CHAPTER

FOUR

CONCEPTS IN HYDROLOGY

4.1 INTRODUCTION

Hydrology is the study of water and its movement along its various pathways within the hydrological cycle; in the atmosphere; in the rivers and oceans; in the soil and in water containing rocks. Hydraulics is the engineering of water flow in pipes, conduits, lakes or rivers. Water resources engineering is the art, science and engineering of surface and groundwaters for human use. Hydrology is applied by engineers who use hydrological principles to compute, for instance, river flows from rainfall, water movement in soils from knowledge of soil characteristics including hydraulic conductivity, evaporation rates from water balance or energy balance techniques. Applied hydrology uses many engineering assumptions in attempting to quantify soil or river responses to rainfall events. It is easy, for instance, to quantify a rainfall event and to quantify streamflow after this event, if field instrumentation has recorded the event. However, it is still almost impossible to predict or model with accuracy what happens to rainfall once it has fallen on land. Does 100 per cent of that rainfall go as surface runoff to the nearest stream or does 100 per cent infiltrate to the soil and show up in the streams, days or weeks later, with impact not only on the streamwater volumes but also on the streamwater quality? In reality, either situation can occur but more likely some precipitation goes as surface run-off, some as infiltration and some is returned to the hydrological cycle via evaporation. What is the role of evaporation? Does precipitation exceed evaporation or vice versa? Can we compute with any accuracy the regional scale evaporation if all our evaporation studies are at the point scale? When can we expect remote sensing to deliver the answers? The influence of surface vegetation, soil type, soil moisture status and topography is significant on water and energy fluxes and the response from one site or watershed to another may be orders of magnitude different. Rain intensity, duration and spatial distribution also play a significant role in the fate of land-fallen precipitation. As such, art, science and engineering are all used to understand the pathways of water in the hydrological cycle. There are still many, unquantified issues, particularly as we take hydrology into meteorology and into climate studies.

This chapter discusses the hydrological cycle and its components as well as the energy cycle. It explains the differences in infiltration and surface runoff. It defines evaporation and shows how to quantify it at a point in space. This chapter also examines why our lack of understanding of evaporation, particularly at the regional scale, is the missing link in closing the hydrological cycle water balance. It

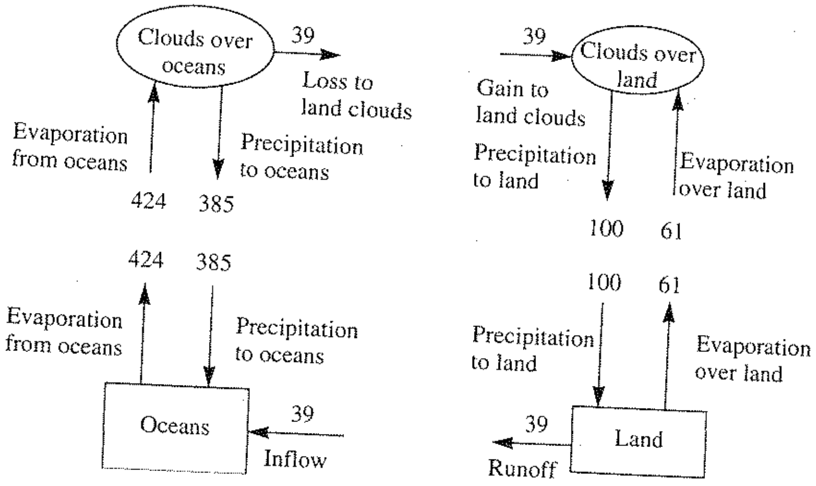


Figure 4.2 Material balance on aspects of the hydrological cycle.

Tables 4.1 and 4.2 show the distribution of the earth's water resources. The oceans contain 96.5 per cent of all water while the rivers occupy only 0.0002 per cent. The great store of usable freshwater is held in groundwater at 30.1 per cent, while soil moisture stores are 0.05 per cent, or 250 times that of rivers.

