A SUMMARY OF URBAN RUNOFF STUDIES IN THE DENVER METROPOLITAN AREA, COLORADO

By Sherman R. Ellis and Martha H. Mustard

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CONVERSION FACTORS

The inch-pound units used in this report may be converted to International System of Units (SI) by the following factors:

Multiply	*By*	*To obtain*
acre	0.4047	hectare
cubic foot per second	0.02832	cubic meter per second
foot	0.3048	meter
inch	25.40	millimeter
inch per hour	25.40	millimeter per hour
mile	1.609	kilometer
pound, avoirdupois	0.4536	kilogram
square foot	0.09294	square meter

To convert degree Celsius (°C) to degree Fahrenheit (°F), use the following formula: (°Cx9/5)+32=°F

National Geodetic Vertical Datum of 1929: A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level, and referred to as sea level in this report.

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ABSTRACT

The Denver metropolitan area has been the subject of urban runoff studies for several years. The first studies, started in about 1968, usually were concerned only with the quantity of urban runoff. In 1974, studies were begun that included both quantity and quality of urban runoff. In 1979, Denver was selected as one of the cities to be included in the Nationwide Urban Runoff Program. The Denver study was called the Denver Regional Urban Runoff Program and was a cooperative study between the Denver Regional Council of Governments and the U.S. Geological Survey.

This report presents the major conclusions of the pre-Denver Regional Urban Runoff Program studies and a summary of the various elements of the Denver Regional Urban Runoff Program. The report summarizes and references urban runoff studies in the Denver metropolitan area and is a guide for planners and other persons interested in urban runoff.

INTRODUCTION

The Denver metropolitan area has been the subject of urban runoff studies for several years. The lead local agencies have been the Denver Regional Council of Governments (DRCOG) and the Urban Drainage and Flood Control District (UDFCD). The city of Northglenn and the Denver Water Board have also participated in the study of urban runoff. The Denver area was selected in 1979 as one of the cities to be included in the Nationwide Urban Runoff Program (NURP), a program sponsored by the U.S. Environmental Protection Agency (EPA) and the U.S. Geological Survey. DRCOG was selected by EPA as the lead agency in the NURP study. The NURP study in the Denver metropolitan area was the Denver Regional Urban Runoff Program (DRURP) and was a cooperative study between DRCOG and the U.S. Geological Survey, with several local agencies performing assigned tasks under the direction of DRCOG.

The primary objective of the DRURP study was to develop a better understanding of the urban runoff processes in the semiarid West. The goals of the study were:

1. Characterization of urban runoff loadings by land use;

2. Definition of the sources of diffuse urban runoff;

3. Determination of the effects of urban runoff on the South Platte River, the major receiving water for urban runoff in the Denver metropolitan area;

4. Investigation of the opportunities for control of urban runoff loadings using best management practices (BMP's);

5. Evaluation of the receiving water-quality benefits from reduction of urban runoff loads;

6. Determination of appropriate semiarid, dry-weather constituent accumulation rates on impervious surfaces suitable for use in urban runoff quality models; and

7. Evaluation of the effectiveness of various local government institutional frameworks for the implementation of the urban runoff BMP's.

The Geological Survey was responsible for the studies for goals 1, 2, and 6. The goals of the DRURP assigned to the Survey were expanded and specific objectives were established for each goal. Once specific objectives were established, a work plan was developed to describe the work elements.

Seven basins were instrumented to monitor rainfall, runoff, and atmospheric deposition and to collect urban runoff water-quality samples. The data collected at these basins were used to characterize runoff loads of constituents by land use. Two basins were characterized by single-family housing, two by multifamily housing, and one each by commercial and multifamily housing, a shopping center, and a natural pastureland. The urban runoff data from these basins were used to identify the specific land surface sources of runoff loads.

Two detention ponds were monitored for inflow and outflow water quantity and quality to determine the effectiveness of the ponds in reducing the runoff loads of selected constituents. The detention ponds were located downstream from two of the monitored basins, one a single-family housing and the other a basin containing commercial development. The detention basin located downstream from the single-family basin did not pool water during the study period; consequently, only one detention basin was studied.

Accumulation rates of selected constituents on impervious surfaces are important variables in describing the processes of urban runoff. Two urban runoff models, a quantity and a quality model, were calibrated and verified on selected basins in the Denver area, providing an estimate of both accumulation and washoff rates of the selected constituents. The models also provided estimations of infiltration, impervious retention, soil moisture accounting, and overland flow parameters. The models were used to evaluate the buildup-rate concept and exponential-washoff equations.

Rainfall simulation on a street surface also was performed to determine the accumulation and washoff rates of selected constituents. The simulation also was performed on a natural pasture site to provide estimations of runoff rates from pervious area and soil moisture accounting parameters. The rainfall-simulation studies provided estimations of impervious and pervious area retention. The data from the rainfall simulation on the street surface also were analyzed to study the buildup-rate concept and the exponential-washoff equations.

Several small-scale studies also were included in the Survey's tasks. Storm loads derived from discrete and composite samples were compared to determine if composite samples were adequate to define the total storm loads. Water-quality samples were analyzed for total and dissolved constituents to determine the fraction of the total constituent that is particulate and the fraction that is dissolved. Runoff samples were separated by particle size, and the various particle fractions of the samples were analyzed for selected constituents to determine the runoff loads that were associated with discrete particle sizes. The data from the atmospheric deposition collectors were used to determine the effects of wet fall and dry fall on the runoff loads from the basins. The runoff from four basins was sampled to determine which of the U.S. Environmental Protection Agency's 126 priority pollutants were present.

Purpose and Scope

The purposes of this report are: (1) To present findings of previous urban runoff studies in the Denver area; (2) to present an overview of technical aspects of the DRURP study, including a synopsis of the elements of the study accomplished by various local and private agencies; and (3) to present, in synopsis form, the Survey's elements of DRURP that were presented in other reports. This report is a summary of the various elements of DRURP and a reference source. This report may be useful to the Federal, State, and local agencies interested in urban runoff in the semiarid West and particularly in the Denver area.

Description of the Study Area

The Denver metropolitan area is in the Piedmont region of Colorado between the Rocky Mountains on the west and the High Plains on the east. The climate is semiarid, with about 14 to 15 inches of precipitation per year. The greater part of the Denver metropolitan area lies within the study area (fig. 1). The study area is about 120,000 acres (187 square miles). The area is defined by the drainage area of a 14.5-mile reach of the South Platte River between two U.S. Geological Survey streamflow-monitoring stations, South Platte River at Littleton (U.S. Geological Survey downstream order number 06710000) and South Platte River at 50th Avenue, at Denver (U.S. Geological Survey downstream order number 06714130), and downstream from two tributary

