HYDROLOGIC INTERRELATIONS BETWEEN LANDS AND OCEANS

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Factors controlling precipitation—Rainfall in a given locality is governed by two sets of factors: (1) Hydrodynamic factors, such as topography and orographic conditions, which, together with atmospheric circulation, general and local, determine the occurrence and frequency of ascending air-masses; (2) moisture-supply. Either of these factors may be adequate to produce rain but if the other is deficient, little or no rain occurs. Air-masses rich in moisture pass in summer from the Pacific Ocean over the coastal plains of California, producing little or no rain until forced above the condensation-level by the coastal mountain ranges.

Relatively dry air-currents ascending mountain slopes in the eastern Rocky Mountain Region produce little rain because of low moisture-content and consequent high condensation-level. Heavy rain generally occurs when the two sets of factors described are both present, as in case of the Blue Ridge Mountains, certain mountain regions in Hawaii, the Mt. Hood region in Washington, and the western Ghats in India. In the upper Mississippi Valley nearly 80 per cent of the total annual rainfall occurs in the six-month warm season, May to October, in spite of the remoteness from the ocean and absence of mountains. This results chiefly from conditions favoring convective and frontal ascent of air and the presence of moisture derived from inland water-losses to windward.

General hydrologic data for the United States—As a basis for the discussion of the interrelations of lands and oceans, certain hydrologic data for continental United States, excluding Alaska, have been compiled as shown in Table 1. A report of the National Resources Board [see 1 of "References" at end of paper] contains maps of average annual precipitation and average annual runoff throughout the United States. The average annual rainfall was determined from the contours for each 2° quadrangle of latitude and longitude; the average annual runoff was similarly determined; the difference between the two represents the average annual water-losses in the 2° quadrangle. Averaging these values for the whole of the United States for either rainfall, runoff or water-losses, the results are given for the United States as a whole, as follows:

<table>
<thead>
<tr>
<th>Region</th>
<th>Precipitation</th>
<th>Runoff</th>
<th>Water-loss</th>
<th>Evaporation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area</td>
<td>% Total</td>
<td>Average</td>
<td>% Total</td>
</tr>
<tr>
<td></td>
<td>Sq. Mi.</td>
<td></td>
<td>Inches</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continental United States</td>
<td>3,026,789</td>
<td>100</td>
<td>31.5</td>
<td>100</td>
</tr>
<tr>
<td>Area East of Continental Divide</td>
<td>2,124,127</td>
<td>71.5</td>
<td>32.8</td>
<td>74.4</td>
</tr>
<tr>
<td>Area West of Continental Divide</td>
<td>882,682</td>
<td>28.5</td>
<td>28.3</td>
<td>25.6</td>
</tr>
<tr>
<td>Great Basin</td>
<td>230,758</td>
<td>7.6</td>
<td>14.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Peripheral Area—west of Continental Divide</td>
<td>401,904</td>
<td>13.9</td>
<td>30.3</td>
<td>20.1</td>
</tr>
<tr>
<td>Peripheral Area—Total United States</td>
<td>2,790,051</td>
<td>92.4</td>
<td>32.8</td>
<td>36.6</td>
</tr>
<tr>
<td>4° Belt—West coast</td>
<td>224,926</td>
<td>7.6</td>
<td>49.4</td>
<td>11.6</td>
</tr>
<tr>
<td>4° Belt—East coast</td>
<td>523,275</td>
<td>17.6</td>
<td>45.1</td>
<td>13.3</td>
</tr>
</tbody>
</table>
Fig. 1--Mean profiles of hydrologic data, yearly basis, United States, latitude $26^\circ$ to $49^\circ$

or for any given portion, the average quantities were obtained for different physiographic regions, as shown in Table 1.

Data for average evaporation from Class-A, United States Weather Bureau evaporation-pans were similarly obtained from evaporation-maps prepared by the author [2]. The average rainfall is 31.5 inches, the average runoff 10.6 inches, the average water-losses 20.9 inches or about two-thirds of the rainfall. The average evaporation from Class-A pans is 58.2 inches, the average evaporation from broad water-surfaces is about 70 per cent of this or roundly 41 inches, or approximately twice the average water-losses.

