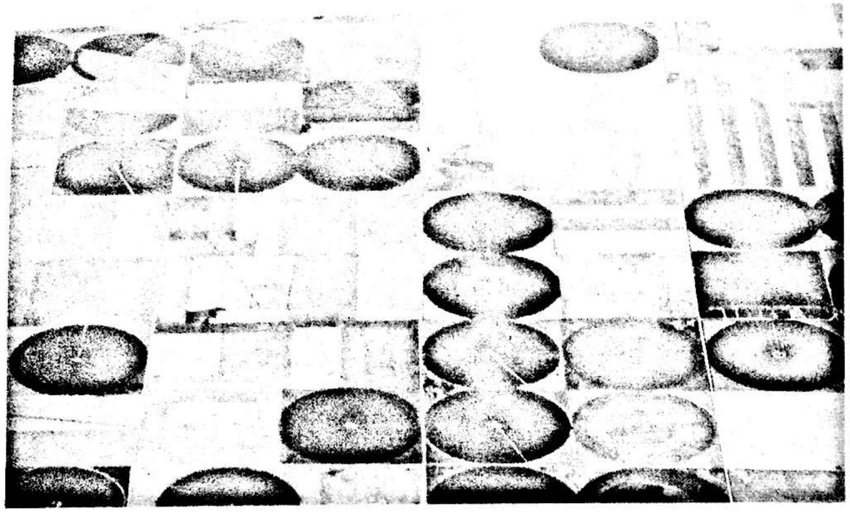


Water for irrigation is dispersed by a variety of means, including huge rotating sprinklers that create patterns when viewed from above.

CHAPTER 13
The Local Water Budget

You will know something about local water budgets and about climate if you can:

1. Analyze the various parts of the water budget.
2. Relate the water budget to patterns of change in the local environment.
3. Describe the factors that affect climate and use them to determine the climate patterns for a continental land mass.

Governments, businesses, and individuals must all keep track of the money they have available for present and future expenses. To do this, they make up a budget of expected income and outgo. They hope that they can at least make income balance outgo, or even have a surplus that can be saved for an emergency or a large purchase in the future. If funds drop too low to cover expenses, they may have to do without something, or else borrow from an outside source.

The water supply of a community or region is at least as important as its money supply. Therefore, many communities work out a local water budget that shows expected income (precipitation), outgo (evapotranspiration), and savings (soil storage of water). With such a budget, a community can plan its use of water. As we will see in this chapter, the water budget of a region is also useful in describing or classifying its climate.

THE LOCAL WATER BUDGET

In Chapter 12 you learned that when it rains, the soil retains some of the water that infiltrates the ground. Between rains, some of this stored water is used by plants and some is lost by evaporation. Thus every region has a local water cycle of income from *precipitation,* outgo through *evapotranspiration,* and variations in soil water *storage.*

A *local water budget* is a mathematical model of the water cycle for a region. It shows how the income, outgo, and storage of water vary over the course of an average year. The local water budget may show periods of water *deficit,* when the total supply is less than the total demand, and it may show periods of *surplus,* when there is more water available than can be used or stored.

During the following discussion of the factors in a water budget, keep in mind that we are talking about the natural water cycle of a region. We are not considering what people may do to alter the supply and demand picture. For example, they can dig wells and draw water from the ground water. They can pump water from a lake or a river. They can bring water in from a distant source through pipes or canals. Nature can do none of these things.

Precipitation (Income). From what has just been said, you can see that the only natural source of water for a region is the precipitation that falls on that region. Precipitation is the source of water income, much like the salary a person receives from an employer. Money income is measured in dollars. How shall we measure precipitation? You might expect it to be measured by volume, in such units as cubic meters. But a cubic meter of water falling on 1 square meter of land is quite different from a cubic meter of water spread out over 1,000 square meters. What really counts is how much water falls on each unit of area.

The simplest way to describe precipitation per unit of area is in terms of a depth of water. If we say that the precipitation in a given region is 10 mm, we mean that the water that falls on that region could cover it everywhere to a depth of 10 mm. It makes no difference, then, whether we are thinking about a backyard garden of 100 square meters or a farm of 100,000 square meters. As far as the plants and soil are concerned, precipitation of 10 mm is the same amount of income in both cases. For the same reasons we will measure outgo and storage of water in millimeters. In the following discussion we will use P as the symbol for precipitation.

Precipitation may, of course, take several forms, such as snow, hail, or mist. In a water budget, we assume that forms other than rain are changed to their equivalent of liquid water.

Figure 13-1 on the next page shows the pattern of average annual precipitation for the continental United States. You can see that there are regions in the Northwest where precipitation during the year totals more than 1,500 mm, and other regions in the Southwest where annual precipitation is less than 250 mm. You can also see that precipitation can vary a great deal within a relatively short distance. Therefore, water budgets are gener-

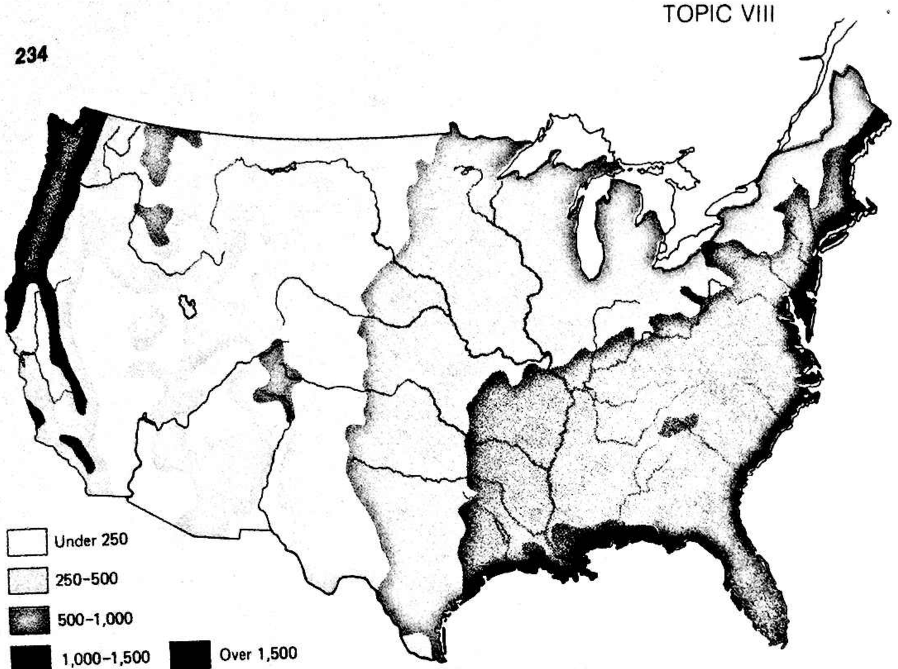


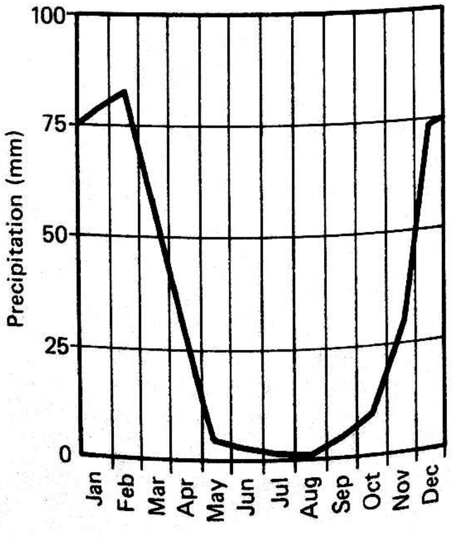
Figure 13-1. Average annual precipitation for the United States (mm). Some of the smaller regional variations have been omitted.

ally calculated for small areas, rather than for whole countries or states.

Precipitation also varies seasonally in most regions, being higher in some months than in others. Figure 13-2, for example, shows the average precipitation in Los Angeles by months. We would want a water budget for Los Angeles to tell us what happens during that dry period from May to September. A water budget is therefore usually constructed on a month-by-month basis.

Evapotranspiration (Outgo). As you already know, evaporation and transpiration (evapotranspiration) are the only means by which water passes from the surface of the earth into the atmosphere. Evapotranspiration can be compared to the amount of money an individual spends. There are two kinds of situations, both in personal money budgeting and in water budgeting. In one case, you have all the money you need to buy whatever you want. What you spend then is the maximum amount you *want* to spend. This is your *potential* maximum. In terms of a water budget, there is also a certain maximum amount of evapotranspiration that could occur in a region. This is the amount of water that will be given up to the atmosphere by evapotranspiration if there is enough water available. We call this the *potential evapotranspiration*, and we use the symbol E_p to represent it.

Figure 13-2. Average monthly precipitation in Los Angeles, California.



