at Klahanie range from 5 to 17%. The permeable surfaces at Klahanie consist mostly of lawns, unlike Novelty Hill, which consist of second growth forest throughout the entire basin except the drainage swale. The other major difference between the basins is the soil column depth and form. The soil column at Novelty Hill consists of approximately 0.8–1.0 m of organic and mineral soil. The soil column at Klahanie consists of approximately 0.1 m of mineral soil. The ground surface at Novelty Hill is extremely uneven, whereas the shallow-rooted lawn areas of Klahanie are much smoother. The surface soils in both catchments are underlain by glacial till that restricts water movement vertically.

Catchment Outflow Characteristics

The precipitation patterns for both catchments are similar in timing and amount of rain, with slightly more wet-season rain at Klahanie than at Novelty Hill (Figs. 7 and 9). With approximately 30% of area covered with impermeable surfaces and the shallow soil column, the Klahanie catchment produces higher flow rates per unit area than the Novelty Hill catchment. However, Novelty Hill provides a sustained base flow that lasts longer than the recession flows at Klahanie. One measure of the dramatic difference in flow response for the two catchments was observed for the large storm of November 23–26, 1990. The depth of precipitation measured in the two catchments was nearly identical: 90 mm at Novelty Hill and 87 mm at Klahanie. Recorded (and simulated) hydrographs and precipitation patterns for this storm are given in Figs. 12 and 13 for Novelty Hill and Klahanie, respectively. This storm gave rise to a recorded peak runoff rate of nearly 7 mm/h at Klahanie and only 0.5 mm/h at Novelty Hill. Flow rates from pervious and impervious areas at Klahanie are compared with total discharge from Novelty Hill in Fig. 14. The pervious and impervious flow rates in Fig. 14 are expressed as average depths per unit pervious and impervious area, respectively, not as average depths over the entire catchment (as presented in Figs. 9 and 10). A peak runoff rate of nearly 6 mm/h was estimated for pervious areas at Klahanie using measured precipitation and runoff in the method described previously. The high peak flow rate at Klahanie is consistent with the high-intensity rainfall and the antecedent catchment state of soil moisture. Fig. 13 shows a rapid return to near zero flow at Klahanie within a day after the cessation of rain. Fig. 12 shows a more sustained flow rate at Novelty Hill for many days after the rain stopped. These different responses are caused by, in large part, the respective soil depths. Novelty Hill stores a large portion of all precipitation in the soil column and drains only as fast as the soil allows the water to flow laterally to the receiving swale. Because the soil column is shallow at Kla-

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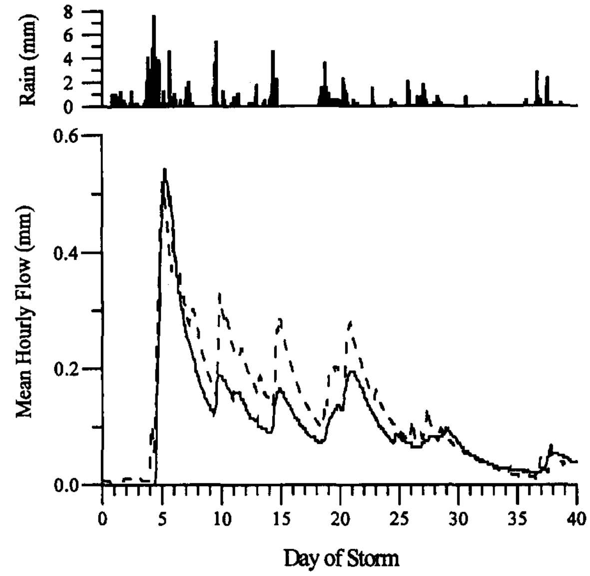

FIG. 12. Hourly Time Series of Rainfall and Recorded (Solid) and Simulated (Dashed) Streamflow for Novelty Hill for the Period November 20, 1990 (Day 0) to December 29, 1990 (Day 40)

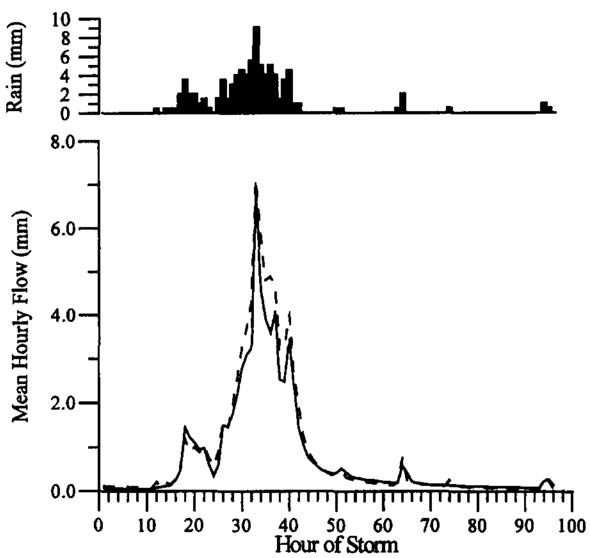

FIG. 13. Hourly Time Series of Rainfall and Recorded (Solid) and Simulated (Dashed) Streamflow for Klahanie for the Period November 23, 1990 (Hour 0) to November 26, 1990 (Hour 96)