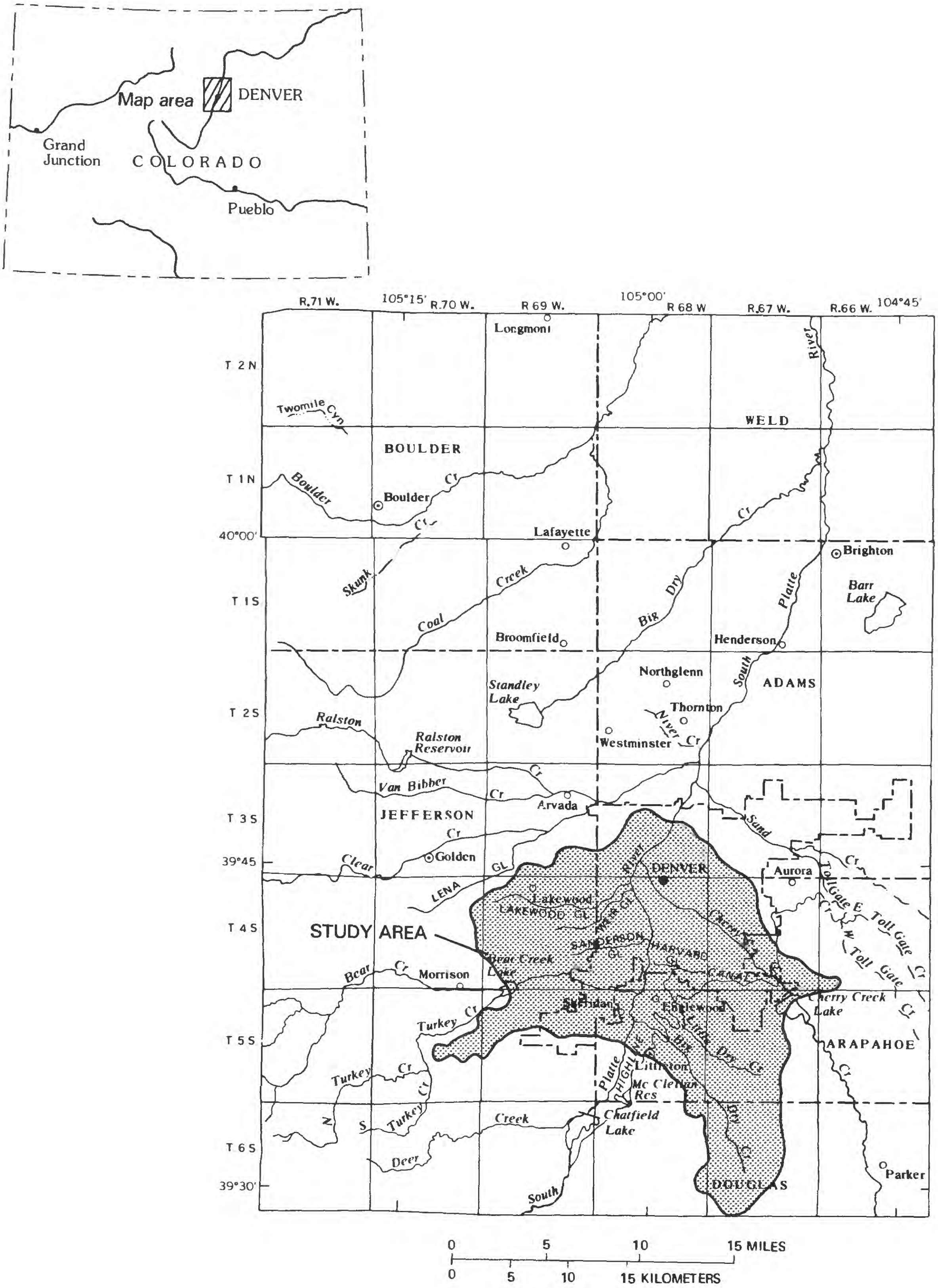

Figure 1.--Location of study area and general features.

reservoirs, Cherry Creek Lake and Bear Creek Lake (fig. 2). The altitude of the study area ranges from 7,965 feet above sea level in the western foothills to 5,310 feet on the eastern side of the basin, with the South Platte River valley extending south to north, ranging in altitude from 5,310 feet on the south to 5,140 feet on the north. The study area is characterized by steep slopes and soils that have a high infiltration rate, except in the western section where clay-bentonite soils are common.

The land-use distribution in the study area is about 43 percent residential, 19 percent commercial and industrial, and 38 percent open space (parks, vacant, and agricultural land uses). The residential land use includes all aspects of a residential area--old and new homes, cluster homes, large estates, apartments, and townhomes. The industrial areas are mainly light manufacturing, with coal-fired electric-generating powerplants, small factories, and no heavy industrial factories. The effective impervious area is approximately 23 percent of the total area.

The Colorado Water Control Commission has classified the reach of the South Platte River in the study area (Segment 14) as a Class 1, Warm Water Fishery (Colorado Water Quality Control Commission, 1980). Beneficial uses of the South Platte River include recreation, agriculture, and water supply. The city of Englewood obtains its water supply from the South Platte River near the upper end of the study area. The city of Thornton obtains a part of its water supply from a well field adjacent to storage ponds which are fed by the South Platte River. The Burlington Ditch and other agricultural ditch headgates are located immediately downstream from the study area.

Some descriptive data for the nine small basins monitored during the study are presented in table 1. The location of the rain gages, subcatchments boundaries, and detailed drainage maps are presented by Gibbs (1981) and Gibbs and Doerfer (1982). See figure 2 for the location of monitoring sites.

Six tributaries to the South Platte River (fig. 2) were monitored for urban runoff; selected data are in table 2. Detailed descriptions of the basins are presented in Gibbs and Doerfer (1982).

Four surface-water monitoring sites (fig. 2) were located in the study reach of the South Platte River and were used to monitor the effects of urban storm runoff on the South Platte River. The official name, U.S. Geological Survey downstream order number, and other basin data are presented in table 2. A detailed description of the monitoring sites is presented in Gibbs and Doerfer (1982).

URBAN RUNOFF STUDIES IN THE DENVER AREA

Urban runoff has been studied in the Denver metropolitan area since about 1968. The earlier studies were data-gathering activities usually concerned only with the quantity of urban runoff. In 1974, studies were begun that included the quality of urban runoff.

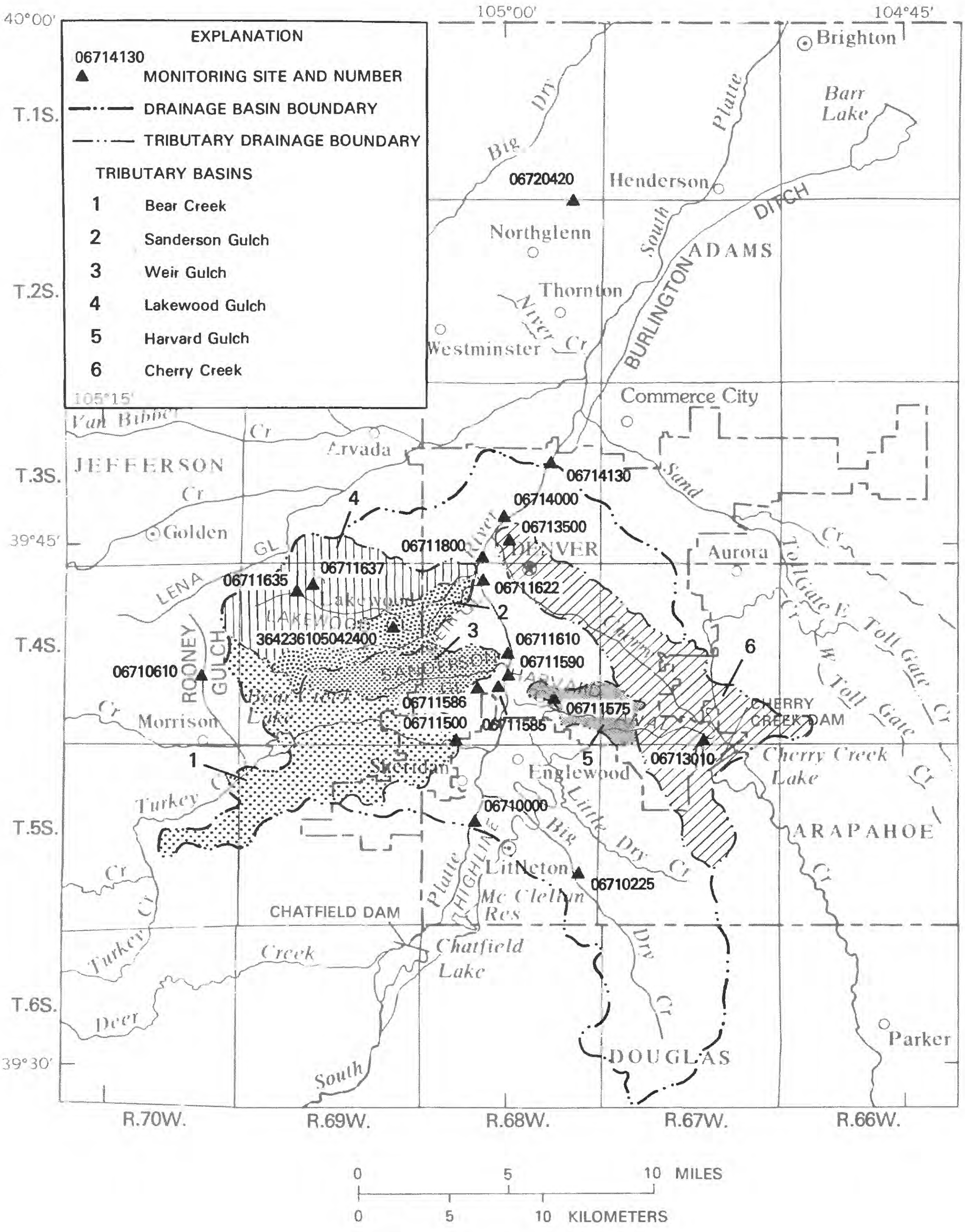

Figure 2.--Location of monitoring sites for the small and tributary basins and main-stem South Platte River.