Factors That Affect E_p. Like precipitation, potential evapotranspiration also varies during the year. The maximum evapotranspiration that *could* occur, assuming plenty of water on hand, is not the same in every month. Evaporation of water and transpiration from plants will vary with the amount of energy available for these processes. In the winter months, when intensity and duration of insolation are both low, there is less energy available than in the summer months. Temperatures are low, so evaporation is reduced. Plants receive less energy from sunlight, so their activities, including transpiration, are also reduced. In regions that have severe winters, surface water may be frozen and plants may be practically dormant. Under such conditions, E_p is very nearly zero.

In the summer, on the other hand, high temperatures tend to produce rapid evaporation. High energy income enables plants to grow actively and therefore transpire more rapidly. We can infer, then, that potential evapotranspiration (E_p) will vary directly with the average temperatures during the year. This relationship is shown graphically in Figure 13-3.

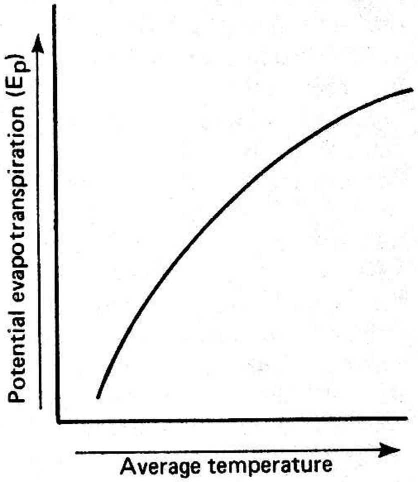


Figure 13-3. Graphic model of the relationship between potential evapotranspiration and average monthly temperature.

Actual Evapotranspiration (E_a). Most of us do not have all the money we would like to spend. We have to limit our purchases to the amount of money our budget tells us we have available. This may, of course, include drawing on our savings. In any case, there is a certain amount of money we do spend. This is our *actual* outgo. Likewise, in a water budget, there is *actual* evapotranspiration (symbol, E_a). This is the amount of water actually given off to the atmosphere in a particular time interval.

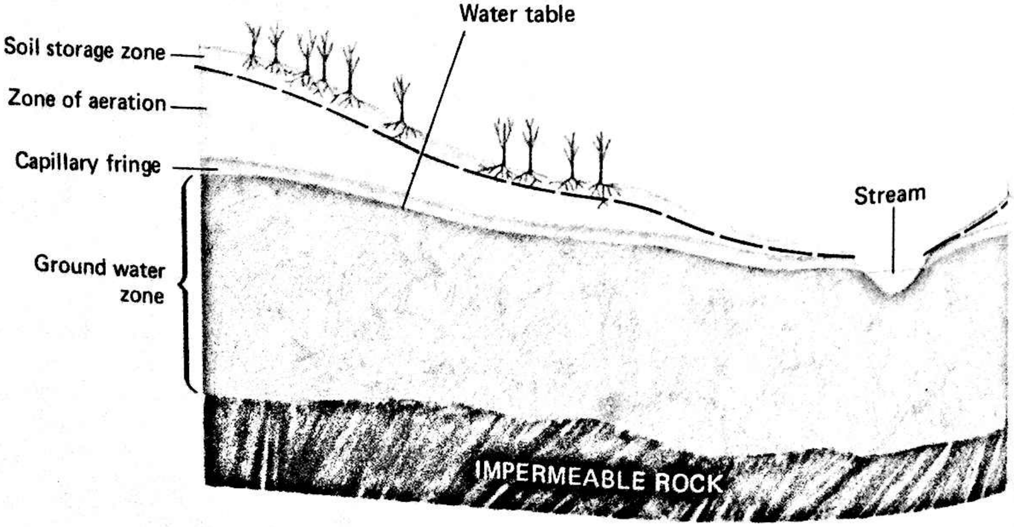
There are a few important points to remember about actual evapotranspiration (E_a). In the first place, it is never greater than potential evapotranspiration at any particular time. The actual outgo (E_a) cannot be greater than the maximum that is possible (E_p). Secondly, E_a will be equal to E_p whenever that is possible, that is, whenever there is enough water available to provide that much evapotranspiration. And finally, E_a will be less than E_p whenever there isn't enough water available to meet the potential demand.

Storage (Savings). Water in the pores of the upper layer of the soil is the water that plants rely on for their needs. The amount of water that can be stored in the pores depends on the type and thickness of the soil. The amount that is available to plants also depends on the depth to which their roots go. These factors vary from one region to another, but it is possible to arrive at an average amount of storage that is fairly typical. Scientists have estimated that this average amount of *maximum* soil storage is the equivalent of 100 mm of precipitation. This does not mean that the zone of soil water extends downward only 100 mm. It means that if all the stored water in the plant root zone were collected, it would be equal to 100 mm of precipitation. The relationship of the soil storage zone to the other zones of subsurface water is shown in Figure 13-4.

Storage (symbol, St) is similar to the money that you may have in a savings account. When current income is not enough to cover current expenses, you can draw on your savings to make up the difference. When income is greater than expenses, the excess can go back into savings. Soil storage is the savings account of the water budget. When precipitation is less than potential evapotranspiration during a certain month, water in the soil can be used to make up the difference. When precipitation exceeds potential evapotranspiration, the excess can go into storage.

Surplus (Unusable Funds). There is an important difference between soil storage and a savings account. For all practical purposes, there is no limit to the amount of money that can be added to a savings account. But there *is* a limit to soil storage—the figure of 100 mm that we have already mentioned. This means that once the soil storage "account" is filled to its maximum of 100 mm, any excess must be wasted. This condition is called a *surplus*. Some of the surplus infiltrates down to the ground water zone, and drains through the ground into streams and lakes. Excess water may also run off the surface. In both cases, the surplus eventually becomes runoff.

Figure 13-4. The soil storage zone. Only the soil water in the zone of root growth is counted as storage. Maximum storage in this zone is estimated to be equivalent to 100 mm of water.



Usage (Drawing from Savings). When precipitation (P) during a particular month is less than E_p for that month, evapotranspiration will continue at its normal rate as long as there is water in storage. This means, however, that storage is decreasing. Plants are drawing on the reserves of water in the soil just as you may draw from your savings account during a month when your income is less than your expenses. This reduction of soil storage is called *usage*.

Deficit (Shortage of Funds). Usage can continue as long as there is some storage left, but, of course, it has to stop when St becomes zero. E_a in any month cannot be greater than $P + St$. Therefore, if $P + St$ is less than E_p, E_a will also be less than E_p that month. This condition is called a *deficit*. The amount of the deficit is equal to $E_p - E_a$. During the first month of a deficit, St drops to zero. The only source for evapotranspiration after that is the precipitation that falls. The deficit continues until P becomes greater than E_p once again.

This situation is like that of an individual whose savings are used up and whose current income is not enough to cover all the purchases he would like to make. He may borrow money to tide him over his deficit period. But if he can't or doesn't want to go into debt, he would use his income for necessities such as food, and postpone other expenses.

Nature has no way to borrow water. So in periods of water deficit, nature makes do with less. Plants are able to reduce their activities during times of deficit. In desert regions, where conditions are almost a continuous deficit, plants have developed many special traits that enable them to survive long periods without precipitation. The giant saguaro cactus, for example, can absorb enough soil water after a single brief shower, and store it in its stem, to last it for two years. Most cactus plants have no leaves, so transpiration is greatly reduced. Photosynthesis (food-making) occurs in the green stems of cactus, which have a waxy surface to limit loss of water. Sharp spines in many species discourage animals from eating the plants for their stored water.

What we have just said applies only to plants that are native to a region. They don't need man's help to survive in their natural environment. But your prize lawn will have to be watered during dry intervals, and a farmer will probably have to irrigate his crops to keep them growing. These are plants that man has brought into the region or developed for his own purposes, and they do need his help to adjust to conditions that are unnatural for them.