Understanding of the hydrologic cycle as it relates to precipitation on land is required by many different professionals—be it an engineer designing a water supply, an agriculturist designing an irrigation scheme, a freshwater biologist investigating adequacy of river flows for fisheries habitats, an industrialist abstracting water or discharging liquid effluent or a meteorologist forecasting weather patterns. What is of

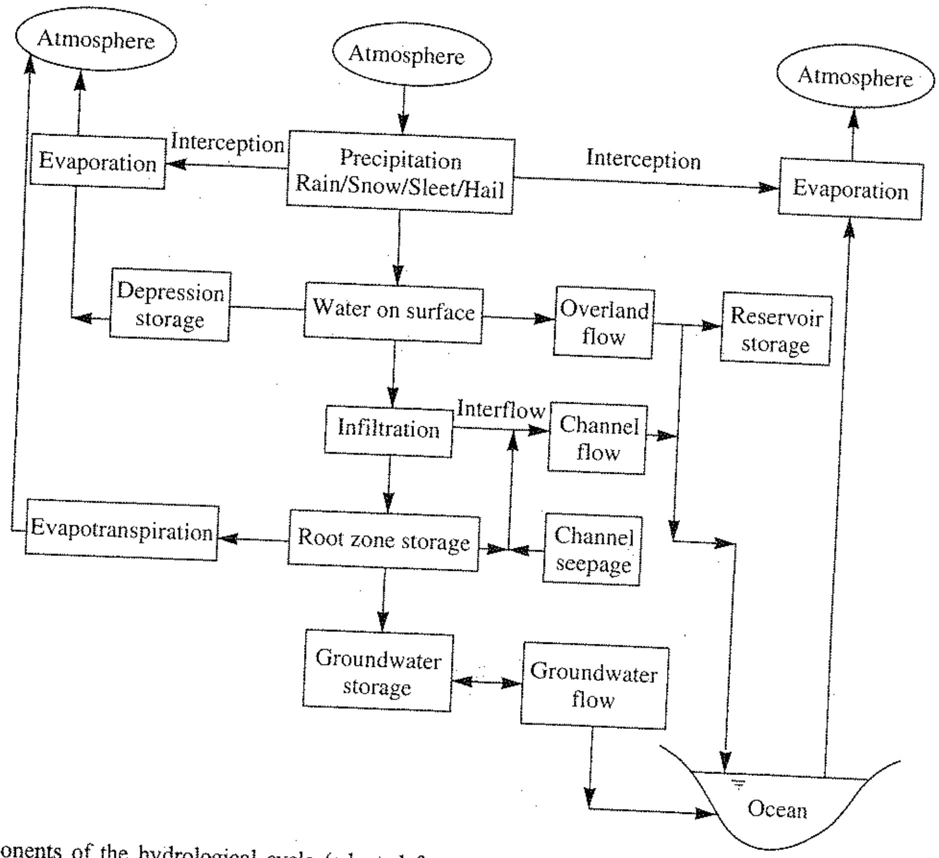


Figure 4.3 Components of the hydrological cycle (adapted from Bedient and Huber, 1988, p. 55, © 1988 by Addison-Wesley Publishing Company, Inc. Reprinted by permission of the publisher).

explains water balance for catchments, looking at hyetographs and hydrographs. It examines rainfall–runoff relationships for flood flows and low flows. It examines the influence of urbanization on hydrological responses. It briefly introduces the student to the physics of the energy cycle. The final section of this chapter looks at both physical and chemical concepts of groundwater. By the end of this chapter it is hoped that the student will have an introductory qualitative and quantitative understanding of the physics of water in the hydrological cycle and also in the sun's energy cycle.

4.2 HYDROLOGICAL CYCLE

The hydrological cycle is central to hydrology. It is a continuous process with no starts or finishes. It is shown schematically in Fig. 4.1. Water *evaporates* from the earth's oceans and other water bodies, and to a lesser extent from the land surfaces. Approximately seven times more evaporation occurs from the oceans than from the earth's land surface. Remember the ocean surface area of the earth is 2.5 times the land surface area. The evaporated water or water vapour rises into the atmosphere until the lower temperatures aloft cause it to condense and then *precipitate* in the form most globally as rain but sometimes as snow. The latter occurs at the more alpine elevations or in cold seasons. The global annual average water balance relative to 100 units of land precipitation is enumerated in the water balance diagram of Fig. 4.2. A schematic of a modeller's flow chart of the hydrological cycle is shown in Fig. 4.3.

Figure 4.2 is a simplistic way of showing the hydrological cycle but the objective is quantitative, whereas Fig. 4.1 is qualitative. The material balance of Fig. 4.2 is based on the conservation of matter. The four subregions of Fig. 4.2 are numerically in equilibrium on their own or taken as the totality of the four. For instance, the equilibrium of the 'oceans balance' is satisfied by two inputs of precipitation plus inflow, being equal to one output of evaporation, i.e.