From the data described, values of the ratios water-loss to precipitation $=(L/P)$, water-loss to evaporation $=(L/E)$, and precipitation to evaporation $=(P/E)$ were determined for each 2° quadrangle. Figure 1 shows an average profile of the various hydrologic elements described, proceeding eastward from the Pacific Ocean to the Atlantic Ocean. Data for this profile were obtained by plotting the values of a given element for each 2° of latitude and for a given longitude.

There will be occasion later to use the data given in Table 1 and on Figure 1 in various ways, but first some general considerations of the hydrologic interrelations of lands and oceans will be developed.

Vapor-exchange--Much attention has been given to the relation of water-losses to precipitation. This paper is largely devoted to the converse question or the relation of precipitation to water-losses. This involves the interchange of vapor between a given area and the surrounding terrain and in particular the interchange of vapor between land-areas and the oceans.

In dealing with the question of the extent to which precipitation in a given locality is derived, respectively, from "oceanic vapor" and "vapor of local origin" it is necessary, in order to avoid confusion, to specifically define the kinds and sources of vapor under consideration. These may include:

1. Vapor truly of oceanic origin, derived by direct evaporation from ocean-surfaces.
2. Vapor imported from the ocean to the land and vice versa. In some localities, especially adjacent to coast-lines, this may include not only vapor derived through evaporation from ocean-
surfaces but also vapor previously exported from the land to the ocean and later returned to the land without precipitation.

(3) Net vapor-exchange--This is the net exchange of vapor between the ocean and the land, regardless of the source of vapor. With respect either to the land or ocean it is the difference between the vapor exported and the vapor imported. This quantity is sometimes referred to as if it were all vapor of truly oceanic origin or as if it represented all the vapor of true oceanic origin entering the land. Neither of these assumptions is necessary nor generally true. Net exchange of vapor is by far the most important of the three quantities described, since it alone determines the water-balance between the oceans and continents.

Wide differences in numerical results may follow attempts to estimate the amount of inland precipitation derived from "oceanic vapor," dependent on which of the three quantities defined is considered to represent "oceanic vapor."

In dealing with the amount of precipitation on a given land-area or drainage-basin derived, respectively, from oceanic and non-oceanic vapor, distinction must be made between vapor derived from water-losses on the given area and vapor also of inland origin imported from adjacent land-areas. The former may conveniently be called "indigenous" or "native" vapor and the latter "exotic vapor of land-origin." In case of an inland area there is, disregarding true oceanic vapor, usually a net vapor-exchange between the given area and the surrounding terrain. With respect to a given land-area the precipitation may be derived in part from each of the three following types of vapor: (1) Native vapor; (2) exotic land-vapor; (3) vapor of true oceanic origin.

Hydrologic balance of a drainage-basin--If the inflow of water in any form to a drainage-basin is balanced with the outflow, then for surface- and subsurface-conditions the equation of continuity gives the result

\[ P = y + L + \Delta S \]  

(1)

where \( P \) = precipitation, \( y \) = total runoff, \( L \) = evaporative water-losses, and \( \Delta S \) = gain or loss of storage in the time-interval under consideration, all quantities being expressed in the same units. This equation holds true for any time-interval and applies to any drainage-basin and to the Earth as a whole.

For steady conditions \( \Delta S \) must be zero, since otherwise either dessication or the reverse would occur. For \( \Delta S = 0 \)

\[ P = y + L \]  

(2)

or

\[ y = P - L \]  

(3)

Next consider the drainage-basin as surrounded by a permeable shell extending up to the limit of vapor-circulation. Let \( O, C, \) and \( L \) represent, respectively, the quantities of vapor entering or leaving this shell and which are derived directly from evaporation from oceans, from lands extraneous to the area and from the area itself, and let \( R \) represent the resultant net vapor-exchange between the atmospheric shell and its surroundings. The subscripts \( i \) and \( e \) will be used to designate vapor flowing into and out of the shell, that is, imported and exported vapor, respectively. For vapor of a given origin, that which merely passes over and through the atmospheric shell need not be separately considered. The prefix \( A \) will be used to designate the net difference between import and export of vapor of a given kind. Then for atmospheric conditions over a given area the storage-equation for steady conditions gives

\[ P = (L - L_e) + \Delta O + \Delta C \]  