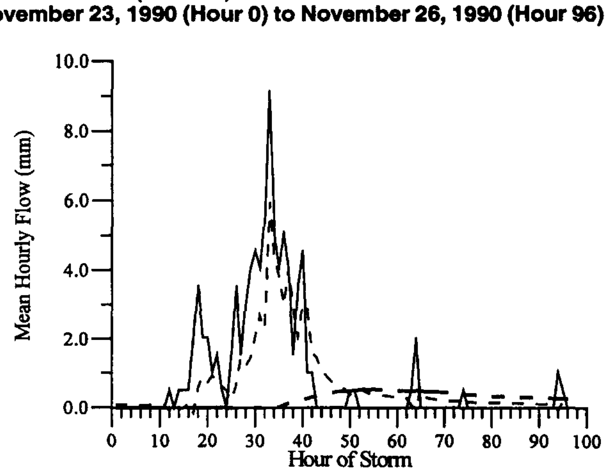

FIG. 14. Hourly Time Series of Recorded Streamflow for Novelty Hill (Heavy Long Dashed) and Estimated Runoff from Impervious (Solid) and Pervious (Thin Dashed) Areas at Klahanie for the Period November 23, 1990 (Hour 0) to November 26, 1990 (Hour 96).

hanie, it requires only a few moderate storms to fill much of the dynamic water-holding capacity. Once the soil is saturated, the surface flow response to the next increment of precipitation is relatively fast. After rain stops there is little drainable stored water in the soil to sustain dry-weather flow (Fig. 13).

The dramatic difference in response at the two catchments to what was an approximately "50-yr 24-h" rainfall volume has significant implications for those concerned with mitigating the hydrologic effects of urbanization. To our knowledge, these are the only gauged catchments at this small scale to provide regional information about the magnitudes of flood response to the smallest receiving channels. We have no way of assigning recurrence frequency to these flood hydrographs: 50-yr rainfall does not give rise to a 50 yr flood hydrograph except under restricted circumstances that are not satisfied in natural or suburban catchments. What is important is the magnitude and duration of the flow rates that the channels, which are fed by these two land areas, experience.

The urbanized catchment delivered a flow rate almost 14 times larger than that delivered by the natural catchment to its receiving channel. The potential deleterious effects of an order of magnitude increase in channel flow rate from the predevelopment to the postdevelopment land-use state on stream habit and stream ecology are significant. It is imperative that when urban landscapes are created, full attention is given to the complete hydrologic response of the catchment in its pre- and postdevelopment states. The only way that this can be done is by considering the mechanisms by which flow is produced in the catchment as we have described. Indicators of deleterious consequences that may result from land-use change are provided by Burges et al. (1989) and elsewhere.

Evapotranspiration

The shallow soil column at Klahanie affects more than the outflow from the catchment. The modeled evapotranspiration at Klahanie is less than for the natural condition at Novelty Hill. There is more water stored in the soil column for longer periods at Novelty Hill than at Klahanie and consequently greater evapotranspiration opportunity at Novelty Hill. These differences are illustrated in Fig. 7 for Novelty Hill and Fig. 9 for Klahanie. Fig. 7 shows that for the 4-yr period, the amount of annual precipitation that becomes modeled evapotranspiration at Novelty Hill ranges between 50 and almost 100%. The latter condition occurred for the relatively dry 1992 water year. At Klahanie the amount of precipitation that becomes modeled evapotranspiration ranges from 26.5 to 50%. The modeled evapotranspiration depths are not inconsistent with regional estimates of evaporation from shallow lakes (Linsley et al. 1982, Figs. 6–7).

The relative temporal distributions of evapotranspiration also differ between the two catchments. For Klahanie, Fig. 9 shows that the dry season evapotranspiration depth is less than the dry season rainfall depth in each year. This is another consequence of the change from natural to shallower soil urban conditions. For Novelty Hill, the same analysis is given in Fig. 7. In 3 of the 4 yr the modeled dry season evapotranspiration depth exceeded the dry season precipitation depth. These differences in catchment scale evapotranspiration contribute to different mesoscale climatologies for the two different vegetation regimes. Bosch and Hewlett (1982), and Ffolliott and Thorud (1977) give more general discussions on the influence of changes in vegetation on water yield and evapotranspiration.