For landmass : Input ± change in storage = output

For oceans : Precipitation + inflow = evaporation

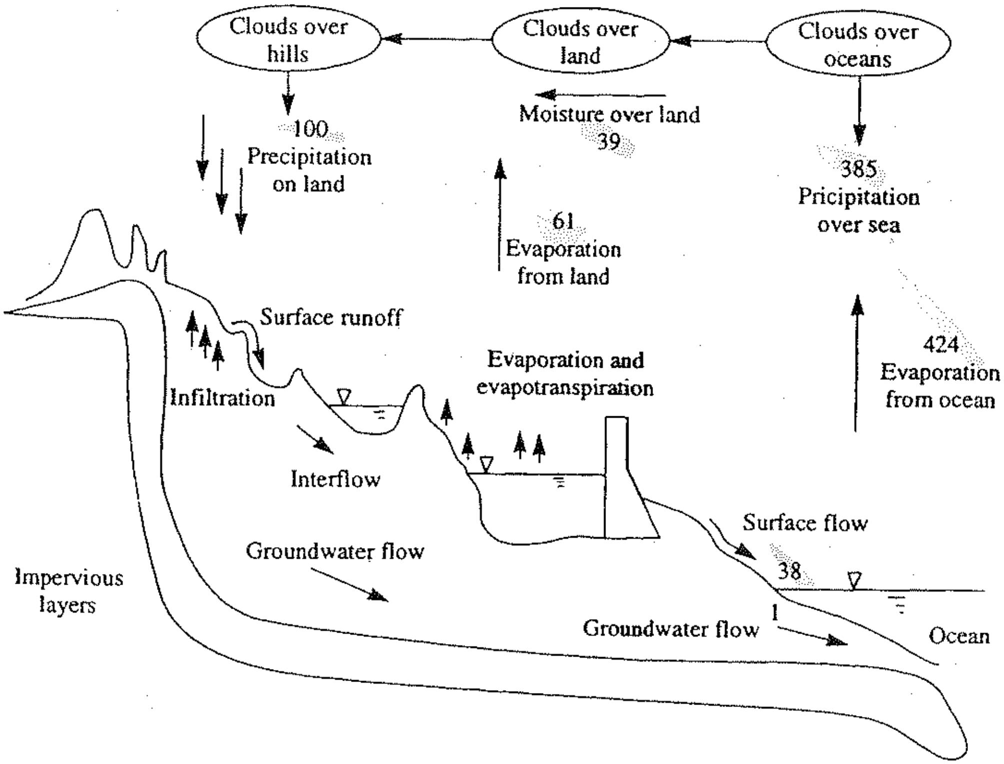


Figure 4.1 Hydrological cycle with global annual average water balance given in units relative to a value of 100 for the rate of precipitation on land (adapted from Chow *et al.*, 1988).

Table 4.1 Estimated world water quantities

Item	Area (10^6 km^2)	Volume (km^3)	Total water %	Fresh water %	Rates of exchange
Oceans	36.31	1 338 000 000	96.5		3000–30 000 yrs
Groundwater					
Fresh	134.8	10 530 000	0.76	30.1	Days to 1000 yr
Saline	134.8	12 870 000	0.93		
Soil moisture	82.0	16 500	0.001 2	0.05	2–52 weeks
Polar ice	16.0	24 023 500	1.7	68.6	1–16 000 years
Other ice and snow	0.3	340 600	0.025	1.0	
Lakes					
Fresh	1.2	91 000	0.007	0.26	1–100 years
Saline	0.8	85 400	0.006		10–1000 years
Marshes	2.7	11 470	0.000 8	0.03	
Rivers	148.8	2 120	0.000 2	0.006	10–30 days
Biological water	510.0	1 120	0.000 1	0.003	7 days
Atmospheric water	510.0	12 900	0.001	0.04	8–10 days
Total water	510.0	1 385 984 610	100.0		2800 years
Fresh water	148.8	35 029 210	2.5	100.0	

Adapted from UNESCO, 1978

most pragmatic interest, then, is what happens to the land-fallen precipitation on a mesoscale of a catchment or region, rather than the global annual water balance. The meteorologist has interests in the hydrological cycle on a larger scale, sometimes global. Precipitation may be intercepted by vegetation, i.e. grass, crops or trees. *Interception* is the evaporation of water from the outer surface of leaves during and after rainfall. *Transpiration* is evaporation of water through foliage. Some may lodge on the soil surface and be retained there in depressions. This is called depression storage or ponding. Some water may become overland flow and eventually reach a stream or river and be discharged as surface runoff. It may infiltrate into the soil and flow horizontally as interflow. It may percolate through the deeper soil layer into the groundwater zone and recharge the waters in the aquifers. A significant volume of precipitation may be returned to the atmosphere through *evaporation* from water bodies and *evapotranspiration* from vegetated surfaces. The extent of the latter depends on many factors, including climate, type of surface vegetation, amount of rainfall and rain intensity. In general, of 100 units of rain that falls on grassland in temperate zones, 10 to 20 units will go to groundwater, 20 to 40 units will evapotranspire and 40 to 70 units will become stream runoff. In arid and semi-arid areas, with little precipitation, not all of the above phenomena may be experienced, as high evaporation tends to dominate the hydrologic cycle.