Recharge (Building Up Your Savings Account). Whenever P becomes greater than E_p after a period of usage or deficit, the excess goes back into storage. A period during which storage is increasing is called *recharge*. Recharge continues as long as P is

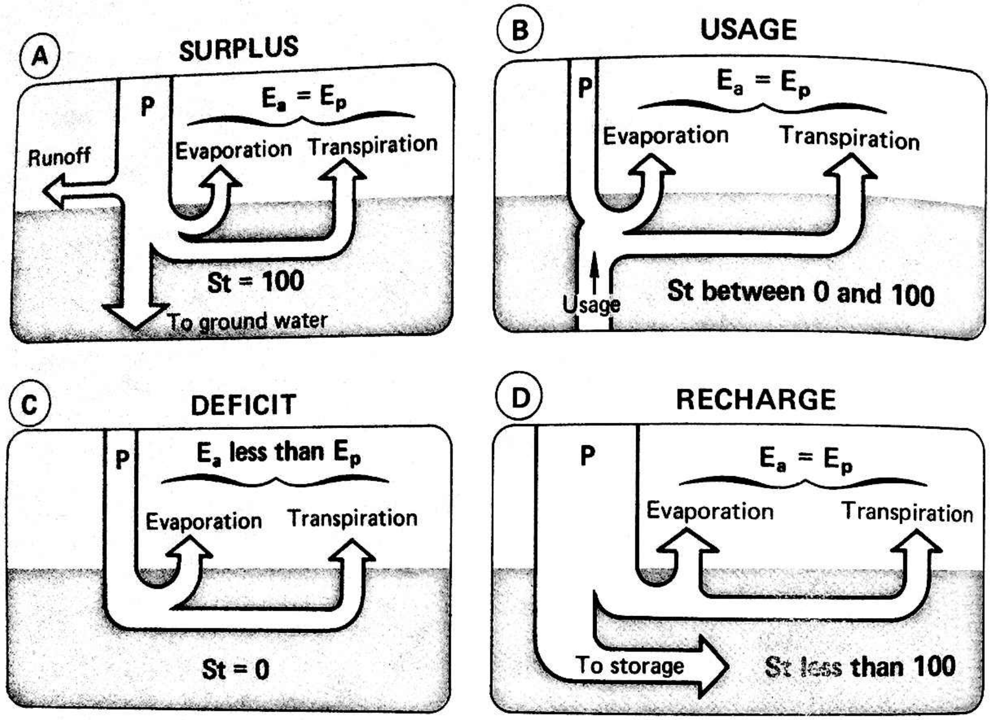


Figure 13-5. The four possible stages of a water budget.

A. Surplus: Storage (St) is at maximum (100 mm). Precipitation (P) is greater than potential evapotranspiration (E_p). Actual evapotranspiration (E_a) equals potential evapotranspiration. Excess water runs off the surface and infiltrates to the ground water.

B. Usage: P is less than E_p. Water is drawn from storage. E_a equals E_p, and St decreases.

C. Deficit: P is less than E_p, and storage is zero. E_a equals P and is less than E_p.

D. Recharge: P is greater than E_p. E_a equals E_p. Water is added to storage. St increases. There is no loss by runoff.

greater than E_p and St is less than 100 mm. Recharge is similar to building up your savings when your income exceeds your expenses.

Summary of Water Budget Factors. Figure 13-5 illustrates the four possible conditions of a local water budget—surplus, usage, deficit, and recharge. Note particularly that only during one of the four possible conditions—that of deficit—is E_a less than E_p. The caption will help you review the ideas that have been presented in this discussion.

SUMMARY

1. Precipitation (P) is the only source of water for a local water budget.
2. Potential evapotranspiration (E_p) is the amount of water that a region is capable of giving up to the atmosphere when precipitation plus soil water is sufficient. It varies directly with insolation of the region.

3. Actual evapotranspiration (E_a) is the amount of water that is actually given up to the atmosphere during a stated period. It is never greater than E_p, but may be less than E_p.
4. The soil can store water up to a specific amount equivalent to about 100 mm of precipitation on the average.
5. Usage occurs when P is less than E_p and plants are drawing water out of storage.
6. A deficit occurs when soil storage is zero and P is less than E_p. Under these conditions, E_a is less than E_p.
7. Recharge occurs when P is greater than E_p and soil storage is less than 100 mm.
8. A surplus occurs when P is greater than E_p and soil storage is full at 100 mm. Surplus water is lost either through surface runoff or infiltration to the ground water.

SAMPLE WATER BUDGETS

Let us see how the factors we have been considering apply to an actual case. Table 13-1 is the basic data for the water budget for the region around Buffalo, New York. P is the average precipitation by months, which has been obtained from weather records collected over many years. E_p is the estimated potential evapotranspiration for the region, based on a study of average temperatures, amounts of insolation, types of plants that grow naturally in the region, and other factors. In the third row of the table, labeled P − E_p, the difference between P and E_p for each month has been obtained by simple subtraction. When P is greater than E_p, the difference is positive. When P is less than E_p, the difference is entered as a negative (minus) number. All figures are in millimeters of water.

Figure 13-6 on the next page is the complete water budget for the Buffalo region. It has been constructed from the information in Table 13-1. Let's approach it step by step.

P and E_p. As you can see, precipitation in the Buffalo area is fairly even throughout the year. This is shown on the graph in Figure 13-6 by a solid line. On the other hand, E_p varies greatly

Table 13-1. Buffalo, New York.

	J	F	M	A	M	J	J	A	S	O	N	D	Totals
P	81	72	71	68	73	69	73	74	75	78	80	81	895
E_p	0	0	0	30	72	111	135	122	84	40	15	0	609
$P-E_p$	81	72	71	38	1	−42	−62	−48	−9	38	65	81	

Buffalo, New York

	J	F	M	A	M	J	J	A	S	O	N	D	Totals
P	81	72	71	68	73	69	73	74	75	78	80	81	895
E_p	0	0	0	30	72	111	135	122	84	40	15	0	609
$P-E_p$	81	72	71	38	1	−42	−62	−48	−9	38	65	81	
ΔSt	0	0	0	0	0	−42	−58	0	0	38	62	0	
St	100	100	100	100	100	58	0	0	0	38	100	100	
E_a	0	0	0	30	72	111	131	74	75	40	15	0	548
D	0	0	0	0	0	0	4	48	9	0	0	0	61
S	81	72	71	38	1	0	0	0	0	0	3	81	347

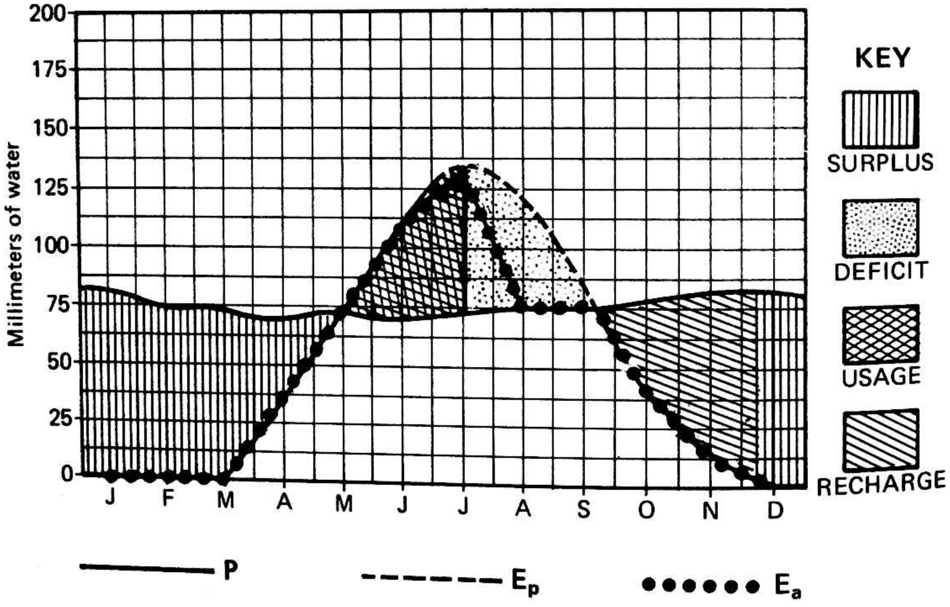


Figure 13-6. The complete water budget for Buffalo, New York.

through the year. During the winter months, it is practically zero. All plant life is dormant, and temperatures are generally so low that almost no evaporation occurs. During the summer months, E_p rises to a peak as temperatures rise and plants become most active. E_p is shown on the graph by a broken line.

The Winter Surplus Months. Look now at $P - E_p$ for October and November. It is 38 mm in October and 65 mm in November. Remember that this is excess moisture that could go into storage. But 38 + 65 is more than 100. This tells us that certainly by November soil storage is filled. And it remains filled for many months thereafter. So we see in Figure 13-6 that St (the fifth row down) is 100 at the start of the calendar year in January. The row headed ΔSt tells us the change in storage that month. Since St cannot increase beyond 100, ΔSt is zero in January.

All the positive amounts of $P - E_p$ that we see in the table while St is 100 are surplus. In Buffalo this surplus in the winter months stays mainly on the surface as snow and ice. It doesn't run off or infiltrate as it might in a warmer region. However, it does eventually do this in the spring, when the snow and ice melt. As far as the water budget is concerned, it makes no difference whether the surplus runs off as it occurs, or whether it accumulates as snow and ice and runs off later. It is surplus in any case. The amounts of surplus are entered in the bottom row of the table in Figure 13-6.

E_p is zero in January, February, and March, so E_a is also zero. This is entered in the row labeled E_a. There is, of course, no deficit, so we see zeros in the row labeled D (for deficit).

The Spring Months of Continued Surplus. With the coming of spring, plants become active. Surface ice and snow melt to water. Both evaporation and transpiration begin to occur in increasing amounts. E_p is 30 in April and 72 in May. But there is plenty of water to meet this demand, and E_a keeps up with E_p. In fact, there is still a surplus. We see these figures for April and May in the table.