Table 1.--*Selected data for the small basins in the Denver Regional Urban Runoff Program*

U.S. Geological Survey site number	Name of monitoring site	Latitude-longitude	Name used in report	Drainage area, in acres	Percent of area covered by effective impervious
06710225	Big Dry Creek tributary at Easter Street, near Littleton.	39°35'17", 104°57'20"	Southglenn basin	33	41
06710610	Rooney Gulch at Rooney Ranch, near Morrison.	39°41'27", 105°11'32"	Rooney Gulch basin	405	.6
06711585	Asbury Park storm drain at Denver.	39°40'52", 105°00'42"	Asbury Park basin	121	22
06711586	Asbury Park storm drain at Asbury Avenue, at Denver.	39°40'51", 105°00'41"	Asbury Park storm drain detention basin	127	22
06711635	North Avenue storm drain at Denver Federal Center, at Lakewood.	39°43'21", 105°07'47"	North Avenue basin	69	50
06711637	North Avenue storm drain at Denver Federal Center North Avenue, at Lakewood	39°43'22", 105°07'36"	North Avenue detention basin	80	46
06713010	Cherry Knolls storm drain at Denver.	39°38'58", 104°52'47"	Cherry Knolls basin	57	38
06720420	Storm Drain at 116th Avenue and Claude Court, at Northglenn.	39°54'23", 104°57'34"	Northglenn basin	167	24
394236-105042400	Villa Italia storm drain at Lakewood.	39°42'36", 105°04'24"	Villa Italia basin	74	91

Table 2.--*Selected data for the tributary basins and main-stem South Platte River sites*

[NA = Not applicable]

U.S. Geological Survey site number	Name of monitoring site	Latitude	Longitude	Drainage area in study area, in acres	Percent of area covered by effective impervious surface
06710000	South Platte River at Littleton------	39°37'08"	105°01'07"	0	NA
06711500	Bear Creek at mouth, at Sheridan-------	39°39'08"	105°01'57"	15,400	16
06711575	Harvard Gulch at Harvard Park, at Denver---------	39°40'21"	104°58'35"	2,830	30
06711590	South Platte River at Florida Avenue, at Denver---------	39°41'23"	104°59'57"	58,810	16
06711610	Sanderson Gulch at mouth, at Denver--	39°41'24"	104°59'57"	4,720	24
06711622	Weir Gulch at mouth, at Denver---------	39°43'52"	105°01'04"	4,790	22
06711800	Lakewood Gulch at mouth, at Denver--	39°44'14"	105°01'21"	10,400	33
06713500	Cherry Creek at Denver------------	39°44'58"	105°00'08"	15,800	27
06714000	South Platte River at Denver---------	39°45'35"	105°00'10"	108,000	22
06714130	South Platte River at 50th Avenue, at Denver---------	39°47'13"	104°58'28"	120,000	23

A series of basic-data reports, prepared in cooperation with various agencies, presented the data collected by the Survey on the quantity of urban runoff. The first report was published in 1971 (Gonzales and Ducret, 1971) and was followed by a series of data reports (Ducret and Hodges, 1972; Ducret and Hodges, 1975; and Cochran and others, 1979). Data collection is continuing as a cooperative study between the Survey and the Urban Drainage and Flood Control District.

In 1974, DRCOG began a study under Section 208 Public Law 92-500 to evaluate the effect of urban runoff on the South Platte River in the Denver metropolitan area. The DRCOG study was titled the Clean Water Program, and its findings were published as the Clean Water Plan (Denver Regional Council of Governments, 1977). As part of the Clean Water Program, DRCOG, UDFCD, and the Denver Water Board entered into a cooperative agreement with the U.S. Geological Survey to monitor the urban runoff from three basins in the Denver area. This study was called the Denver Urban Runoff Study.

The three basins chosen for the Denver Urban Runoff Study were the 36th Street basin, an older residential and commercial area; Big Dry Creek Tributary basin, a newer single-family housing residential area with some open space; and the North Avenue basin, which was a multifamily housing area and a light commercial area consisting mainly of office buildings and restaurants. The study collected urban runoff data from 1975 through June 1977. Equipment was installed at each site to measure rainfall, runoff, and specific conductance and also to collect discrete water-quality samples. The data were presented in Ellis (1978), and an interpretive report was presented by Ellis and Alley (1979).

The findings of Ellis and Alley (1979) were that antecedent precipitation or the number of days since the last street sweeping had no apparent effect on the rainfall-runoff quality. However, snowmelt-runoff loads apparently increased with the number of days snow had been on the ground. A first flush, defined as a disproportionately large part of the total storm-runoff load in the initial part of the storm runoff, was rare in the Denver area. In addition, urban storm runoff may be a significant contributor of total ammonia nitrogen, total nonfiltrable residue (total suspended solids), total copper, total lead, and total zinc to the South Platte River.

In a report by Alley and Ellis (1978) on data collected for the Denver Urban Runoff Study, it was concluded that concentrations of total copper, total iron, total lead, and total zinc were in excess of Colorado Water Quality Standards (Colorado Department of Health, 1977) for various beneficial uses of receiving waters. Using model-simulated and observed hydrographs and regression equations, the estimated April 1 through October 31, 1976, loads of trace elements for a 606-acre residential basin were: copper, 4.4 pounds; lead, 44 pounds; and zinc, 23 pounds. For comparison, during the same period, the estimated basin trace element loads from secondary wastewater were: copper, 28 pounds; lead, 14 pounds; and zinc, 98 pounds. The basin was found to be a significant contributor of total lead and total zinc to the South Platte River, and the loads of total lead approached the loads of total lead from the Argo Tunnel, a major source of mine drainage in the South Platte River basin. The Argo Tunnel is located in Idaho Springs, west of the Denver area.

Urbonas and Tucker (1978) used the data from the Denver Urban Runoff Study to estimate the percent of the total load (urban runoff plus secondary-treated effluent) from the Denver urban area that came from urban runoff. The secondary-effluent loads were estimated based on 60 gallons per capita per day and the concentrations reported by the Metropolitan Denver Sewage Disposal District Number 1. It was estimated that from 17 to 25 percent of the total organic carbon, 38 to 46 percent of the total nitrite plus nitrate as nitrogen, 76 to 88 percent of the total lead, and 19 to 56 percent of the total zinc loads originating in the study area were from urban runoff.

The DRCOG Clean Water Program, of which the Denver Urban Runoff Study was a section, utilized a deterministic model for simulation of the relation between urban runoff and instream water quality. The model used land-surface constituent buildup rates found to be appropriate in other areas of the country (mainly Tucson, Ariz., and Tulsa, Okla.), but did not use any data collected by the Denver Urban Runoff Study. Unfortunately, insufficient long-term, locally collected data plus substantial estimating of control-measure effectiveness has caused concern about the reliability of the model output. DRCOG concluded that only establishing an urban runoff data base and implementing projects to evaluate the effectiveness of control measures could overcome the poor reliability of model evaluation studies.

Hall and Duncan (1980 and 1981), in a cooperative study between the Geological Survey and the city of Northglenn, reported that lead, manganese, cadmium, and copper occurred in urban runoff at concentrations exceeding Colorado water-quality standards for agricultural water. The study objectives were to determine the feasibility of using urban runoff for irrigation. The study concluded that agricultural use of urban runoff from Northglenn sometimes will require reducing concentrations of selected trace elements. It was suggested that the concentrations could be reduced by trapping sediment in a reservoir, using filtration or precipitation of sediments, or by diluting urban runoff with other water available to the city of Northglenn.

A report by the Colorado Department of Health (Anderson, 1978) concluded that the South Platte River and other receiving waters in the Denver area are heavily impacted by nonpoint sources, including urban storm runoff. Bacteria, plant nutrients, and trace elements have been primarily attributed to urban runoff. The Colorado Department of Health has concluded that the receiving waters in the Denver area are unsuitable for the intended beneficial uses such as recreation, agriculture, and water supply due to the effect of nonpoint sources, including urban storm runoff.