Table 4.2 Global annual water balance

		Ocean	Land
Area (km^2)		361 300 000	148 800 000
Precipitation	(km^3/yr)	458 000	119 000
	(mm/yr)	1 270	800
Evaporation	(km^3/yr)	505 000	72 000
	(mm/yr)	1 400	484
Runoff to ocean			
Rivers	(km^3/yr)		44 700
Groundwater	(km^3/yr)		2 200
Total runoff	(km^3/yr)		47 000
	(mm/yr)		316

Adapted from UNESCO, 1978

The way precipitation becomes spatially distributed depends on climate, soils, geology, topography and land use. For instance, if a soil vegetation matrix is saturated with water from a previous rainstorm, a new precipitation event may become distributed solely to streamflow (via overland flow) with no contribution to evaporation, infiltration or percolation. Alternatively, if a soil matrix is very dry with a low water table, a precipitation event may be distributed to infiltration followed by percolation to groundwater, with no quantity to streamflow. Therefore, to be able to quantify the distribution of precipitation, knowledge of the soil and the response of soil to water is required.

4.3 WATER BALANCE

The water balance or water budget is the accounting of water for a particular catchment, region or even for the earth as a whole. As seen in the preceding sections, the hydrologic cycle considers all the phenomena of water phases in a qualitative description. The water balance is the quantitative account of the hydrologic cycle. The input to the cycle is precipitation, either as rainfall, snow or sleet. The precipitation is distributed as surface runoff, evaporation, infiltration to the unsaturated zone, changing its storage, and deep percolation to the saturated zones.

The equation for the water balance, which is the conservation of mass in a lumped or averaged hydrological system on a regional or catchment scale is

$$P = R + E \pm \Delta S \pm \Delta G \tag{4.1}$$

where

P = precipitation, mm/day

R = stream runoff

E = evaporation

ΔS = change in soil moisture status

ΔG = change in groundwater status

Equation (4.1) assumes that there is no 'flow' across catchments. While this is correct for surface water, it is not always possible to verify that there is zero flow in the subsoil regions across catchment boundaries, i.e. no interflow. If Eq. (4.1) is averaged over the hydrologic year (in northern temperate climates this is typically 1 October to 30 September), there may be no significant change in ΔS or ΔG. Thus

$$P = R + E \tag{4.2}$$

and so

$$E = P - R \tag{4.3}$$

Equation (4.3) is often used to determine evaporation from the 'annual' water balance of closed systems.

Water balance data are required for a myriad of uses. If water is to be abstracted from surface waters for irrigation, hydropower, cooling water or industrial requirements, it is necessary to understand not only the absolute values of precipitation, evaporation and streamflow but also the trends over time. If a land use change is proposed for a catchment, it may alter the water balance. For instance, it is most likely that a grassland catchment in the temperate zone, if converted to forestry, would see an increased evaporation on maturation of the plantations. This is due to the increased transpiration rates of trees over grassland. This would leave less water for streamflow and its human and ecological uses may be impacted. Table 4.3 lists water balance results for many catchments throughout the world for different land uses (mainly forest). Evaporation losses (defined as evaporation/precipitation) vary from 15 per cent for upland moorland catchments in the United Kingdom to about 70 per cent for fully forested catchments. Table 4.4 shows the water balance of the continents. It is seen that the water loss due to evaporation varies significantly with about 60 per cent for South America and 93 per cent for Australia.