Regional Ground-Water Recharge

Water flows to the strata beneath the catchments after passing through a relatively impermeable (but lightly fractured) dense layer of glacial till. The till can transmit water, as long as the upper surface of the till is supplied with water. The maximum rate is approximately equivalent to a depth of water ranging from 150 to 300 mm per year (Olmsted 1969). This water supplies the ground-water recharge for the plateau regions in King County. Any reduction in the supply to the till layer will reduce the recharge to the regional ground water. This is an issue that must not be overlooked. Simulated recharge to the till layer at Klahanie (Fig. 9) is less than for the Novelty Hills site (Fig. 7) except in water year 1992 when modeled till leakage was negligible at Novelty Hill and modeled evapotranspiration dominated the vertical movement of water. Although the modeled recharge estimates are approximations that include all errors associated with runoff and evapotranspiration, they still illustrate the need to consider potential changes in ground-water recharge in the planning process.

Summary

Adaptive Modeling and Monitoring

A major thrust of this work was to develop combined hydrological monitoring and modeling to describe relevant flow paths and fluxes to improve our understanding of catchment hydrology and to provide information that would lead to designs that would mitigate the hydrologic effects of urbanization. The model we developed was essential for providing information that has been used to determine the components of the catchment water balance that are not readily measurable. Our observations are based on measured precipitation and streamflow time series, but we had to use the model to estimate catchment evapotranspiration and recharge to the till layer beneath each catchment. We have no direct measurements of evaporation fluxes and had to revert to estimating potential evapotranspiration from environmental measurements taken some distance from each site. This is a far from satisfactory state of affairs, but we believe that the combination of using a conceptual model for which key parameters are estimated directly from field integrated measurements (including estimates of soil lateral hydraulic conductivity) with measurements of precipitation and estimates of potential evapotranspiration offers an effective blend of modeling and measurements that will lead to improved hydrological and environmental design.

We emphasize the value of using continuous time series of measured precipitation and basin outflow in conjunction with modeled evapotranspiration and basin recharge (vertical leakage) over a period of several years to obtain quantitative measures or estimates of all relevant catchment hydrologic fluxes and volumes. These fluxes and volumes, on timescales having durations of a storm, a season, and a year, are likely to change when the land use is altered, and the magnitude of change is needed to assess the adequacy of different hydrologic designs. This makes a strong argument for additional monitoring in small catchments of the scale examined here; without measurements of hydrologic fluxes and states, model predictions have little plausibility. Wigmosta and Burges (1990) suggested that the costs of hydrologic monitoring for several years prior to development and several years after development, while not inconsequential, were a relatively small price to pay to learn more about the effectiveness of various measures taken to mitigate the hydrologic effects of land-use change and urbanization in particular. That suggestion, which has been made by others over the years, was made before measurements were available for calibrating the type of model proposed by Wigmosta and Burges (1990). The present work reports on use of such a model and measurement scheme; the vastly different hydrologic time series from the two catchments for the common 3 yr of measurement and modeling emphasizes the need for additional work of this type. Pre- and postmonitoring is being utilized in some urbanizing areas of King County, Wash., as well as other parts of the Country (Collins 1996).

Flow Production from Catchment Pervious and Impervious Areas—Klahanie

Fig. 10 provides a summary by water years of the contributions of the impervious and pervious land segments to annual flow volume production. The volume is expressed as an equivalent depth of water distributed uniformly over the plan area of the entire catchment. Impervious surfaces that are connected hydraulically to the receiving channel account for almost 30% of the catchment area. There is no simple way to determine apriori what fraction of total flow per year is contributed from which landform; the time patterns and depths of rainfall determine the respective distributions. Fig. 10 was produced by analysis of the measured precipitation record and measured catchment outflow hydrograph. For the 3 water yr, the pervious areas contributed between 39% (1993) and 60% (1991) of total basin runoff. During the November 1990 storm, the pervious area (70% of the total basin area) contributed 60% of the peak flow rate and 63% of the total flow volume. These findings emphasize the need to consider contributions to surface flow from all sources in the catchment when considering alternative urban designs and associated mitigative measures. Consideration of the impervious area alone or assuming that a "pervious area" is relatively benign will lead to designs that have deleterious ecological effects on receiving streams, wetlands, lakes, or tidal seas.