(4)

and

\[ R = P - L = \Delta O + \Delta C - L_e \]  

(5)

Equating (3) and (5) gives

\[ y = \Delta O + \Delta C - L_e = R \]  

(6)

or the resultant vapor-transfer or net vapor-exchange between the given area and its surroundings
is precisely equal to the runoff. This rule is true for any area, large or small, on which precipitation occurs. It applies equally well to the drip from a single leaf of a broad-leaved tree, to a drainage-basin draining directly to the ocean, to a remote interior tributary of a stream draining to the ocean, to a closed interior basin, to the continents as a whole or to the oceans alone.

The statement is sometimes made that the runoff from the land-surfaces of the Earth to the oceans is equal to the vapor imported from the oceans to the land. This statement is precisely true if the term "vapor imported from the oceans" means "net vapor-exchange" between the oceans and the lands.

With respect to an individual area the statement may also be made that the runoff passing out from the area is precisely equal to the net vapor-exchange between the given area and its surroundings. This does not mean that the quantity of vapor actually of oceanic origin transferred from the oceans to the land equals the runoff from the land. There are, in fact, large differences in the quantity of vapor actually of oceanic origin transferred to the land under different conditions, even though in every case the net vapor-exchange between the ocean and the land-area of the given drainage-basin is, for steady conditions, precisely equal to the runoff.

**Inland drainage-basins**—The term "inland drainage-basin" will be used to describe a basin more or less remote from the ocean but which produces runoff to the ocean through a larger stream to which the given drainage-basin is tributary. An inland drainage-basin is not to be confused with an interior or closed drainage-basin which produces no runoff to the ocean. In most cases the determination of the quantities of vapor of any actual source of origin contributing to precipitation on an inland drainage-basin is complicated by the fact that the vapor-exchange may take place through a series of barterers, much as a Chinese fur-importer may buy furs gathered through various intermediaries, and although the voyageur is not paid in Chinese money, the exchange is nonetheless real and there is an export of money from China equal to the value of the furs, and an export of fur from Canada equal to the value of the money.

Consider next the case of a single leaf of a broad-leaved tree. Rain dripping from the leaf represents runoff, and this may pass through various stream-channels, finally reaching the ocean. In this case it is improbable that any of the vapor emitted from the leaf by transpiration and evaporation of intercepted rain is reprecipitated on the leaf—in other words, all the vapor originating on the leaf-area is exported and $L_c = L$. For these conditions equation (6) gives

$$ y = \Delta 0 + \Delta C - L = R $$

Again the resultant vapor-exchange between the leaf and its surroundings equals the runoff from the leaf. Equation (7), however, gives no clue as to the fractions of this vapor-exchange represented, respectively, by oceanic vapor $\Delta 0$ and vapor from adjacent land-areas $\Delta C$. This relation depends largely on the position of the tree, whether closely adjacent to or remote from the ocean. Since, however, the runoff into the ocean from the leaf can be considered by itself, it is still true that there is a net vapor-exchange between the ocean and land adjacent to the ocean precisely equal to the runoff from the leaf. If this exchange was, for example, vapor wholly of oceanic origin, still there might be other exchanges between the coast-line and the location of the tree such that none of the vapor finally precipitated on the leaf would be derived directly from evaporation from the ocean. Confusion has arisen in dealing with this problem through failure to take into account the difference between the resultant vapor-transfer, regardless of the origin of the vapor, and the quantity of vapor of a given kind which is transferred in a given case.