The Summer Months of Usage and Deficit. In June the demand for moisture (E_p) exceeds the income (P) for the first time. However, there is enough water in storage to make up the difference. So we see a usage amount (−42) in the ΔSt row, and we see the storage drop by that amount to 58. E_a can still equal E_p, but there is no surplus. In July E_p is again greater than P, this time by 62 mm. But there was only 58 mm in storage at the start of this month. Adding P of 73 and St of 58 gives us only 131. This, then, is the figure for E_a. There is a deficit of 4 mm. The deficits continue through August and September. In these months storage is zero and E_a simply equals P.

The Fall Months of Recharge. By October evaporation is decreasing because of lower temperatures, and transpiration is decreasing because the growing season is ending. Once again, P becomes greater than E_p, and there is excess water that can go into storage. In October 38 mm is available for storage. There is still no surplus, however. But in November the storage maximum of 100 mm is reached, and the period of winter surplus begins, completing the yearly cycle.

Annual Summary. Note the totals in the last column of the table in Figure 13-6. Even though there is a short deficit period in this water budget, the annual income of precipitation (895 mm) is well above the total demand of 609 mm. The year as a whole has a surplus of 347 mm of water. In short, the Buffalo region has more than enough precipitation for the natural needs of its vegetation. We will see later what this means in terms of describing the climate of this region.

The Water Budget Graph. To show this cycle on the graph in Figure 13-6, we add the curve for E_a, using a series

	J	F	M	A	M	J	J	A	S	O	N	D	Totals
P	10	11	8	7	8	18	40	41	33	17	13	12	218
E_p	11	18	37	75	117	163	171	152	111	62	24	10	951
$P-E_p$	−1	−7	−29	−68	−109	−145	−131	−111	−78	−45	−11	2	
Δ St	−1	−1	0	0	0	0	0	0	0	0	0	2	
St	1	0	0	0	0	0	0	0	0	0	0	2	
E_a	11	12	8	7	8	18	40	41	33	17	13	10	218
D	—	6	29	68	109	145	131	111	78	45	11	—	733
S	—	—	—	—	—	—	—	—	—	—	—	—	—

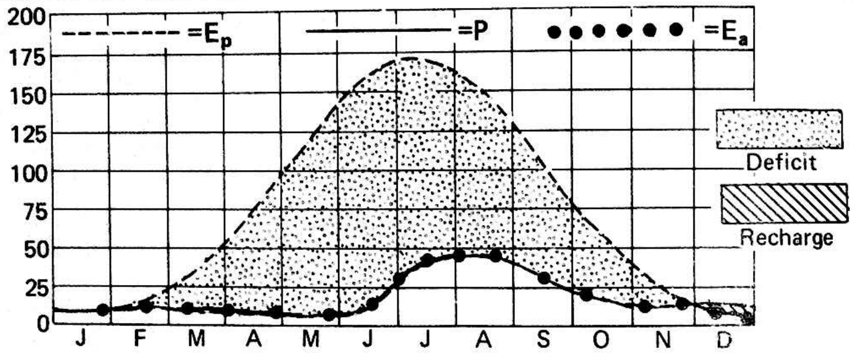


Figure 13-7. The water budget for El Paso, Texas.

of dots. The E_a curve matches the E_p curve except during the deficit period. In this period, the E_a curve drops down and follows the P curve. By using different types of shading, we can show the periods of surplus, usage, deficit, and recharge.

Water Budget for a Dry Region. As an interesting contrast, look at the water budget for the El Paso region in Figure 13-7. Here is a situation in which an almost continuous deficit exists through the year. Only in the single month of December does P exceed E_p, and then only by 2 mm. Most of the time E_p is far greater than the water available. What this means is that there is enough energy (insolation) to support much more abundant plant growth than occurs naturally. This is borne out by the fact that when water is brought in by irrigation, the land will produce a fine growth of crops. The "potential" is there, but the actual moisture supply cannot meet that potential demand.

This is clearly a climate quite different from that of Buffalo. We will have more to say about this later on.

SUMMARY

1. A local water budget can be constructed from monthly data for precipitation and potential evapotranspiration.
2. Monthly changes in soil storage and values of actual evapotranspiration can be calculated from the basic data.
3. Periods of surplus, usage, deficit, and recharge can be determined from the calculations and shown graphically.

STREAMS AND THE WATER BUDGET

In discussing periods of surplus in the water budget we mentioned that some of the surplus water may run off over the surface, while the rest of it infiltrates down to the ground water. Recall that ordinarily the pores in the storage zone near the surface of the soil are not filled with water, even at maximum storage capacity. Stored soil water is only a film on the walls of the pore spaces. During a heavy rain, these pores may be temporarily filled. Surplus will then largely run off the surface. But after the rain, surplus water in the pores will also drain away and join the ground water.

Streams. What happens to surface runoff during heavy rains? Some may gradually infiltrate the soil in less saturated areas. The rest runs downhill into the lowest channels in the local contours, forming little streams. Small streams join to form larger streams, which join other streams, eventually forming the largest streams, usually called rivers, which empty into the oceans.

There is no generally accepted rule for deciding when a stream is big enough to be called a river. The solution to this problem is to avoid the word "river." We will use the word "stream" to mean any natural channel on the earth's surface that carries water downhill.

If the bed of a stream is not below the water table, water will steadily infiltrate the stream bed and drain away. A stream of this kind will be only temporary. Between periods of rain, it will tend to become a trickle and then dry up. However, most streams flow over a saturated bed. That is, the bed is actually below the water table of the surrounding land, as shown in Figure 13-4 on page 236. Such a stream will flow continuously, even during periods of little rainfall. The stream will be fed not only by surface runoff, but also by flow from the ground water through the pores of the stream bed. This flow from the ground water is very slow, but it occurs continuously all along the stream bed. So it is enough to keep the stream well supplied with water. Water that enters a stream from the ground water is called the *base flow* of the stream.

Stream Discharge. The discharge of a stream is the volume of water that passes a point in the stream during a given amount of time. It is the rate of flow of the stream, not in terms of velocity, but in terms of amount of water. A broad river, slowly and majestically making its way to the sea, may have an enormous discharge. A racing mountain stream is likely to have a relatively small discharge.

The U.S. Geological Survey measures, or *gauges,* the discharge of many streams. Automatic instruments make a continuous record of the discharge, which may then be studied for information that is related to the local water budget.

The discharge of a stream will usually vary from day to day, depending on recent precipitation. Figure 13-8 on the next page shows the record of stream discharge for a stream during a period of about 36 hours, and a record of local rainfall during the same period. As the graph shows, the base flow of this stream is normally around 0.5 cubic meters per second (m^3/sec).

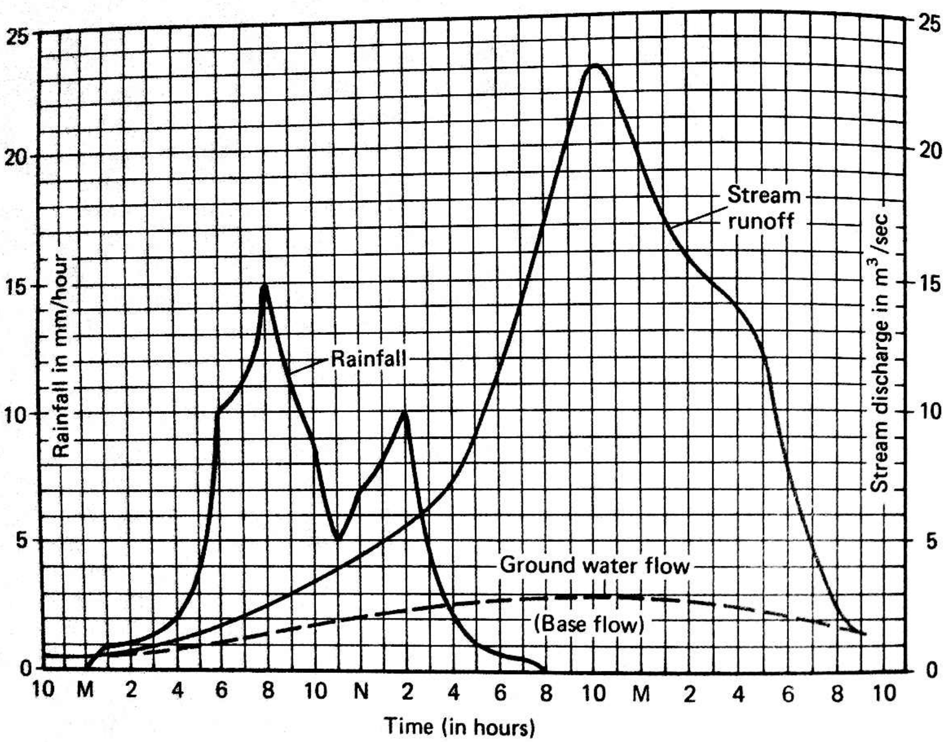


Figure 13-8. The effect of local precipitation on the discharge of a small stream.