CONCLUSIONS

It was not possible to determine a priori what runoff mechanism would dominate storm runoff in the study basins. At the start of the study it was suspected that saturation overland flow would drive peak discharge in the Novelty Hill catchment and Horton overland flow from impervious surfaces would dominate storm runoff at Klahanie. It was the combination of modeling and measurements—continuous precipitation and streamflow (and piezometer water depths at Novelty Hill)—that was essential to elucidate the likely mechanisms and flow paths. The emphasis was on determining the hydrologic balance. It was necessary to consider the complete hydrologic balances over several water years to show differences in hydrologic flux patterns between a natural catchment and one of similar initial state that had been urbanized. It is the changes in such patterns that are of ecological consequence. These considerations are not new although they appear to have been underemphasized by two generations of professionals. The importance of the water balance was understood and articulated with blinding clarity by Horton (1931).

The model we developed was designed to be compatible with field observable spatial hydrologic process zones (infiltration, Horton overland flow, saturated overland flow, etc.) and to use hillslope average soil vertical and lateral hydraulic conductivities. For both catchments, the combination of measurements and modeling, even for relatively short periods (1 water yr or slightly longer), was critical to help elucidate the principal hydrologic mechanisms, their magnitudes at short and seasonal time horizons, and the resulting flow paths. Such information is essential when the hydrology of postchange land use needs to be estimated. It will be necessary to continue combined continuous simulation modeling and monitoring, no matter what model (or suite of models) is used, until we gain greater hydrologic predictive capability for land elements on the order of a few tens of hectares and can produce hydrologic designs that will minimize potential environmentally harmful consequences of land-use change.

APPENDIX I. STREAMFLOW DATA CREDIBILITY

There are many difficulties associated with taking environmental measurements in surburban streams and it is not always clear when and if obstructions may have been placed in the channel causing an increase in water depth and overestimates of the actual flow rate. Fig. 11 was created using time series of measured precipitation and measured streamflow. The latter was determined by converting measured water depth to flow rate through a 151° v-notch weir, which had been calibrated for a flow rate of approximately 30 L/s. During the first year (water year 1991) the catchment was visited on most occasions when substantial precipitation was anticipated. On those occasions the two weirs (shown at the catchment outlet in Fig. 4) were free flowing. During several visits in the early autumn and in late spring and summer (when flow rates were low and the days pleasantly warm), we noticed that children from the neighborhood had placed rocks a short distance upstream from the v-notch weir to cause a small shallow pool to form. We removed these obstructions and expect that the recorded flow rates represent reality for almost all of the first year.

Our only opportunities for calibrating the v-notch weir were for flow rates close to 30 L/s. For this flow rate the weir equation we used agreed to within 3.7% of the flow rate determined with a pigmy current meter at a section approximately 15 m upstream of the gauge. Because the maximum average daily flow rate did not exceed 100 L/s on more than two occasions during the 3 yr of measurement, we believe that the daily volumetric flow rates estimated from the measured weir stages are reliable.

We checked the three highest recorded flow rates for physical plausibility. This was done at the daily average scale by assuming the entire catchment to be saturated and that 100% of measured precipitation could become streamflow. If the recorded average daily streamflow rate exceeded this magnitude, there would be cause to question the measured quantity. Small differences could be accounted for by release of stored water from the shallow soil column. The three hydrograph peaks are apparent in Fig. 8 and occurred on November 24, 1990 (107.7 L/s); April 4, 1991 (99.7 L/s); and January 28, 1992 (68.6 L/s). The first two were plausible and consistent with regional rainfall patterns and regional hydrologic responses. We know that the weir equipment functioned properly and that there were no obstructions in the channel upstream of the weirs that would affect the flow rates for those time periods. The January 28, 1992 hydrograph is also plausible. The daily precipitation depths at Seattle Tacoma International Airport for the period of January 23 – January 31 were consistent with those recorded at Klahanie. The recorded average daily flow rate was less than the maximum estimated rate, assuming that 100% of the measured precipitation became channel flow. Close examination of the pervious flow components in Fig. 11 further supports our observations that the recorded flow pattern is likely to be correct.

One possible anomalous pattern in Fig. 11 occurs on September 4, 1992. This was the Friday before Labor Day weekend, and we think, but do not know for sure, that the local children impounded water behind the weir. [Our modeled hydrographs for the pervious area for September 1992 were consistent with the measured total flow rate (Wigmosta et al. 1994).] Although the measured September 4, 1992 flow rate was greater than the modeled rate, it did not suggest an artificially enhanced water level upstream of the weir. When the gauge was visited afterward, there was no evidence that water had been impounded upstream. We did not visit the site regularly during the summer months after the first year because we noted in the first year that there was little to no flow for most of the summer and early autumn.

We have included this discussion to emphasize the difficulty of obtaining reliable hydrograph time series in urban catchments, even in communities where there is strong support for environmental measurements. We also emphasize the value of simple checking schemes and the use of a calibrated model to help check the fidelity of hydrographs estimated from continuous water stage records.

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