Milk River rises in Alberta Province, Canada, and discharges its runoff through Missouri and Mississippi rivers into the Gulf of Mexico, more than 2,000 miles away. There is a net vapor-exchange between this drainage-basin and the Gulf of Mexico or Atlantic Ocean equal to the runoff, but the vapor which finally arrives on Milk River Drainage-Basin may none of it come from the Gulf of Mexico. Athabasca River, rising near the same point in South Alberta, discharges into the Arctic Ocean through Mackenzie River. There is a net vapor-exchange between this drainage-basin and the Arctic Ocean equal to the runoff, but again little or none of the actual vapor may have originated in the Arctic Ocean 1,200 miles to the north. In these two cases the vapor actually replacing the runoff is undoubtedly derived both directly and indirectly from the same sources, chiefly from evaporation from the Pacific Ocean and from land surrounding the two drainage-basins. Abstraction of water from the Pacific Ocean is replaced by an exchange through ocean-currents.

In case of an inland drainage-basin with precipitation P and runoff y, there is a net vapor-exchange with the ocean equal to a fraction $(y/P)$ of the precipitation, although the drainage-basin may receive little or no vapor actually of oceanic origin. Conversely, the precipitation on a coastal...
drainage-area or an oceanic island may nearly all be derived from vapor evaporated directly from ocean-surfaces although the area or island is dependent on oceanic vapor for only a fraction $y/P$ of the precipitation.

Interior drainage-basins--Interior or closed basins constitute about 20 per cent of the land-surfaces of the Earth, some of the larger being those of Salt Lake, the Dead Sea (1,290 feet below sea-level), the Caspian Sea (84 feet below sea-level), Lakes Baikal, Balkash, and the Aral Sea in Asia. Most closed basins produce runoff from their higher land-areas but this is lost by evaporation from playas or undrained lakes and none of it reaches the ocean.

For a closed basin which is neither undergoing dessication nor the reverse, the net vapor-exchange $R$ is zero but, from equation (6)

$$ R = AO + AC - L_e = 0 $$

and such an area may actually receive vapor from contiguous lands or from the ocean and export some of the native vapor. If the quantities of vapor imported and exported do not balance, then the basin either undergoes dessication or is increasing in humidity. Dessication has occurred over long periods of years in Salt Lake Drainage-Basin, Utah, and Winnemucca Lake Drainage-Basin, Nevada, indicating that during these periods native vapor has been exported in excess of imported vapor from extraneous sources.

Seasonal cycle of storage and vapor-exchange--Rainfall and evaporation are readily determined separately for the warm or summer, and for the cold or winter, seasons. In most regions water is carried forward from the cold to the warm season in the form of stored soil-moisture, ground-water, storage in lakes, swamps and marshes, and in mountain regions as snow- and ice-fields. This water is disposed of in the warm season as runoff or water-losses. The difference $(P - y)$ between rainfall and runoff for either the warm or cold season, considered alone, does not therefore represent the actual water-losses but instead it may be designated the apparent water-losses, $L'$. In order to determine the actual water-losses it is necessary to correct the apparent water-losses for gain or loss of storage in the drainage-basin. Requisite data for making this correction are not always available. The correction varies from zero for impervious areas without lakes or ground-water, up to several inches depth on the drainage-basin for areas with deep soil, abundant ground-water, or with large lakes or snow-fields. From field-studies, COLE, MATTHEWS, and CHILCOTT [5] found, in the western Mississippi Valley, from one to three inches of water were abstracted from previously stored soil-moisture during the crop-season on lands planted to spring wheat. This was equivalent to 20 to 40 per cent of the total water used by the crop. Similar use of soil-moisture storage in the growing season occurs also in the corn-belt. Studies of the abstraction of water from ground-water storage as ground-water runoff during the warm season shows that this varies from zero in semi-arid and arid regions where there is no perennial water-table, up to two to four inches in eastern humid regions with moderately deep permeable soil and abundant rainfall and ground-water. While precise figures are unavailable, it is certain that the average depletion of storage in the warm season throughout the United States is of the order of at least two inches on the land-surface. There is a corresponding accretion of storage during the cold season. Storage of moisture as vapor in the atmosphere can rarely exceed two inches depth of water. The air, even that which has recently produced rain, contains moisture, so that the available storage of moisture in the atmosphere, on an average, is only a fraction of an inch in depth. The seasonal cycle of gain and loss of storage from land-areas is therefore necessarily accompanied by a corresponding seasonal loss and gain of storage in the oceans.