This is the discharge during dry intervals. Note what happened to the discharge after the rain started. It reached a peak of about 23 m³/sec. Some of this increase came from an increase in the base flow. This was water that infiltrated to the water table and entered the stream from the ground. Most of the increase, though, was apparently due to runoff from the surface. As you can see, it took about 15 hours for these two factors to have their maximum effect on the discharge.

The discharge of a stream may also vary seasonally through the year. Figure 13-9 shows the discharge record for a stream for a typical year. The water budget for the region is also shown for comparison. As you might expect, the stream discharge is least during periods of usage and deficit, and greatest during periods of surplus. Note, however, that the stream does not stop flowing even at the height of the deficit. It continues to be supplied from the ground water.

The Water Table and the Water Budget. The water table is the level of the ground water, or the level to which the permeable surface layer of rock and soil is saturated. A lake or a stream is in most cases simply a place where the water table comes up above the surface of the land. As explained in Chapter 12, the water table generally follows the ups and downs of the surface, but at some depth below it. Under the action of gravity, the ground water slowly flows through underground pores and enters streams, lakes, and oceans. This steady downhill flow of ground water tends to lower the water table. But infiltration of water from precipitation tends to raise it.

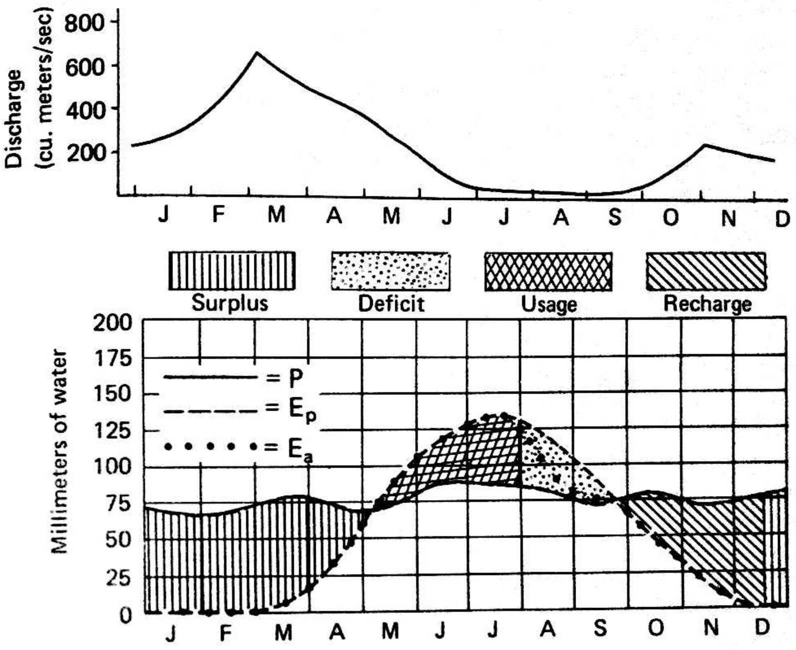


Figure 13-9. The discharge of a stream compared with the local water budget. Note that although the precipitation is fairly constant through the year, the stream discharge is large during periods of surplus, when there is much runoff, and small during periods of usage and deficit. The peak in March is due to the melting of accumulated snow and ice.

During periods of little precipitation, the water table tends to drop. During periods of heavy precipitation, it tends to rise. The change in the level of the water table over the course of a year is usually not very great. However, the effect may be quite noticeable where the water table is normally above the land surface (See Figure 13-10 on the next page). A stream during the deficit months may be, say, 50 cm deep. With the heavy runoff of surplus during a spring thaw, the stream may rise to a height of 300 cm (3 m). Its depth has increased six times! But the actual change is only 2.5 m. In other words, the water table at the stream has risen 2.5 m.

A change of 2.5 m may make a big difference in the shoreline of a pond. A drop of this amount may cause a marshy area to become quite dry. But except along the margins of streams and lakes, the ordinary changes in the water table in the course of a year have only minor effects.

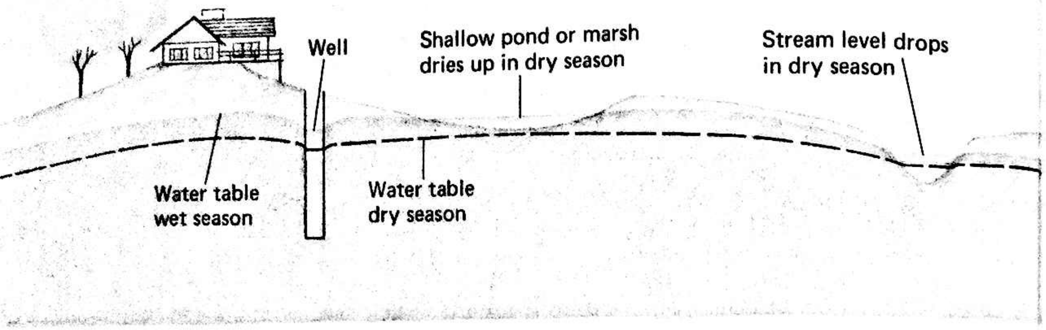


Figure 13-10. Some effects of changes in the water table.

SUMMARY

1. A stream is a channel in the earth in which runoff collects and moves downhill under the force of gravity.
2. The discharge of a stream is the volume of water that passes a certain point in the stream during a given period of time.
3. The discharge of a local stream varies with the amount of runoff from the surrounding area.
4. Streams are fed by ground water and by surface runoff.
5. Stream discharge during dry periods is maintained by the use of ground water.

CLIMATE

When we talk about climate, we are referring to the average weather conditions in a region over a period of many years. Which conditions would you consider the most important in describing climate? Think about the various types of climates that you have heard about or experienced—hot, dry deserts; hot and steaming rain forests; cold, snowy polar climates. In each, the two conditions used to describe climate are temperature and moisture.

Since temperature and moisture are the two most important factors in describing climate, most systems of climate classification begin by breaking down the earth's surface into zones according to temperature patterns and moisture patterns.

Temperature Patterns and Climate. To describe the temperature characteristics of a region, you must know the *average* monthly and yearly temperatures. Another useful temperature characteristic is the yearly temperature *range*. This is the difference between the warmest average monthly temperature and the coldest average monthly temperature.

We know that average temperatures are highest near the equator and become lower as latitudes increase. We can therefore begin to classify climates by dividing the earth into temperature zones by latitude. One common system of doing this is shown in Figure 13-11.

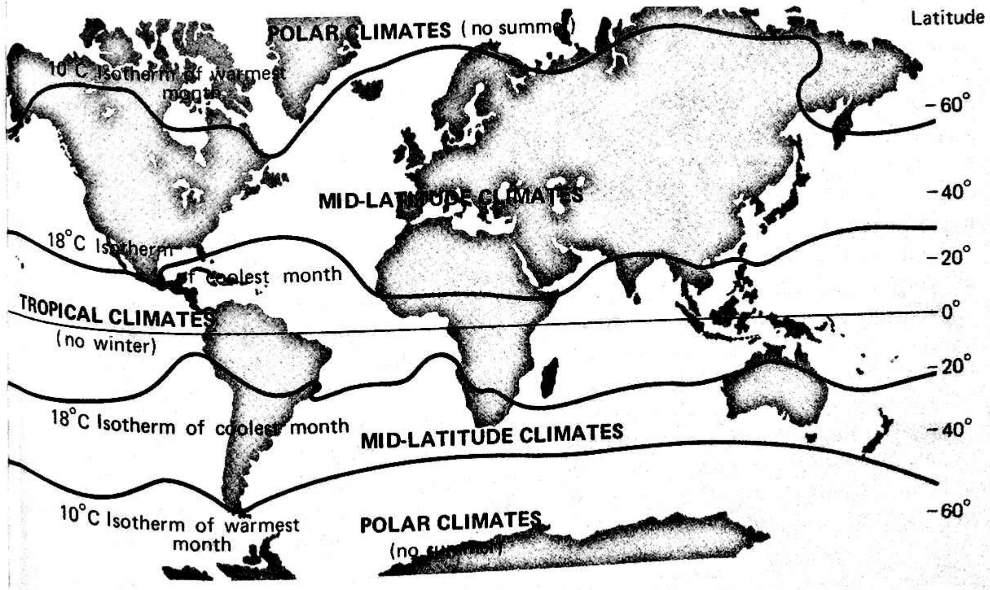
In Figure 13-11, the boundary of the cold zones around the poles has been set by places where the average temperature of the warmest month is 10°C. The line through these places is the 10°C *isotherm* for the warmest month (usually July in the Northern Hemisphere and January in the Southern Hemisphere). Average monthly temperatures along this isotherm are never higher than 10°C. At higher latitudes, average temperatures are even colder. These regions have *polar climates,* in which there is essentially no summer.