Table 4.3 Water balance for different land uses

Author	Location	Land use	Annual rainfall P(mm)	Runoff Q(mm)	Total evaporation losses (mm)	Losses (%)
Law (1956) 1955–6	Stocks Reservoir (UK)	Coniferous Forest 100%	984	273	711	72
Institute of Hydrology 1967–70	Stocks Reservoir (450 m^2)	100% forest	1496	555	953	64
Institute of Hydrology 1956–70	Stocks Reservoir (37.5 km^2)	22% forest	1662	1204	454	27
Institute of Hydrology 1956–70	Stocks Reservoir (10.6 km^2)	70% forest	1544	1049	495	32
Law (1956)	Stocks Reservoir (UK)	Grassland, moorland	1135	717	421	37
Law (1956) and Calder *et al.* (1982)	Stocks Reservoir	Grass, lysimeter irrigated	1702		467 (PET)	28
Law (1956) and Calder *et al.* (1982)	Stocks Reservoir	Heather, lysimeter irrigated	1702		520 (PET)	31
C[illegible]ary (1990)	Black Forest	Norway spruce, 100% forest	Dormant season 950	484	466	49
			Growing season (1975) 600	200	400	67
			Growing season (1985) 600	350	250	41
Mulholland *et al.* (1991)	Walker branch, Tennessee	100% deciduous	1400	728	672	48
Farrell (1991)	Ballyhooley, N. Cork, Ireland	100% forest	1022	(throughfall) 576	446	44
Bishop (1991)	Loch Fleet, Scotland	Grassland, moorland	2200	1740	460	21
Cooper (1980)	Thetford, East Anglia	100% forest	640	—	430	67
Shuttleworth (1988)	Amazonia	100% rainforest	2593	—	1393	53
Kirby *et al.* (1991)	Wye, Plynlimon, Severn	Grassland, moorland	2394	2041	353	15
Kirby *et al.* (1991)	Plynlimon, Wales (1977)	68% forest	2620	1820	770	30
FRI New Zealand (1980) McDonnell (1990)	Mamai, New Zealand	100% beech forest	2600	1500	1000	39
Pearce *et al.* (1976)	Big Bush, New Zealand	100% beech forest	1500	600	800	54
F[illegible] Watson	New Zealand	Tussock grassland, pine forest	1150 1150	620 500	530 650	46 57

4.5 PRECIPITATION

Precipitation in the form of rain, hail or snow is one input to the hydrologic cycle. If we are interested in predicting or assessing a hydrologic response we need to be able to determine the amount, rate and duration of precipitation on a spatial and temporal basis. In Sec. 4.14 we discuss the water quality aspects of rainfall.

Precipitation occurs when air rises, expands (on cooling) and cools sufficiently for the water vapour in the air to reach condensation point. The atmosphere is rich in nuclei, mainly soil/clay particles, hydrocarbon waste products, sea salts, etc., with a size requirement greater than about 0.1 μm. Additionally, for precipitation to occur, there must also be:

1. The presence of condensation nuclei on which condensation can start. In their absence, the air can become supersaturated.
2. These condensed droplets should not evaporate when passing through drier air and should be of sufficient size to free-fall under gravity to the earth's surface. If the droplets are too small, they may have an inadequate 'settling' or falling velocity to reach the ground.

Rain droplets increase in size either by coalescence (liquid to liquid) producing rain or when solid aggregates with solid as with snow. An intermediate phase of aggregation of solid with liquid produces hail, Bras (1990) identified the forms of rainfall precipitation, as in Table 4.6.

Precipitation in the form of rainfall has a large spatial variability for local thunderstorms covering an area as small as 5 km^2 to a synoptic storm covering up to 250 000 km^2. Table 4.7 outlines the spatial characteristics of general storms. In general, we have cellular thunderstorms during the warmer periods (but not exclusively so). Details of the physics of rainfall can be found in many books, including Bras (1990) and Eagleson (1970).

4.5.1 Measurement of Precipitation

The three means of determining the magnitude of rainfall, spatially and temporally, are:

- Precipitation gauges
- Radar
- Satellite remote sensing

The traditional means of measurement was to use a network of raingauges which were read manually on a daily basis, and this gave daily rainfall at a single point in space. Today, raingauges are predominantly continuous rainfall recorders, with attached electronic data recorders. Typically, these will record rainfall at a point for a particular magnitude of rainfall, e.g. in increments of 0.2 mm. The mechanism may be a tipping bucket, of capacity 0.2 mm and each time 0.2 mm falls, the start and finish time are recorded. Analysis of the record can then be for hourly, daily, weekly, rainfalls. If an area has a sufficient number of raingauges, then the temporal and spatial distributions of rainfall may be determined. Raingauges connected to a telemetry system are now being used for real-time runoff forecasting. Raingauge networks

Table 4.6 Forms of precipitation

Name	Description	Size
Drizzle	< 1 mm/h	0.1–0.5 mm
Rain	Light < 2.5 mm/h Moderate 2.5–7.5 mm/h Heavy > 7.5 mm/h	> 0.5 mm

Adapted from Bras, 1990

Table 4.7 Characteristics of general storms

Name	Size (km^2)	Intensity (mm/h)	Duration
Synoptic	25 000–250 000	0.2–2	Few days
Large mesoscale	2300–4600	1–3	< 12 h
Small mesoscale	100–400	2–5	< 3 h
Cellular	< 10	> 5	Minutes

Adapted from Bras, 1990

have been used in determining rainfalls that should be used in flood analysis, low flow in stream analysis, groundwater recharge analysis, water balance studies of catchments and, to a lesser extent, water quality analysis of rainfall. It is important to be aware that there are serious limitations to using raingauge data from an insufficient network of gauges. Essentially a raingauge is a point measurement of rainfall and rainfall will vary widely (spatially and temporally) depending on the type of rainfall. For instance, two raingauges, 2 km apart, may record significant differences during a thunderstorm, but most likely similar falls during a mesoscale storm.