ELEMENTS OF THE DENVER REGIONAL URBAN RUNOFF PROGRAM BY THE DENVER REGIONAL COUNCIL OF GOVERNMENTS

Three types of studies were conducted by local agencies and private consultants for DRCOG: (1) Best management practices (BMP's); (2) radar precipitation mapping and tracking; and (3) effects of urban runoff on the South Platte River in the Denver metropolitan area. The BMP's studies included evaluation of detention ponds for improvement of urban runoff quality, percolation pits, erosion control, storm-water drainage maintenance programs, and alternative storm-water treatment methods. The lead agencies in the BMP studies were DRCOG, the city of Littleton, the city of Englewood, and Adams County. The radar precipitation-mapping and -tracking study included a summary and description of using radar and digital-processing equipment to quantify and track precipitation crossing the Denver metropolitan area; the lead agency was UDFCD and GRD Weather Center, Inc. (GRD). DRCOG was the lead agency in evaluating the effect of urban runoff on the South Platte River. Included in the evaluation were a study of bottom materials, a regression analysis of base and stormflow, the estimation of seasonal loads of selected constituents in base and stormflow, the effects of secondary-treated effluent on the South Platte River, and a determination of the secondary-treated effluent loads generated in the study area. These studies were published by the Denver Regional Council of Governments (1983).

Structural Best Management Practices

A detention pond on the Denver Federal Center was monitored for inflow and outflow to determine the effectiveness of the ponds in reducing storm loads of constituents. The pond, North Avenue detention pond, is downstream from the North Avenue basin. The North Avenue basin monitoring site was used to provide the inflow data, and a monitoring site on the outflow was established to provide outflow data. The detention pond has 11 more acres of drainage area than the North Avenue basin, most of the additional drainage area being mainly undeveloped. Only those storms that did not produce runoff from this additional area were used in the analysis of the detention pond.

The detention pond was cleared of all vegetation and was contoured before the start of the study. The pond was operated in an unaltered state for about 1 year, during which grass, cattails, and small trees grew in the pond. The vegetation stabilized the bottom of the pond and erosion from the pond was curtailed. A dam about 2 feet high was constructed across the lower end of the pond to increase detention of the storm-runoff water. The dam allowed the dry-weather flow to pass through the pond with little or no detention, but increased the detention time of the stormflows.

The modified detention pond was monitored for inflow and outflow of storm runoff and selected constituent loads from May through September 1981, during which 17 storms were monitored. The average percent reduction of the loads by the detention pond were: total suspended solids, 11 percent; chemical oxygen demand, 19 percent; total nitrogen, 20 percent; total phosphorus, 9 percent; total lead, 16 percent; total zinc, 27 percent; and total manganese, 38 percent. The storm-runoff volume reduction was about 25 percent for the modified pond, but the reduction may be partly due to flow-measurement errors, and the total reduction of volume may be somewhat less. Infiltration into the ground is the most probable reason for reduction of flow.

A special study to determine particle-size distribution of selected constituents was begun by the Survey and DRCOG on four runoff samples from the North Avenue basin. The runoff samples were filtered through 16-, 8-, 3-, 2.5-, and 0.45-micron-diameter pore-size filters. The results of this study indicate that lead, zinc, and iron are associated with the 8-micron and smaller particle sizes, copper was usually in the dissolved state (less than

0.45 microns), and nitrogen was associated with all particle sizes tested. Cadmium was primarily in the particulate phase (that is, larger than 0.45 microns), but was not associated with any particular size. It should be noted that this study may contain biases due to the use of filter paper for particle separation. The pore size in the paper filters may not have been uniform and smaller particles may have been trapped above larger particles, resulting in improper particle-size determination. The study indicates that iron, lead, zinc, manganese, and some nitrogen may be removed by settling of the urban runoff.

Percolation pits are another BMP that need to be considered for controlling storm-water runoff in suitable areas. The lead agency in evaluation and design of percolation pits was Adams County (Adams County Planning Department, 1982b). The two main considerations in the suitability of percolation pits are the types of subsoils and the depth to the ground-water table. The subsoils need to be highly permeable, such as sandy and gravelly subsoils, and need to be of sufficient depth to allow for rapid percolation of the storm waters through the sides and bottom of the pit. The ground-water table needs to be of sufficient depth to allow for percolation, while not rising to a level where basements are subjected to flooding, foundations are damaged, or pavements are degraded. An advantage of the percolation pits is that the storm runoff may be used to recharge the ground water. The pits are not suitable where toxic substances are present in the runoff.

In conclusion, the report prepared by the Adams County Planning Department (1982b), indicates that percolation pits are a practical BMP for storm-water control where soils have percolation rates greater than 0.6 inch per hour and local ground water is of sufficient depth to allow percolation without harm to near-surface structures. The report presents a detailed design of the pits, including sizing of the pits, types of pit liners, placements of pits, costs of construction, and recommended maintenance procedures.

Several other structural methods exist for controlling storm water, including porous pavement, parking-lot detention, rooftop storage, and underground drainage. The city of Englewood was the lead agency in the evaluation of other structural BMP's. One source of the city's water supply is McClellan Reservoir, which is the receiving water for urban runoff that may be generated from a new development. The city contracted with Black and Veatch Consulting Engineers (1982) to investigate and recommend control methods for removing undesirable constituents in the urban runoff, thus protecting the city's water supply. Four types of storm-water control alternatives were evaluated: Wetlands, sediment ponds followed by rapid infiltration, package treatment plants, and a procedure called the Swedish treatment method. The Swedish treatment method is a system using flow-balancing tanks placed at the mouth of the stream entering the reservoir. The sedimentation pond followed by rapid infiltration alternative was recommended as the most economical system that would protect the reservoir and maintain the city's water supply. The other methods were too costly to either build or maintain, and no suitable area was available for wetlands.

Nonstructural Best Management Practices

Nonstructural controls (BMP's) can be effective and cost-efficient means of controlling urban runoff. Three main nonstructural BMP's that were considered in DRURP were street sweeping, erosion control, and maintenance of drainage facilities. Six NURP cities, not including Denver, evaluated street sweeping, but only one city reported reduction of constituent loads in urban runoff resulting from street sweeping (U.S. Environmental Protection Agency, written commun., 1982). Erosion control was investigated by Adams County (Adams County Planning Dept., 1982a) and by Wright-McLaughlin Engineers (1982) through a contract with DRCOG. Construction sites provide the best opportunity to control erosion; methods such as wind fences, mulching exposed soils, and temporary onsite sediment ponds may be used. The city of Littleton, in a contract with Simons, Li and Associates, Inc. (1982), reported that maintenance of detention and drainage systems improved water quality of the urban runoff and provided aesthetic benefits in the form of attractive detention ponds and drainageways. It was determined that drainage maintenance may be abandoned due to high costs if the maintenance is not properly planned. It also was concluded that proper maintenance of the detention ponds and drainage systems, in the long run, reduces costs and flooding and lengthens the life of the facilities.

Radar Precipitation Mapping and Tracking

UDFCD was the lead agency both in the evaluation of radar precipitation (rainfall) mapping and in the effort to determine if preferred thunderstorm tracks exist within the Denver metropolitan area. UDFCD contracted with GRD to design and carry out a study of thunderstorm intensity and movement. GRD monitored rainfall May through September 1980 and April through September 1981--a total of 74 rainfall storms. The study report was prepared by John F. Henz and Edward W. Pearl (1982).

The system used to provide the radar-derived rainfall data consists of the National Weather Service WSR-57 radar, a 10-centimeter band radar located at Limon, Colo., a Kavouras[1] computerized color radar receiver equipped with a radar-interface circuit board, and a computer system consisting of a microcomputer and floppy-disk file system. The system used an existing network of rain gages to provide actual rainfall data.

The radar-derived rainfall maps were very useful in obtaining basin rainfall for several rainfall storms. The radar-reflectivity maps were not proven to be accurate estimators of rainfall without the use of the rain-gage network. Further work is necessary to develop procedures for real-time prediction of rainfall using only the radar data. The radar-derived rainfall maps calibrated using the rain-gage network were proven to provide a better estimate of basin rainfall than that obtained using only a widely spaced rain-gage network.

[1]Use of the brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Data from the Limon radar was stored in the computer system when meteorologists at GRD observed rainfall echoes on the color radar. The radar data were summed to provide 15-minute summaries. The rainfall data from the rain-gage network, also summed to 15 minutes, were used to correlate the radar reflectivity data using linear, power, and log-transform equations. The output was in the form of 15-minute rainfall and total storm rainfall tables. The tables were transformed to plots of areal rainfall, and the plots were compared to known point rainfall. The final product was a series of 15-minute and total storm rainfall maps, as determined by radar reflectivity and rain gages, for the Denver metropolitan area.