The water-losses from land-areas in the warm season average about 85 per cent of the precipitation. Under conditions like those existing in the upper Mississippi Valley, the actual water-losses may exceed the precipitation during the warm season, as part of the water-losses are derived from antecedent storage. Under these conditions there is transferred from the land to the ocean during the warm season not only the runoff but a certain amount of net vapor-exchange, which is precipitated on the ocean-surface, and these two items build up ocean-storage during the summer season.

During the cold season the water-losses from land-areas represent only about one-third of the precipitation. The remaining precipitation is made up by net vapor-exchange from the oceans and part of the precipitation goes into storage, which is carried forward to the warm season while the runoff in the cold season is usually greater than in the warm season, it is not sufficient to balance the net vapor-exchange between ocean and land, with the result that in the cold season there is depletion of ocean-storage. The relation between the principal hydrologic factors for the warm and cold seasons in the United States as a whole and on the peripheral areas is shown approximately by the figures in Table 2.
The figures given in Table 2 are illustrative rather than precise, as they have been derived from various sources by various methods. As to rainfall, its division between warm and cold seasons is definitely known. Runoff during the warm season ranges from a few per cent of the annual total in semi-arid regions where only ephemeral runoff occurs and there is no water table, up to about 40 per cent of the annual total in the upper Mississippi Valley, where approximately 80 per cent of the precipitation occurs during the warm season. In the upper Tennessee Valley and Blue Ridge Mountain regions, with rainfall from 60 to 80 inches per year, quite equally divided between warm and cold seasons, about 30 per cent of the runoff occurs during the warm season, while in case of western mountain streams having their sources above the snow-line, more than 50 per cent of the runoff occurs during the warm season. Table 2 indicates an increase of storage on the land-area in the cold season equivalent to two inches depth and a corresponding depletion of land-storage in the warm season. About three-fourths of the actual water-losses occur in the warm season and only about one-third the total runoff.

The seasonal cycle of transfer of storage between the land and the oceans does not necessarily affect the annual water-balance or the total amount of precipitation received on the land. If this exchange of storage in liquid form did not occur there would still be net vapor-exchange between the oceans and land but it would be more nearly continuous and a larger proportion of the annual precipitation would occur in summer and a smaller proportion in winter. Indirectly this would affect the water-losses, which occur mostly in summer and increase with increasing precipitation up to a limit determined by the evaporation-rate.

A similar cycle of exchange of storage between lands and oceans occurs in connection with each succession of dry and wet periods. If the net vapor-exchange between a drainage-basin and its surroundings took place at a continuous and uniform rate, then, because of the small atmospheric storage, all native vapor must soon be reprecipitated and the total rainfall would be equal to native vapor plus runoff. Actually vapor is exported during dry periods and imported during rainy periods and this results in the concentration of the precipitation on the land in a smaller number of heavier rains. This has important economic effects. Very light rains in general produce neither direct surface-runoff nor ground-water. Neither do they penetrate the soil sufficiently to support other than shallow-rooted vegetation. The economic value of both streams and lands depends to a large extent on the occurrence of "soaking" rains, and the exchange of storage between the lands and oceans, in conjunction with vapor-exchange, favors the occurrence of such rains.

Evaporation, water-losses, and vapor-transfer--The storage-equation gives a basis for determining the net vapor-exchange under all conditions but it does not provide a quantitative basis for determining the relative quantities of vapor of different origins precipitated on a given area. Other lines of evidence are available which throw light on the composition of precipitation in terms of fractions of vapor derived from different sources. These include:

(1) The sources, characteristics, and frequency of occurrence of air-masses passing over the given area
(2) Considerations of the relative occurrence of evaporation and water-losses in wet and dry periods
(3) Chemical composition of rain, particularly its chlorine-content
(4) The equations of rain-profiles