The boundary of the *tropical climate zone* around the equator has been set by temperatures of the coldest month. The 18°C isotherm for the coldest month (January north of the equator, July south of the equator) has been selected. Average monthly temperatures inside this zone are never lower than 18°C. Places with a tropical climate have no winter.

The zones between the polar zones and the tropical zone have *mid-latitude climates,* in which there is generally a definite winter and summer.

In drawing the isotherms that are the boundaries of the climate zones in Figure 13-11, the effects of elevation have not been included. The map shows the temperature pattern we would find if all the land areas had elevations near sea level. Actually, there are places within the tropical

Figure 13-11. Latitudinal climate belts of the world. In the tropical climate zone, the average monthly temperatures at sea level never drop below 18°C. In the polar climate zones, the average monthly temperatures never rise above 10°C. Effects of altitude have been omitted.



zone that have mid-latitude temperatures, or even polar temperatures, because of their high elevations.

Moisture Patterns and Climate. A classification of climate based on temperature alone gives only half the picture. It may be helpful to know that a certain area has a tropical climate—warm all year long. But it would be just as important to know that it is a desert or that it is a rain forest. To get a truly useful description of any climate, we must include information about moisture.

When we try to classify climates according to moisture conditions, we need to consider the water budget of the region. The water budget tells us not only how much precipitation the region receives, but also how this compares with the natural demand for water—the potential evapotranspiration. Two regions may have the same amount of annual precipitation, say, 500 mm. But one may have tropical temperatures, with a potential evapotranspiration of 1,000 mm. This area would be considered to have a dry climate—less rainfall than it could use. The other area may have cold climate, with a potential evapotranspiration of only 250 mm. This area, with the same precipitation as the other, would have a wet climate—more water than it can use.

To describe the moisture side of climate, then, we should compare P with E_p for the region. One way to do this is to express the comparison as a ratio (P/E_p). When potential evapotranspiration is greater than yearly precipitation, this ratio is less than 1. When precipitation is greater than evapotranspiration, the ratio is greater than 1. Regions in which P/E_p ratio is much less than 1 are said to have an *arid* climate. Where the P/E_p ratio is more than 1, the climate is called *humid*. Intermediate climates are described as *semiarid* or *subhumid*. Table 13-2 shows one system for classifying climates according to P/E_p ratios.

Table 13-2. Classifying climate types.

P/E_p	Climate type
Less than 0.4	Arid
0.4 – 0.8	Semiarid
0.8 – 1.2	Subhumid
Greater than 1.2	Humid

Let's consider two examples using this system.

Example 1: Reno, Nevada

$P = 193 \quad E_p = 628$

$P/E_p = 193/628 = 0.3$

Climate type: Arid

Example 2: New Brunswick, N.J.

$P = 1183 \quad E_p = 693$

$P/E_p = 1183/693 = 1.7$

Climate type: Humid

As we have already noted, a region need not have a great deal of precipitation to be classified as humid. The yearly precipitation rate could be low, but if E_p is even lower, the climate would still be humid. These points are illustrated by the simplified water budget graphs in Figure 13-12.

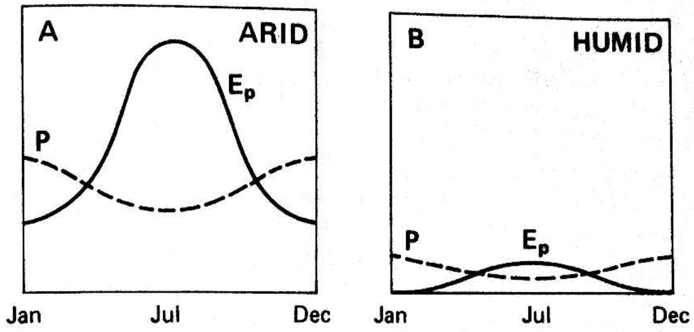


Figure 13-12. Example of the relationship between precipitation and potential evapotranspiration in an arid and a humid climate. Graph *A* shows the relationship between P and E_p for a region in which there is moderate rainfall but high values of E_p. Since there is a net moisture deficit for the year, the region has an arid climate. Some regions around 30° latitudes have climates of this type. Graph *B* represents a climate in which there is little precipitation, but even smaller values of E_p. Since there is a moisture surplus for the year, the climate is humid.

SUMMARY

1. Climatic regions can be described in terms of average monthly temperatures.
2. Climatic regions can be described in terms of the relationship between precipitation and potential evapotranspiration—for example, as the ratio P/E_p.

FACTORS AFFECTING CLIMATE PATTERNS

The climate of a region is determined by a number of different factors, the most important of which is latitude.

Latitude. In Chapter 9 we learned that the intensity and duration of insolation received at the earth's surface varies with latitude. We also learned that temperature depends on duration and intensity of insolation. Latitude, the distance north or south of the equator, is the most important factor in determining the average monthly and yearly temperatures, as well as the yearly temperature range of a location.

At low latitudes, the angle of insolation is high throughout the year. Duration of insolation is about 12 hours a day all year long. Because the intensity of insolation is high all year, and the duration of insolation is about the same throughout the year, the average yearly temperature is high and there is very little variation in temperature. So, at low latitudes, there is relatively constant high temperature all year long, and the annual temperature range is very narrow.

In mid-latitudes, the angle of insolation is quite high during the summer, so the intensity of insolation is high. The duration of insolation during the summer is 15 to 16 hours a day. So, at these latitudes the summer is generally quite warm. During the winter, the angle of insolation is low, so intensity of insolation is low. Duration of insolation is only 8 to 9 hours a day. Thus winter temperatures are low. At mid-latitudes, the average yearly temperature is much lower than around the equator, and the annual temperature range is fairly large.

At high latitudes, average temperatures are very low, because even in summer the angle of insolation is never large, and during the winter insolation may be zero for months at a time. The temperature range is also very great. During the long winter period with little or no insolation, temperatures drop steadily to extremely low readings. During the summer, when the sun shines continuously, temperatures rise steadily and become rather moderate.

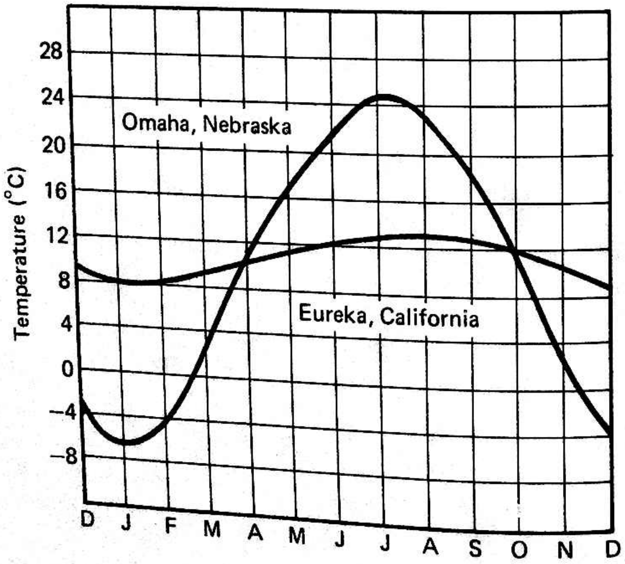
If you look back at Figure 13-11 (page 247), you can see that the isotherms that determine the climate zones are roughly related to latitude. But you can see that temperature must be affected by other factors. Otherwise, the isotherms would be straight lines.

Elevation. We know from Chapter 11 (page 202) that as air rises, it expands and cools. So, as altitude increases, temperature decreases. The higher you go, the cooler it gets. Air temperature changes with altitude at a rate of 10°C/km. So increasing altitude, or elevation, modifies the climate pattern in the same way as increasing latitude. There are mountains located on or near the equator that have snow-covered tops all year long.

Altitude also affects precipitation patterns. Air temperature and saturation vapor pressure decrease with increasing altitude. Therefore, as air rises, it approaches the dew-point temperature (see Figure 11-18, page 207). So, areas at higher elevations generally receive more precipitation than nearby areas at lower elevations.

Large Bodies of Water. Figure 13-13 shows average monthly temperatures for the West Coast city of Eureka, California, and the mid-continent city of Omaha, Nebraska, both of which are at about 41° north latitude. One reason for the difference between these graphs is that climate patterns are modified by the presence of large bodies of water, such as oceans or large lakes. We know from Chapter 9 (page 148) that bodies of water heat up and cool off more slowly than land areas. This modifies the climate pattern of shore areas so that they have warmer winters and cooler summers than inland areas at the same latitude. Such climates are called *marine climates*. Inland areas, which have cooler winters and warmer summers than shore areas, are said to have *continental climates*. Because of the moderating effects of large bodies of water, marine climates show a narrower annual temperature range than continental climates.