The monitoring of rainfall storms using the color radar receiver resulted in the identification of two preferred tracks for thunderstorms. The two storm tracks are in the southern third (the south metro track) and the north-central (the north-central metro track) parts of the Denver metropolitan area (fig. 3). The southern boundary of the south metro track extends from the area near Chatfield Lake to just north of Castle Rock. The northern boundary of the track extends from south Lakewood to south Denver to north-central Aurora. The thunderstorms originate in the foothills and travel in an east-northeast direction in the south metro track. Approximately 65 percent of the intense thunderstorm tracks are in this corridor. The north-central metro track northern boundary is ill-defined, but extends from just north of Golden to Lafayette to near Brighton. The southern boundary extends from central Lakewood to northwestern Denver to Commerce City. The thunderstorms originate in the foothills and travel in a northeast direction in the north-central metro track. Approximately 27 percent of the intense thunderstorm tracks in the Denver metropolitan area are in this corridor. During the study period, about 8 percent of the intense thunderstorms in the Denver area occurred outside the two thunderstorm tracks.

Bottom-Sediment Chemistry of the South Platte River

Three reconnaissance-level bottom-sediment chemistry surveys were conducted at 18 to 22 sites along the South Platte River in the Denver metropolitan area (Steele and Doerfer, 1983). The study was conducted jointly by DRCOG and Woodward-Clyde Consultants, under a contract with DRCOG. Sampling sites were located relative to outflows from major tributary streams and discharge points from industrial and municipal sources. The bottom-sediment samples were sieved into five particle-size classes for chemical analysis of selected trace elements, nutrient species, and organic matter.

Relative contributions from point and nonpoint sources were distinguished in a qualitative manner from the results of the bottom-sediment study. Inverse relations were found between particle size and constituent concentrations. Stream-reach profiles for nutrient and organic matter were indicative of point-source loading from waste-water treatment-plant discharges. The cadmium reach profile indicated point-source contributions, possibly from near upstream industrial and utility facilities. The lead reach profile was indicative of urban nonpoint-source loading.

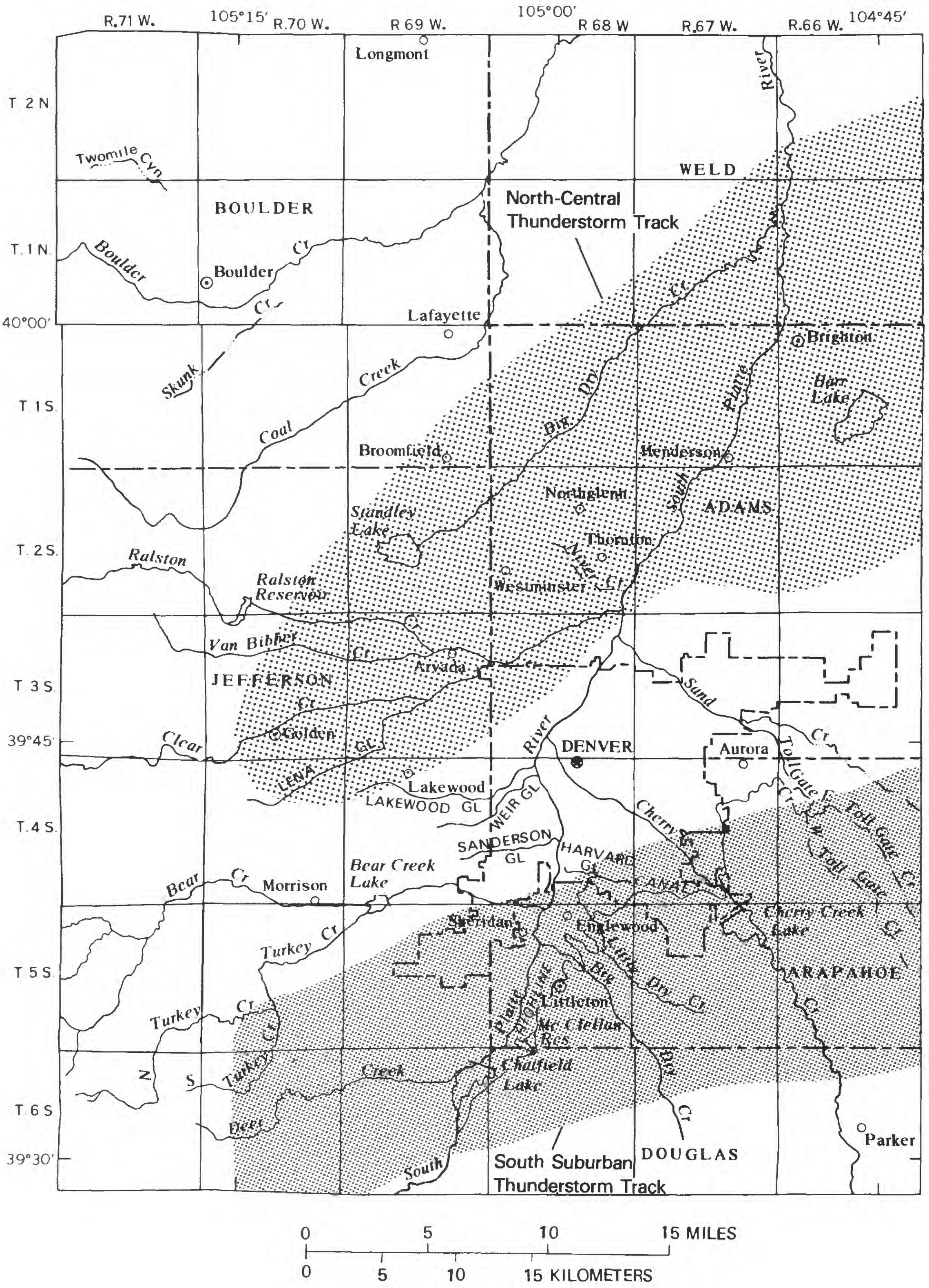

Figure 3.--Boundaries of the thunderstorm tracks in the Denver metropolitan area.

Priority Pollutants

EPA priority pollutants (see Gibbs and Doerfer, 1982, for a complete list of the EPA priority pollutants) were detected in storm runoff from four small basins. The pollutants found at the specific basins are listed in table 3. The most frequently detected priority pollutants were trace elements. Organic priority pollutants were found at all four of the basins; the most common was α-BHC, a pesticide.

Synthetic organic compounds, other than the EPA priority pollutants, detected in storm runoff from the small basins are presented in table 4. The most significant pollutant detected in the storm runoff was 2,4-D, a herbicide, at the Southglenn basin, where the concentration was 180 micrograms per liter.

The EPA priority-pollutant monitoring study included the collection of discrete and flow-weighted composite samples. The discrete samples were taken from the initial storm runoff, while the composite represented the complete storm-runoff period. It was assumed that higher concentrations of the pollutants would be found in the discrete sample and that more of the priority pollutants would be detected in the composite samples. The assumption was found to be not true for the Denver metropolitan area.

U.S. GEOLOGICAL SURVEY'S ELEMENTS OF THE DENVER REGIONAL URBAN RUNOFF PROGRAM

Several elements and findings of the DRURP have been published by the U.S. Geological Survey in a variety of formats. Two basic-data reports (Gibbs, 1981; Gibbs and Doerfer, 1982) were published as Open-File Reports. A model calibration and verification report (Lindner-Lunsford and Ellis, 1984) was published as a Water-Resources Investigations Report. The results of a rainfall simulation on a street and a natural land use site were published as an Open-File Report pending publication as a Professional Paper (Mustard and others, 1985). An analysis of a large thunderstorm occurring on August 14, 1980, was published as a Water-Resources Investigations Report (Blakely and others, 1983). The effect of urbanization on the quantity and quality of storm runoff was published in the proceedings of the International Symposium on Urban Hydrology, Hydraulics, and Sediment Control (Ellis and others, 1983). A summary of data, regression analysis, application and comparison of deterministic and regression models, and the effects of urban runoff on the South Platte River in the Denver metropolitan area were presented in a Water-Resources Investigations Report (Ellis and others, 1984). A brief synopsis of these reports is presented in the following paragraphs.

Urban storm-runoff data, collected from April through September 1980, from nine urban runoff sites, were presented by Gibbs (1981). Precipitation, rainfall-runoff, water-quality (common constituents, nutrients, coliform bacteria, solids, and trace elements), and basin-area data that are necessary to use the U.S. Geological Survey's Distributed Routing Rainfall-Runoff Model, Version II (DR_3M-II) (Alley and Smith, 1982a) were published in this report. The urban storm-runoff data (Gibbs, 1981) may be used to characterize runoff-constituent loading for various land use types in Denver and other semiarid regions.