Errors in the absolute magnitudes from raingauges can occur from poor siting (too close to buildings or trees), overgrowth of ground cover, winds and other types of shielding. Figure 4.5 is a typical bar chart (hyetograph) of a heavy rainstorm. It is seen that the record is not continuous. The storm duration is 24 h with a total rain of 91.8 mm. The peak intensity is 14.2 mm/h with an average intensity of 3.8 mm/h. This rainstorm would be considered an infrequent event in a temperate wet climate like Ireland.

Ground-based radar is used to estimate the areal distribution of the instantaneous precipitation rates in clouds. As such, it should be a more sophisticated and reliable method of rainfall determination than raingauges. In theory, it should be able to provide a continuous description of rainfall over the cone of influence of the radar. The radar image needs to be calibrated with on-ground raingauges or raindrop size measurements. Because of many factors, including evaporation of falling rain and distortion of the precipitation field by winds at elevations lower than clouds, a precise image of precipitation cannot be obtained. While the precise magnitude of rainfall estimates from radar can be in error by factors of 0.5 to 2.0, radar does give a good picture of the areal extent of precipitation. The student is referred to Bras (1990) and to Collinge and Kirby (1987) for further details on rain-radar.

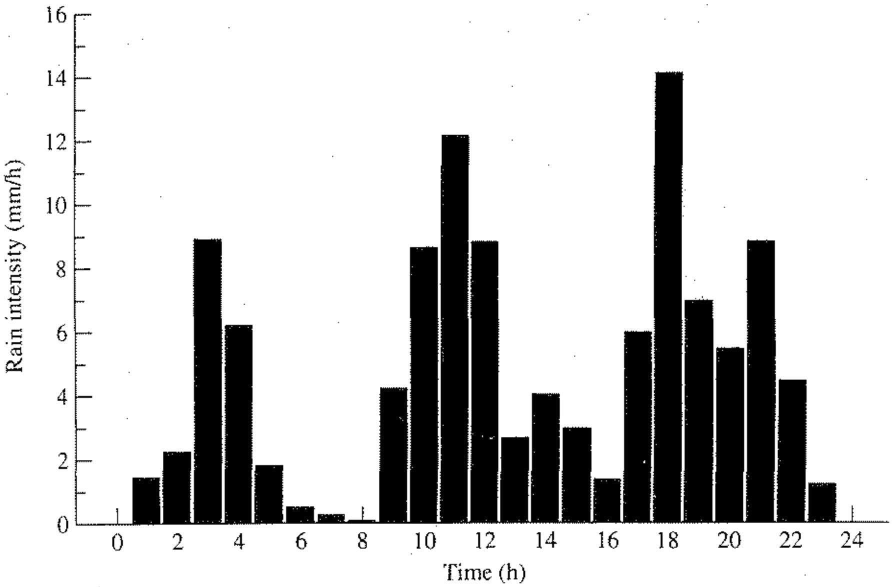


Figure 4.5 Typical hyetograph of a severe 24-hour winter rainstorm.

Satellite observations can provide information on the areal distribution of precipitation working on the principle that the atmosphere selectively transmits radiation at various wavelengths, and more particularly in the visible and thermal infra-red wavelengths. The visible wavelengths are of the order of 0.77 to 0.91 μm (Bras, 1990) and give information on the distribution of clouds, and therefore possible areal locations of rainfall. The infra-red wavelengths, 8 to 9.2 μm and 17.0 to 22.0 μm (see the electromagnetic spectrum in Chapter 8), can be used to locate high clouds and their associated convective precipitation cells. In the United States the polar orbiting satellites provide two visible and one infra-red pass per day and from geostationery satellites providing images at intervals of a half hour (Dingman, 1994). Very obvious benefits of satellite imagery is for areas of low inhabitation, where raingauges or radar are not available and particularly remote island locations, e.g. the South Pacific.