Figure 13-13. Average monthly temperatures for a coastal city (Eureka) and a mid-continent city (Omaha), both at 41° north latitude.



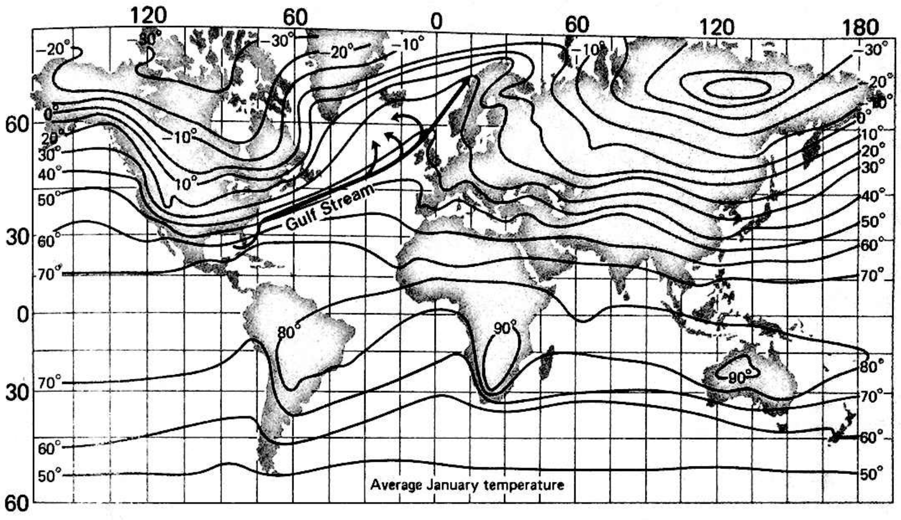


Figure 13-14. Average temperatures for January.

Ocean Currents. Study the pattern of the isotherms on the map in Figure 13-14. Notice how much warmer it is in Great Britain and Scandinavia than in other regions at the same latitude. Compare the pattern of the isotherms with the flow of the Gulf Stream as shown on the map. The Gulf Stream is a current of water that is several degrees warmer than the surrounding waters of the Atlantic Ocean. The climates of many coastal areas are modified by ocean currents. Some of these currents, like the Gulf Stream, flow away from the equator to higher latitudes; they raise the average temperatures of coasts and islands they pass near. Others are cold currents flowing from higher to lower latitudes; they have the opposite effect on latitudinal climate patterns.

Mountains. Climate patterns are affected by mountains, which act as barriers to prevailing winds. Figure 13-15 on the next page shows the *orographic effect*—the effect of mountains on climate. The side of the

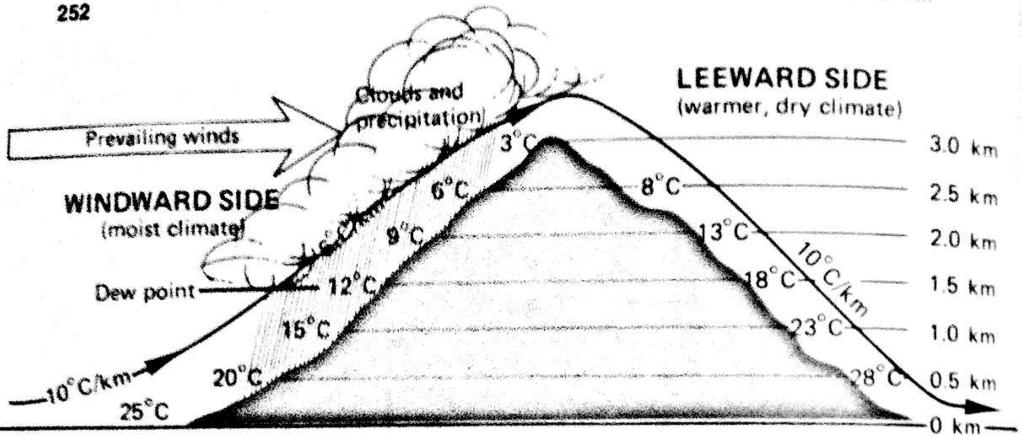


Figure 13-15. Orographic effect. The orographic effect occurs where mountains intersect moist winds. Compare the temperatures at the same altitude on the two sides of the mountain.

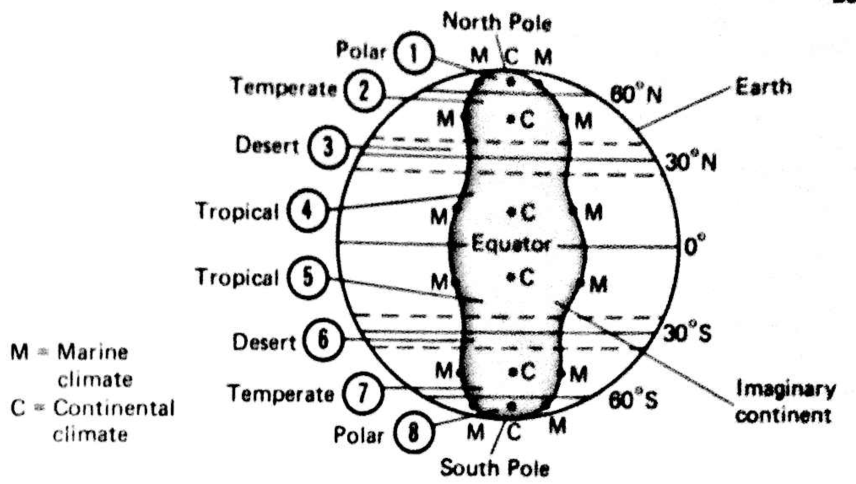
mountain hit by prevailing winds is called the *windward side* — in the diagram, the left side. When the air hits the windward side of the mountain, it is forced to rise. As it rises, it undergoes adiabatic cooling (see Figures 11-14 and 11-18, pages 203 and 207). If the air cools to the dew-point temperature, condensation occurs. Clouds form, and precipitation may occur. So the windward side of the mountain will be cool and humid.

The opposite side of the mountain is called the *leeward* side. On this side the air is descending, and as it descends, it undergoes adiabatic warming. So, the leeward side of the mountain will be warmer than the windward side. Also, most of the moisture will have been lost from the air on the windward side, so the leeward side will tend to be arid.

Planetary Wind Belts and Climate Patterns. In Chapter 11 (page 199) we saw the general pattern of circulation of the atmosphere. This pattern produces a belt of low pressure around the equator and belts of high pressure at latitudes around 30°N and 30°S, with zones of prevailing winds on either side of these pressure belts.

The planentary circulation of the atmosphere affects the general climate pattern at various latitudes, as shown in Figure 13-16. The rising, low-pressure currents near the equator result in much precipitation, so that the climate near the equator tends to be not only hot, but also very humid. In the high-pressure zone of descending air around 30° latitudes, the air is quite dry. This results in a belt of warm, arid climates at these latitudes. At the higher latitudes the climate is generally humid, with temperatures becoming colder as latitude increases. On a continent these basic climates would be modified by distance from the coast, with temperature ranges greater in the interior than along the ocean margins.

This basic latitudinal climate pattern is further modified by continental land masses because of the tendency of land to heat up and cool off to a greater extent than water. As a result, large-scale convection currents between the land and the water disturb



CLIMATE TYPE			
Polar	**Temperate**	**Desert**	**Tropical**
Cold, arid, with large temperature variation	Moderate temperatures, humid, with moderate temperature variation	Hot, arid, with moderate temp. variation	Hot, humid, with little temperature variation
1,8	2,7	3,6	4,5
Zones			

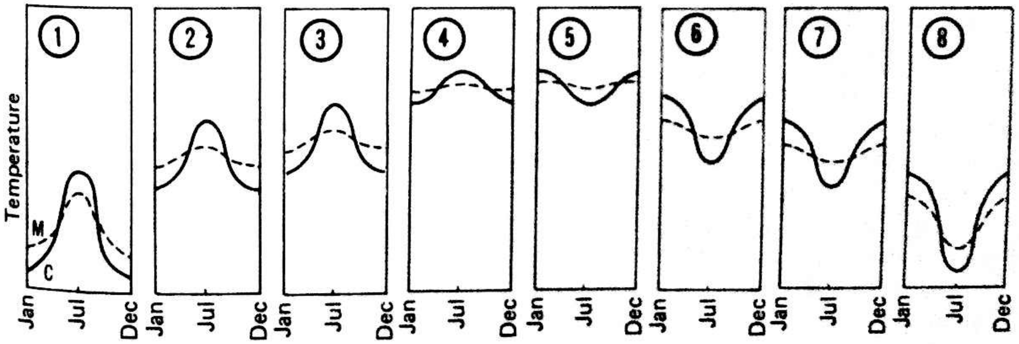


Figure 13-16. Basic latitudinal climate pattern on an imaginary continent. The arid belts around 30° latitudes are the result of descending air in the atmospheric circulation at those latitudes. The modification of this basic pattern by prevailing winds and distance from oceans is illustrated in Figure 13-17.