Table 3.--*Environmental Protection Agency priority pollutants detected in samples collected from small basins*

Date sampled	Monitoring basin	Trace elements	Pesticides	Volatile compounds	Other
5/28/81	North Avenue	Copper, Nickel Lead Selenium Zinc	α-BHC λ-BHC	Chloroform	
8/12/81	North Avenue	Arsenic Copper Lead Zinc	α-BHC λ-BHC		Bis (2-Ethylhexyl) Phthalate Cyanide
5/28/81	Asbury Park	Arsenic Copper Lead, Antimony Nickel Selenium Zinc	α-BHC		Bis (2-Ethylhexyl) Phthalate
5/28/81	Villa Italia	Arsenic Copper, Nickel Lead Selenium Zinc	α-BHC		
8/12/81	Villa Italia	Arsenic Chromium Copper Lead Nickel Zinc Cadmium	α-BHC	Tetrachloroethylene Methylene Chloride	Cyanide Di-N-Butyl Phthalate
5/26/81	Southglenn	Copper Lead, Nickel Selenium Zinc	α-BHC λ-BHC	1,1,1, Trichloroethane	
8/13/81	Southglenn	Arsenic Copper Lead Selenium Zinc	α-BHC	1,1,1,-Trichloroethane	Bix (2-Chloroisopropyl) Ether

Table 4.--*Synthetic organic compounds produced by industrial sources and detected in samples collected from small basins*

Synthetic organic compound	Basin
6-Methoxy-N,N'-bis(1-methylethyl) -1,3,5-triazine-2,4-dione	Villa Italia
4-Propoxyphenol	Southglenn
Methylheptanol	Villa Italia
3-Methyl-2-cyclohexene-1-one	Villa Italia North Avenue Southglenn
1-(2-Butoxyethoxy) ethanol	Southglenn North Avenue
2,2,4-Trimethyl-1,3-pentanediol	North Avenue
Tributylphosphate	North Avenue
9,10-Anthracenedione or 9,10-Phenanthrenedione	Southglenn
2,4-Dichlorophenoxyacetic acid (2,4-D)	Southglenn
(1,1' biphenyl)-carboxaldehyde	Southglenn
Unidentified substituted alkyl hydrocarbon #1	Villa Italia North Avenue Southglenn
Unidentified substituted alkyl hydrocarbon #2	Villa Italia
Unidentified substituted alkyl hydrocarbon oil	North Avenue Southglenn
Unidentified substituted polycyclic aromatic	Villa Italia
2,/2-(2-Butoxyethoxy) ethoxy/ethanol	Southglenn

The report by Gibbs and Doerfer (1982) presented data collected from the DRURP study from September 1980 through September 1981. The data included quantity and quality of snowmelt runoff, rainfall-runoff from the nine urban runoff sites, urban storm runoff from six major tributaries and four main-stem sites of the South Platte River, and precipitation. Data from two rainfall simulation studies on a street (North Avenue on the Denver Federal Center) and a natural site (Rooney Ranch) also were presented. Analytical methods, detection limits, and information on the accuracy of the water-quality data were also presented. The basin data needed to apply DR_3M-II to the natural basin at Rooney Gulch were presented as well as an aerial photograph showing the basin, subcatchments, location of rain gages, and monitoring site.

DR_3M-II was calibrated and verified on five urban basins and the results were reported by Lindner-Lunsford and Ellis (1984). The basins were North Avenue, Southglenn, Cherry Knolls, Northglenn, and Villa Italia. The average accuracy of the model for prediction of peak flows and runoff volumes was about 15 percent for storms having runoff volumes of more than 0.01 inch and rainfall intensities of less than 1 inch per hour. In addition, DR_3M-QUAL (Alley and Smith, 1982b), a multievent urban runoff-quality model, was calibrated and verified on four of these basins. Southglenn basin did not have sufficient data to apply DR_3M-QUAL. DR_3M-QUAL was found to be most useful in the prediction of seasonal loads of constituents in the runoff resulting from rainfall. The model was found to be not very accurate (at times, the error of estimation exceeded 200 percent) in the prediction of individual runoff constituent loads.

On August 14, 1980, an intense convective storm occurred over the Denver metropolitan area. Urban runoff from this storm was monitored for both quantity and quality at three sites on the South Platte River and at one site on each of six major tributaries to the river. The effect of this storm was reported by Blakely and others (1983). Tributary basins were analyzed and total areas, land use, and effective impervious areas were determined for comparison with storm-runoff loads. The total measured rainfall ranged from 0.00 to 1.41 inches in various sections of the basin. The maximum 5-minute rainfall measured was 0.37 inch. Basin rainfall totals were determined by use of radar reflectivity, which was correlated with rain-gage data. The report indicated that rain-gage data alone are not sufficient to obtain average basin rainfall for large drainage basins during this type of intense storm in the Denver area, but the basin rainfall may be more accurately determined by use of both rain-gage and radar-reflectivity data.

Blakely and others (1983) also reported that the storm runoff to the South Platte River increased the volume of flow to nearly three times the base flow. The increase in the main-stem storm-runoff loads ranged from 2.6 times the base-flow load (total orthophosphate) to nearly 30 times the base-flow load (total suspended solids). The event mean concentrations of copper, lead, manganese, and zinc exceeded the 1979 water-quality standards (Colorado Water Quality Control Commission, Colorado Department of Health, 1979) for aquatic life in Colorado at several monitoring sites. Further analysis of the storm-runoff load data indicated that a significant part of the main-stem storm-runoff loads may be resuspended bottom material.

Two rainfall-simulation studies were performed on nine 1,000-square-foot impervious plots and two 400-square-foot native pastureland plots. The procedures and results were reported by Mustard and others (1985). The objectives of the first study were to compare the quantity and quality of two different intensities of rainfall on impervious plots with identical antecedent conditions, to document a first flush of constituent loads from the impervious plots, to compare runoff constituent loads with constituent deposition, to develop regression equations predicting constituent loads in the runoff, and to compare the runoff characteristics from a street surface with those from an adjacent 69-acre urban basin. The objectives of the second study were to determine infiltration rates at the native pastureland sites and to compare quantity of runoff from the 400-square-foot plots and an adjacent 405-acre basin of native grass.

The rainfall-simulation report concluded that the higher intensity simulated rainfall had a higher percentage of rainfall that ran off than the lower intensity rainfall. A first flush of constituent loads occurred for most constituents on the small plots; however, a first flush did not occur in the runoff from simulated rainfall on the native grass sites. A first flush was not common in the 69-acre urban basin. The event mean concentrations in the runoff from the street plots generally were smaller than those from the adjacent urban basin. The washoff loads of most constituents from the street plots generally were smaller than the constituent deposition measured by street vacuuming. It was not statistically valid to develop regression equations for constituent loads as a function of total rainfall, intensity of rainfall, and days since street vacuuming. The runoff-to-rainfall ratios for the native-grass sites were within the range of ratios measured from the natural storms occurring in the adjacent 405-acre basin of native grass.

Ellis and others (1983) reported that a small urban drainage basin has undergone several changes from 1977 to 1980; the major changes were a reduction in size from 76.7 acres in 1977 to 68.7 acres in 1980 and an increase in effective impervious area from 29 percent to 50 percent. Two methods were used to determine the effects of these basin changes on the storm runoff. First, runoff from two storms in 1977 was compared with runoff from two similar storms in 1980. Second, the results of rainfall-runoff simulation using the U.S. Environmental Protection Agency's Storm Water Management Model II (SWMM-II) (Huber and others, 1975) were calibrated for 1977 and 1980 conditions. Both methods indicated larger runoff volumes in 1980 than in 1977.

The effects of basin changes on the quality of storm runoff were determined by comparing storm and runoff loads from two storms in 1977 with storm and runoff loads from two similar storms in 1980. Also, flow-weighted mean concentrations of selected constituents from 1976-77 were compared with those from 1980. The loads and mean concentrations of total lead, total zinc, total orthophosphate, and total suspended solids decreased, while the loads and mean concentrations of total nitrogen increased. The effect of urbanization on the quantity and quality of urban storm runoff was published in the proceedings of the International Symposium on Urban Runoff (Ellis and others, 1983).