4.5.2 Precipitation Analysis

Analysis of precipitation results include the determination of:

- Areal precipitation
- Depth–area–duration analysis
- Precipitation frequency
- Intensity–duration–frequency analysis
- Extreme values of precipitation

Determination of areal precipitation from point measurements The mean areal precipitation of a storm event is

$$P_1 = \frac{1}{A}\int_A p(x)\mathrm{d}x \tag{4.7}$$

and the time-averaged mean areal precipitation is

$$P_2 = \frac{1}{T}\frac{1}{A}\sum_{i=1}^{m}\int_A p(x, t_i)\mathrm{d}x \tag{4.8}$$

where $p(x)$ is a function describing the total accumulation of precipitation at all points x_i in the catchment and $p(x, t_i)$ describes the total precipitation at x and time t_i. A is the catchment area and T is the total storm period. Several methods are used to determine the areal average of a storm's precipitation, including the arithmetic mean, the Thiesson polygon, the Isohyetal method, the hypsometric method and the multiquadratic method (Shaw, 1994). The use of the above methods is best illustrated by means of examples.

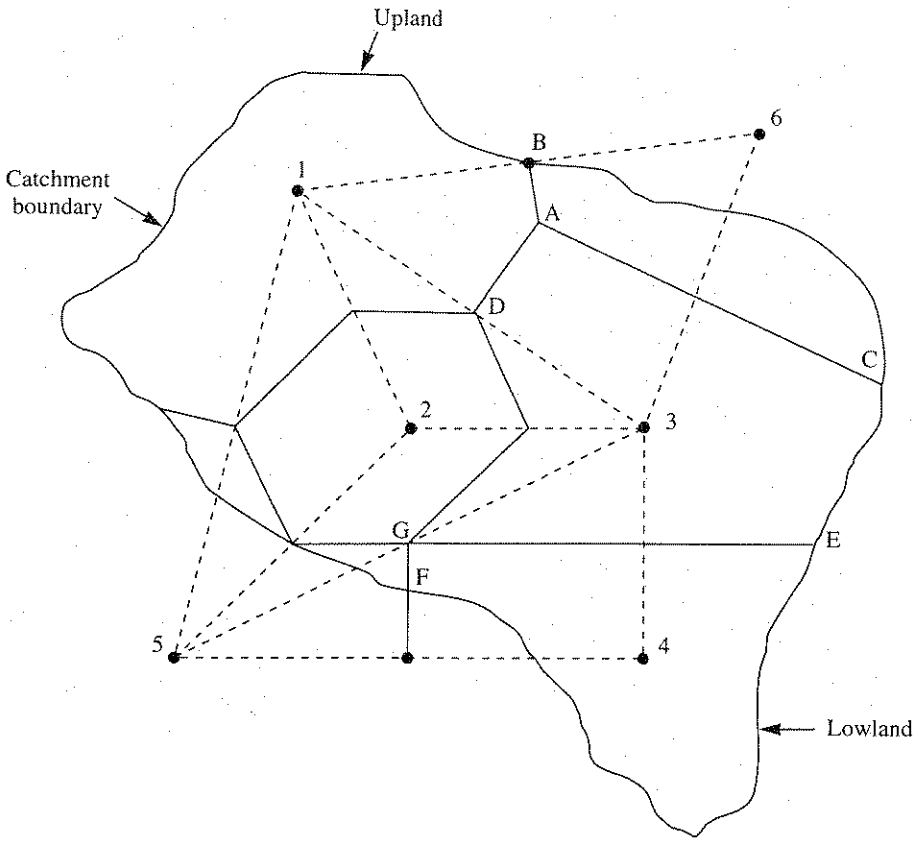
Example 4.1 The catchment shown in Fig. 4.6 has six raingauges which recorded the intensities of a storm event as illustrated in column 2. Two of the gauges are outside the watershed line. Determine the areal precipitation using the Thiessen polygon method.

Solution

Step 1. Join with broken lines each of the six gauges as shown, 1 to 6, 1 to 3, 1 to 2, 1 to 5, 6 to 3, 3 to 4, 4 to 5, 5 to 2, 3 to 2, etc.

Step 2. Draw the orthogonal bisectors of these lines, i.e. AB is the bisector of 1 to 6, AC the bisector of 3 to 6, etc.

Step 3. Identify the contributing areas to each raingauge. The area BAC within the catchment is attributed to raingauge 6. The area of the catchment bounded by GEF is attributed to gauge 4. These areas are divided by the the total watershed area and reported as the Thiessen weights in column 3.