the normal pattern of the planentary winds. Figure 13-17 on the next page shows how the latitudinal climate pattern is modified by a large land mass. Note that as you move eastward across the continent, the arid belt that is expected around 30° latitudes shifts to higher latitudes and then is cut off, while the humid climate zone is extended to lower latitudes in the eastern portions of the continent. These effects are quite noticeable in the de-

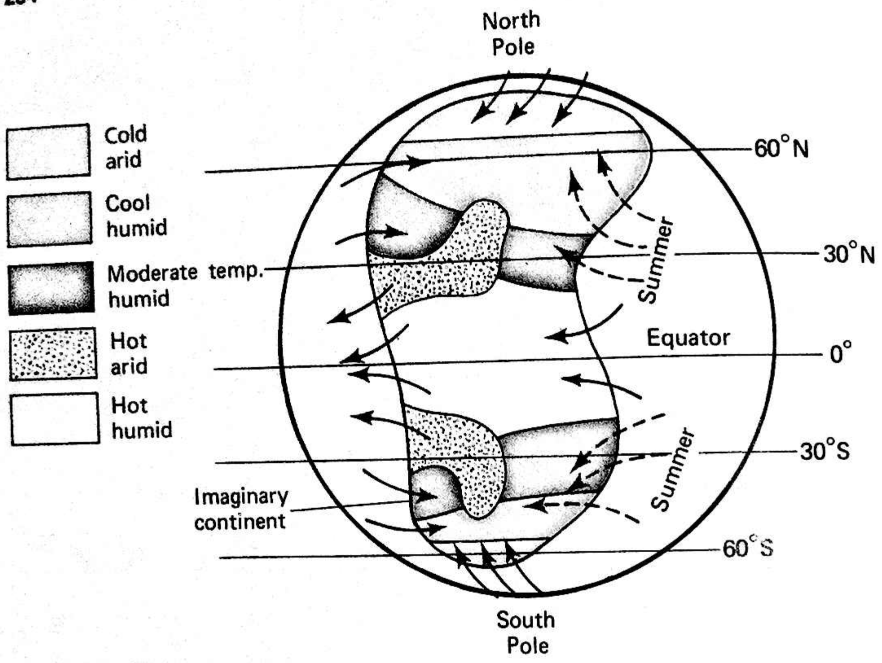


Figure 13-17. Modification of basic climate pattern by prevailing winds. Note that the arid belts around 30° latitudes do not extend across the eastern regions of the continent. One reason for this is that heating of the landmass during the summer produces convection currents that draw moist air over the land from the oceans on the east, thus making the climate more humid. Note also that the central regions of the continent in the mid-latitudes (40° to 50°) are arid. The reason for this is that the westerly winds at those latitudes have lost most of their moisture as precipitation over the western regions of the continent; the high summer temperatures in the central regions also result in lower relative humidity and less chance of precipitation.

sert climate of the southwestern United States and the humid climate of the southeastern states. Remember, however, that local climate is also affected by other factors, such as mountains.

SUMMARY

1. Latitude affects temperature patterns.
2. Elevation influences both temperature and moisture patterns.
3. Large bodies of water modify the latitudinal climate patterns of their shoreline areas.
4. Ocean currents modify the coastal climate patterns.
5. Mountains act as barriers to atmospheric circulation and so modify the latitudinal climate pattern.
6. Planetary wind and pressure belts affect moisture and temperature patterns.

REVIEW QUESTIONS

Group A

1. What is the only source of water for a local water budget?
2. What is meant by the term *potential evapotranspiration?* How is potential evapotranspiration related to insolation?
3. What is meant by *actual evapotranspiration?*
4. What is the maximum amount of water that can be stored in average soil?
5. Under what conditions does usage occur?
6. Under what conditions does a deficit occur? How does E_a compare with E_p under deficit conditions?
7. Under what conditions does recharge occur?
8. Under what conditions is there a surplus? What happens to the surplus water?
9. What data do you need to construct a local water budget?
10. What is a stream?
11. What is meant by the *discharge* of a stream?
12. What factor affects the discharge of a local stream?
13. From what sources do streams receive water?
14. How is stream discharge maintained during dry periods?
15. In what terms are climatic regions described?
16. What factors affect temperature and/or moisture patterns?
17. What factors modify latitudinal climate patterns?
18. What factor modifies coastal climate patterns?

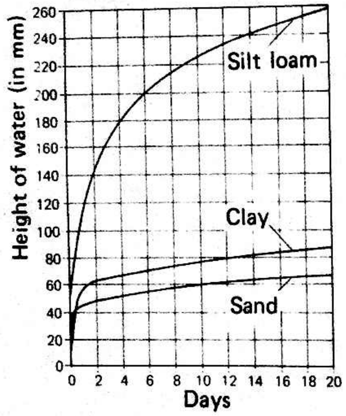
Group B

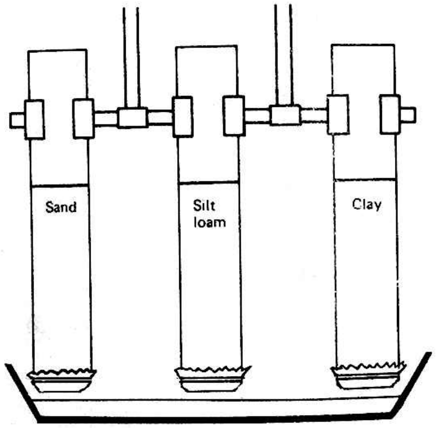
1. a. Describe the conditions that exist in a "normal" (humid) climate during the four stages of a water budget. Explain how E_a relates to E_p in each stage.
   b. Describe how the conditions that exist in a dry, desert-like climate affect the water budget in that area.
2. Explain what changes would be observed in (a) a small pond, (b) a small stream, and (c) a very large river, as the water budget went through the four stages of a normal climate.
3. a. The continental United States is regarded as a mid-latitude climate, and yet Reno, Nevada, and New Brunswick, New Jersey, have very different climates. Explain how a difference like this can occur. (See page 248.)
   b. Are there any special local conditions that affect your climate and modify it from that of other locations near you?

REVIEW EXERCISES

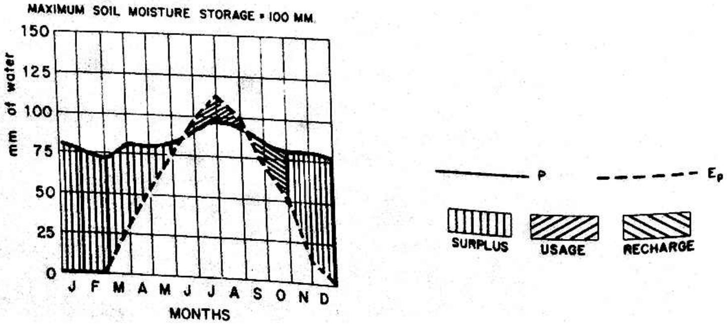
1. Determine the source of the water supply for your home. Do you have your own supply, such as a well? Are you supplied by your city or town? If so, what is their source of supply?
2. It is estimated that in the United States, each person uses about 265 l of water per day for personal use. Estimate how much water you use daily. You may have to use a reference source, such as an encyclopedia, to get an idea of how much water is used in certain activities. For example, a bath takes from 115 to 150 l of water.

3. Samples of three different soils were put into glass columns, and the ends of the columns were covered with cloth. The columns were then turned upside down and lowered into a container of water. The height to which the water rose in each column was then measured over a period of time. The results are shown in the graph below. Using the information provided, answer the following questions.
   a. In which soil is the capillary migration the greatest? What soil characteristic affects capillary migration?
   b. Which of the three soils will be the most permeable?
   c. Which of the three soils will have the highest rate of infiltration?
   d. Which of the three soils will have the highest porosity? Which one will have the lowest porosity?
   e. Which of the three soils will be the best for growing crops?





4. To answer the following questions, study the water budget below.
   a. During which months is the available energy for this area the greatest?
   b. During which months did recharge take place?
   c. During which month would the amount of water in the streams of this area be the greatest?
   d. What is the total precipitation for the year?
   e. Why was the potential evapotranspiration of this area approximately 0 mm during January?



5. The hydrographs below are from two streams in the area of Buffalo, New York, during one year. The Niagara River is a fairly large river, while the Scajaquada Creek is a small stream. Using information from the hydrographs and from the water budget for Buffalo (page 240), answer the following questions.
   a. Which stream has the more irregular flow? What causes this?
   b. Did the Scajaquada Creek run dry during this particular year?
   c. There is an increase in flow in both streams in early December. Is this to be expected from the information given in the water budget, or was it an unusual occurrence during the year the hydrographs were made?