Ellis and others (1984) presented data and regression analysis, application and comparison of deterministic and regression models, and the effects of urban runoff on the South Platte River in the Denver metropolitan area. The major topics of the report included analysis of the small basin data, regression analysis to estimate storm-runoff volumes and loads of selected water-quality constituents, comparison of the mean seasonal storm-runoff volumes and constituent loads estimated by deterministic and regression models, and three ways to describe the effects of urban runoff on the South Platte River.

The section on data analysis of the small basins presented a summary of all data collected at the sites, including the maximum, minimum, and mean values of rainfall, storm-runoff volumes, constituent loads and concentrations, and runoff-rainfall ratios. The section contained a summary of the atmospheric deposition data, including an estimation of the deposition that fell on the effective impervious areas of the basin from April 1 through September 30, 1981.

The data analysis section reported the findings of three special studies to: (1) Determine the impervious retention for each basin, (2) determine if a single flow-weighted composite water-quality sample can be adequately used to determine constituent storm loads, and (3) determine during which phase, dissolved or suspended, selected constituents occurred in urban runoff.

Impervious retention values obtained for the basins from regression analysis were as follows: North Avenue, 0.03 inch; Southglenn, 0.03 inch; Villa Italia, 0.04 inch; Northglenn, 0.05 inch; and Asbury Park and Cherry Knolls, 0.13 inch. Regression analyses were made using the combined data from all the basins. The impervious retention for the combined basins was 0.09 inch. Impervious retention may be used in the estimation of runoff from unmonitored basins.

A special study was performed to determine if storm constituent loads could be adequately measured using one flow-weighted composite sample and the volume of runoff. Discrete water-quality samples and flow-weighted composite samples were analyzed for 16 storms, and the results from the constituent loads calculation using the discrete- and composite-sample techniques were compared. The composite-sample technique produced results not significantly different from the discrete-sample technique, but the composite-sample loads averaged about 7 percent smaller than the discrete-sample loads.

The results of analysis of 68 samples for dissolved and total concentrations concluded that most trace elements were predominantly in the suspended phase. The average percent of the constituents that were in the suspended phase were: cadmium, 61 percent; copper, 58 percent; iron, 98 percent; lead, 94 percent; manganese, 74 percent; and zinc, 77 percent.

The data from six small and five tributary basins were analyzed using regression techniques. Two sets of regression equations were developed to predict storm-runoff volume and runoff loads of total suspended solids, chemical oxygen demand, total nitrogen, total phosphorus, total lead, total zinc, and total manganese. The first set of regression equations, derived using the small basin data, is applicable to unmonitored basins from 15 to 600 acres and for effective impervious areas from 15 to 90 percent. The results of the regression analysis of the small basin data are presented in table 5. The second set of regression equations, derived using the combined small and tributary basins, is applicable to unmonitored basins from 600 to 16,000 acres and for effective impervious areas from 15 to 90 percent. The combined small and tributary basin regression equations are presented in table 6.

Several applications were demonstrated for DR_3M-II, DR_3M-QUAL, and the statistical models. DR_3M-II and Log Pearson-Type III analysis (Interagency Advisory Committee on Water Data, 1981) were used to estimate the mean seasonal peak flows from the North Avenue, Southglenn, Cherry Knolls, Northglenn, and Villa Italia basins (table 7). The estimated mean seasonal peak flows were obtained by using 5-minute incremental rainfall data for the three to five storms per year that would produce the greatest runoff peaks; rainfall data were obtained from the National Weather Service's Stapleton Airport weather station for 1898 through 1970. DR_3M-II also was applied, using hourly rainfall data from Stapleton Airport weather station for 1951-70, to estimate the mean seasonal runoff volumes from the same basins. DR_3M-QUAL was used to estimate the mean seasonal storm-runoff constituent loads from the North Avenue, Cherry Knolls, Northglenn, and Villa Italia basins (table 8). The rainfall data used were the same as those used to estimate the mean seasonal storm-runoff volume.

An application of the small-basin regression models was to estimate the water quality associated with atmospheric deposition. The regression equations were used to estimate the 1981 seasonal runoff loads of selected constituents, which were compared with the measured atmospheric deposition loads in the basins. The results indicated that chemical oxygen demand, total nitrogen, and total phosphorus are associated with atmospheric deposition. Total nitrogen was associated with both wet and dry deposition, and chemical oxygen demand and total phosphorus were associated with dry deposition. The constituent loads of total suspended solids, total lead, total manganese, and total zinc were much larger in the estimated runoff loads than in the combined wet and dry deposition. The results indicated that the atmospheric collectors do not measure the transport mechanism of certain constituents, such as solids and trace elements.

A comparison was made between the estimation of mean seasonal storm-runoff volumes and constituent loads from the deterministic and regression models (table 8). The regression equations used to determine the runoff volumes and constituent loads were a basin-specific model. The results for the Villa Italia basin differed by as much as 400 percent, and the deterministic model estimations were closest to the most probable results. Because deterministic models require extensive basin data and the use of computers, the regression models probably are the most suitable for use in unmonitored basins where the results would be used for planning purposes.

Table 5.--*Regression equations to estimate storm-runoff volume and loads of selected constituents derived from the small basins*

[Storm-runoff volume in cubic feet; constituent load in pounds; TA = total area, in acres; PEIA = percent effective impervious area; RF = total rainfall, in inches]

Dependent variable	Independent variables and constants	Coefficient of determination (r^2)	Standard Error of estimate (percent)	Number of observations
Storm runoff volume	$= 4.0\ TA^{1.17}\ PEIA^{1.34}\ RF^{1.19}$	0.90	39	81
Total suspended solids	$= 0.41\ TA^{0.96}\ PEIA^{0.949}\ RF^{0.883}$	.44	113	80
Chemical oxygen demand	$= 2.4 \times 10^{-3}\ TA^{1.4}\ PEIA^{1.59}\ RF^{0.582}$	.58	70	80
Total nitrogen	$= 4.3 \times 10^{-5}\ TA^{1.56}\ PEIA^{1.59}\ RF^{0.764}$	.67	67	80
Total phosphorus	$= 4.9 \times 10^{-4}\ TA^{1.15}\ PEIA^{0.919}\ RF^{0.956}$	.48	114	81
Total lead	$= 2.6 \times 10^{-6}\ TA^{1.58}\ PEIA^{1.51}\ RF^{0.808}$	.59	85	81
Total manganese	$= 1.7 \times 10^{-6}\ TA^{1.17}\ PEIA^{1.52}\ RF^{0.780}$	.50	93	80
Total zinc	$= 1.9 \times 10^{-6}\ TA^{1.42}\ PEIA^{1.81}\ RF^{0.775}$	.62	76	81

Table 6.--*Regression equations to estimate storm-runoff volume and loads of selected constituents derived from the combined small and tributary basins*

[Storm-runoff volume in cubic feet; constituent load in pounds; TA = total area, in acres; PEIA = percent effective impervious area; RF = total rainfall, in inches]

Dependent variable	Independent variables and constants	Coefficient of determination (r^2)	Standard Error of estimate (percent)	Number of observations
Storm runoff volume	$= 8.61\ TA^{1.07}\ PEIA^{1.25}\ RF^{1.18}$	0.94	42	89
Total suspended solids	$= 0.0483\ TA^{1.36}\ PEIA^{1.07}\ RF^{0.882}$	.79	110	88
Chemical oxygen demand	$= 0.0105\ TA^{1.15}\ PEIA^{1.49}\ RF^{0.600}$	.83	70	88
Total nitrogen	$= 4.93 \times 10^{-4}\ TA^{1.15}\ PEIA^{1.40}\ RF^{0.763}$	.84	70	88
Total phosphorus	$= 3.76 \times 10^{-4}\ TA^{1.20}\ PEIA^{0.929}\ RF^{0.950}$	.76	110	89
Total lead	$= 1.83 \times 10^{-5}\ TA^{1.23}\ PEIA^{1.40}\ RF^{0.844}$	.80	88	89
Total manganese	$= 3.6 \times 10^{-6}\ TA^{1.46}\ PEIA^{1.60}\ RF^{0.792}$	.84	93	88
Total zinc	$= 4.37 \times 10^{-6}\ TA^{1.29}\ PEIA^{1.74}\ RF^{0.780}$	.85	80	89

Table 7.--*Mean seasonal rainfall-runoff peak flows derived from the Distributed Routing Rainfall-Runoff Model--Version II (DR_3M-II) for the small basins*

[Peak flows in cubic feet per second]

Basin				
North Avenue	South-glenn	Cherry Knolls	North-glenn	Villa Italia
51	24	19	68	73

The effects of urban runoff on the South Platte River in the Denver area were described in three ways. The first was to compare selected constituent concentrations during dry-weather flow with event mean concentrations during storm runoff. The constituents that had larger event mean concentrations during storm runoff than during dry-weather flow were total suspended solids, total organic carbon, total iron, dissolved iron, total manganese, total lead, and total zinc. The constituents that had larger concentrations during dry-weather flow than the storm runoff event mean concentrations were total nitrite as nitrogen, total nitrate as nitrogen, and dissolved manganese. The constituents that had about the same concentrations in both dry-weather and storm-runoff flows were total nitrogen, total ammonia as nitrogen, total phosphorus, total cadmium, and total copper.