Raingauge	Precipitation P_i (mm)	Thiessen weight ω_i	$\sum_{i=1}^{6} P_i$
1	45	0.280	12.6
2	39	0.135	5.3
3	32	0.275	8.8
4	34	0.190	6.5
5	27	0.025	0.7
6	48	0.095	4.6
		Total	38.5

Figure 4.6 Areal average precipitation determination by Thiessen polygon.

Step 4. The total areal precipitation is then computed from weighted contributions of each gauge as in column 4. Therefore,

$$P = 38.5 \text{ mm}$$

Another common method for areal precipitation determination is the isohyetal method. The isohyetal map of a catchment shows the contours of precipitation. These could be composed from Example 4.1. The contours of precipitation as determined from the raingauges and the contour map are drawn in fine increments. The weights attributed to a contour interval are assigned w_i, similar to the way weights of area were assigned in the Thiessen polygon method. Depending on the range of rainfall, the contour increments may or may not exceed the number of raingauges. For instance, in Example 4.1 with a range of 27 to 48 mm, i.e. 21 mm, a contour precipitation interval range might be, say, increments of 3 mm each. The reader is referred to Shaw (1994) for further details.

Depth–area–duration analysis As the area of a catchment increases, typically the depth of precipitation decreases and this is accounted for in the UK *Flood Studies Report* (NERC, 1975) which uses an areal reduction factor (ARF) for precipitation. For short duration storms, the ARF is significant, as short duration storms also tend to spread over smaller land areas than longer duration storms. As the depth and duration increase, so does the areal average precipitation. For many environmental engineering applications, it is relevant to know the areal extent of a particular depth of precipitation and to know how the depth varies with area. This is best illustrated by an example.

Example 4.2 Determine the precipitation depth–area curve for the hypothetical storm given in Fig. 4.7(a).

Solution Table 4.8 is computed as follows:

Step 1. Identify the isohyets, as shown in Fig. 4.7a, as being 100, 90, 80, 70, 60 and 50 mm, total precipitation. Associate with each interval its contributing catchment area and enter as column 2 of Table 4.8.

Step 2. Identify the area between isohyets as column 3 and the average rain between isohyets as column 4.

Step 3. The volume of rainfall between isohyets is the product of columns 3 and 4 and is entered in column 4. Column 6 is the cumulative rain.

Step 4. Column 7 is the areal rain which is column 6 divided by column 2.

Step 5. Figure 4.7(b) is now drawn with column 7 as ordinate and column 2 as abscissa. This is usually drawn on a log scale for the x axis if the range covers several orders of magnitude. It is seen that as area increases, rainfall depth decreases.

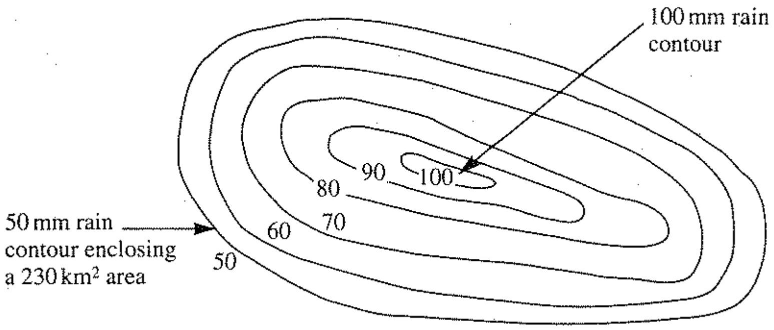


Figure 4.7(a) Schematic of isohyets of a single storm cell (in mm) (Example 4.2).

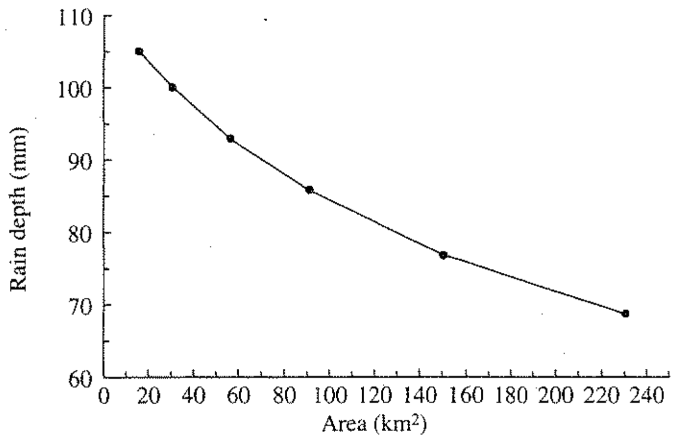


Figure 4.7(b) Precipitation depth–area analysis (Example 4.2).