The second method used to describe the effects of urban runoff on the South Platte River was to compare the percent exceedence of water-quality standards for the dry-weather flow and storm-runoff periods. The constituents that exceeded the standards more than 50 percent of the time during dry-weather flow were total copper, total iron, total manganese, and dissolved manganese. The constituents whose storm runoff event mean concentrations exceeded the standards more than 50 percent of the time were total cadmium, total copper, total iron, total manganese, dissolved manganese, total lead, and total zinc. An analysis of these data indicates that an opportunity exists to improve the stream quality of the South Platte River by reducing the loads of total lead and total zinc in storm runoff.

The third method used to describe the effects of urban runoff on the South Platte River was to compare the selected constituent loads in the base flow, storm runoff, and point sources (secondary-treated effluents). Most of the point-source load originating in the study area is discharged to the South Platte River downstream from the lower study reach of the river; therefore, two comparisons of loads were made. The first comparison was with the loads that were in the river at the downstream end of the study area and the second was with the loads that originated in the study area.

Table 8.--*Mean seasonal storm runoff and loads of selected constituents predicted by deterministic and regression models*

[Storm runoff in thousands of cubic feet; loads in pounds; loads of constituents in pounds]

Model Parameter	North Avenue basin model		Cherry Knolls basin model		Northglenn basin model		Villa Italia basin model	
	Deterministic	Regression	Deterministic	Regression	Deterministic	Regression	Deterministic	Regression
Storm runoff------	930	780	430	370	1,300	1,300	2,200	1,200
Total suspended solids----------	14,000	22,000	1,200	2,400	5,300	12,000	5,800	16,000
Chemical oxygen demand----------	5,200	5,800	1,900	850	3,600	7,000	4,000	16,000
Total nitrogen----	140	150	35	59	92	250	180	420
Total phosphorus--	18	24	4.4	8.8	14	33	14	66
Total lead--------	7.0	8.5	1.3	2.8	4.6	12	5.3	19
Total zinc--------	8.6	12	1.4	2.2	4.7	10	9.4	28
Total manganese---	8.6	14	1.3	2.3	3.6	9.2	7.3	28

Analysis of the constituent loads at the downstream end of the study area (South Platte River at 50th Avenue at Denver) indicated that point sources were the major contributors of total nitrogen and total phosphorus and were significant contributors of total organic carbon. Storm runoff was the major contributor of total suspended solids, total organic carbon, and total lead, and was a significant contributor of total zinc. Base flow was the major contributor of flow volume and total zinc, and was a significant contributor of total organic carbon, total nitrogen, and total lead.

Analysis of the estimated total basin loads indicated that point sources were the major contributors of flow volume, total organic carbon, total nitrogen, and total phosphorus, and were significant contributors of total zinc. Storm runoff was the major contributor of total suspended solids and total lead. Base flow was the major contributor of total zinc and a significant contributor of flow volume and total lead.

URBAN RUNOFF TOPICS REQUIRING FURTHER STUDY

Several urban runoff topics have been identified by DRURP as requiring further study. These topics comprise both physical processes of urban runoff and institutional processes. The physical processes of urban runoff that need further study are the accumulation, washoff, and transport of constituents, the effects of urban runoff on the receiving waters, the ultimate fate of toxic substances in urban runoff, physiographic features, air quality, and man's activities. The institutional processes that need further study are the citizens' perception of urban runoff, citizens' acceptance of litter control ordinances to improve the quality of urban runoff, developers' acceptance of zoning ordinances, and requirements for detention ponds or percolation pits to improve the water-quality of urban runoff.

The physical processes controlling constituent accumulation, washoff, and transport are not well understood. The current deterministic models apply simplistic equations for these processes that do not accurately describe the processes. Several well-designed and carefully run experiments need to be made on small impervious plots and need to include: (1) Climatological and air-quality data, (2) measurement of constituent accumulation, (3) determination of the effects of raindrop size, rainfall intensity, and depth and velocity of flow over impervious surfaces on washoff loads. Mustard and others (1985) described a limited investigation of urban processes that was partly able to describe the factors affecting urban runoff. Researchers need to use the available knowledge, carefully design their experiments, focus on specific processes, and share their results on a timely basis with other researchers in the urban runoff field.

Constituents in urban runoff have been accumulating in the bottom sediments of the Nation's receiving waters for many years. It has been shown that accumulation of toxic substances in bottom sediments is correlated with industrial growth, the advent of the automobile, and the growth in the use of organic substances (David Galvin, Municipality of Metropolitan Seattle, Wash., oral commun., 1983). Studies by DRURP have shown that there is accumulation of trace elements and nutrients in the South Platte River downstream from major-storm drain outfalls. The long-term effects of these accumulated substances in receiving waters are not fully understood. It is possible that accumulation of toxic substances and nutrients is already at a level sufficient to inhibit the cleanup of the receiving waters for several years, even if the incoming urban runoff no longer contains these substances. Therefore, an investigation is needed of the long-term effect these accumulated substances will have on the ecosystem.

The ultimate fate of toxic substances that originate in the urban runoff and enter the receiving waters has not been fully investigated. The usual method to determine if toxic substances are in the receiving waters is to analyze the water column. Most of the toxic substances are only slightly soluble in water; thus, the largest concentration of the substances is in the sediments. S. A. Rice (Mote Marine Laboratory, Tampa, Fla., oral commun., 1983) successfully raised several species of aquatic life, such as shrimp, minnows, and crabs, in urban runoff with no noticeable adverse effects. David Galvin (Municipality of Metropolitan Seattle, Wash., oral commun., 1983) reported that toxic substances (mainly trace elements and organic compounds), which originated from urban runoff, are accumulating in the bottom sediments of Lake Washington and Elliot Bay, Wash. Galvin also reported a correlation between carcinogenic growth in bottom fish and large concentrations of toxic substances in the bottom sediments. Galvin further stated that aquatic life seems to be chemically altering the organic substances in their digestive processes. Therefore, although aquatic life may be raised in urban runoff, there is strong evidence that the toxic substances in urban runoff are making their way up the aquatic food chain. Further research, therefore, is needed to determine the ultimate fate of toxic substances originating in urban runoff.

The effects of physiographic features, air quality, and man's activities on urban runoff have received little attention in the past. Physiographic features of a basin in the Denver area have been shown to be an important factor in the amount of rainfall that a basin receives. The placement of large effective impervious areas could be important in the overall urban runoff quantity and quality. The DRURP has shown how the quality of rainfall, a surrogate for air quality, affects the loads of nutrients that are washed from a basin by urban runoff. Therefore, the location of a basin in relation to physiographic features and whether or not the basin is downwind from a source of atmospheric emissions may be important in the overall quantity and quality of the urban runoff from the basin. Samuel Martin (Baltimore Regional Planning Council, Md., oral commun., 1983) has shown that similar single-family housing areas with different litter practices have a vastly different urban runoff quality. Martin also stated that while effective impervious area is important in storm-runoff quantity, the activities of man are more important in determining the urban runoff quality. Further studies are needed to quantify the effects of physiographic features, air quality, and man's activities on the quantity and quality of urban runoff.

Institutional processes are as important as physical processes in understanding the total impact of urban runoff on the ecosystem. Advancement in the control of urban runoff is more difficult without citizen support. Studies need to be made to determine how the public perceives urban runoff--is it a recognized problem? These studies need to focus on whether or not the public would support ordinances requiring litter control, the construction of detention ponds and percolation pits, and the use of zoning to improve urban runoff quality. Studies need to focus on the developers' support of water-quality enhancement. The local governments usually are the agencies that write and enforce ordinances; therefore, without their support, which is drawn from the citizens and business community, urban runoff controls will not be enacted or supported.

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