HOLZMAN [3] and HOLZMAN and THORNTHWAlTe [4] have considered the relation of air-masses to precipitation and have pointed out that evaporation from water-surfaces mostly occurs during dry periods and that much of the vapor originating over inland water-bodies in fair weather is carried aloft and thence passes out over the ocean. With the exception of the Great Lakes,
Direct evaporation from leaves and stems of plants during rain; interception---are involved: deciduous leaves on and below evaporation of lakes, reservoirs, and streams in the United States occupy only a minute fraction of the land-area. The extent to which precipitation on a given land-area is derived from native and exotic land-vapor rather than from true ocean-vapor is determined chiefly by water-losses from land-areas and not by evaporation from open water-surfaces. Figure 1 shows that evaporation from water-surfaces decreases quite rapidly proceeding from the Great Basin eastward to the Atlantic coast. Water-losses, on the other hand, gradually increase proceeding from the Great Basin to the Atlantic Ocean.

The relation between water-losses in rainy and fair weather is also to a considerable degree the converse of the relation of evaporation from water-surfaces under the two conditions. Water-losses—all evaporative in nature—are of three kinds: (1) Direct interception by vegetation; (2) transpiration; (3) evaporation from the soil.

Interception occurs only during and immediately following rain and involves two items: (1) Direct evaporation from leaves and stems of plants during rain; (2) evaporation of interception-storage immediately following rain. Everyone who has stood under a tree to escape a passing shower knows that with good vegetal cover interception may dispose of 100 per cent of a light shower. Various series of experiments show that the percentage of rain disposed of by interception varies inversely as the rain-intensity and increases with the density of vegetal cover. In general, for areas with mixed vegetation, some forest and most of the remaining area cropped land, interception takes a toll of ten to 20 per cent of the precipitation in summer and about an equal fraction in winter, in spite of the absence of growing crops and leaves on deciduous trees. The approximate equality of the interception-percentage in summer and winter results chiefly from the lower rain-intensities prevailing in the cold season. Interception represents generally about 30 per cent of the total water-losses and this 30 per cent occurs only during or immediately following rain.

The question naturally arises how so large a percentage of rain can be disposed of by interception in view of the low rate of evaporation during rain. Evaporation nearly always continues during rain and the humidity is rarely 100 per cent during rain. The evaporation-rate from Class-A evaporation-pan during the summer season. The water-loss from the former, measured in inches depth on the exposed surface, was 3.5 times that from the evaporation-pan. This is believed to be fairly representative of the evaporation-rate from the leaves and stems of plants.

(1) The evaporation-rate from small surfaces, such as individual leaves and twigs, is much higher, other things equal, than that from an evaporation-pan or a broad water-surface. WILSON [8] made a ten-year comparison between evaporation from a black porous-cup atmometer and a Class-A evaporation-pan during the summer season. The water-loss from the former, measured in inches depth on the exposed surface, was 3.5 times that from the evaporation-pan. This is believed to be fairly representative of the evaporation-rate from the leaves and stems of plants.

(2) The total leaf- and twig-surfaces with good vegetal cover is much greater—often five to ten times greater—than the projected or ground-area. The combination of these factors permits evaporation from plant-surfaces to take place during rain at a rate, measured in terms of depth of water on the ground-surface, of the same order of magnitude as in fair weather.

(3) The third factor is interception-storage, which amounts to as much as 0.05-inch depth with good vegetal cover, and with 100 showers during the six-month warm season this may dispose of as much as five inches of rain.

The most important element of water-loss is transpiration by vegetation. For cropped or forest areas transpiration disposes of an amount of water in the form of vapor of the same order of magnitude as the total runoff. Transpiration under ordinary fair-weather conditions is quite closely correlated with the same physical factors which govern evaporation but under extreme conditions, for example, either during rain or in severe drought, this is not true. MAXIMOV [9], from a careful review of the extensive literature of the subject, concluded that while there is a fairly close correlation between transpiration and humidity within a certain range of relative humidity, yet "with an increase of relative humidity the rate of transpiration increases; with a decrease of relative humidity the rate diminishes." F. DARWIN [10] concluded that transpiration does not stop at 100 per cent humidity but may continue with supersaturation up to 105 to 110 per cent.

It appears certain that as long as there is soil-moisture available contiguous to plant-roots in an amount ranging from that at the wilting-point to that at capillary capacity, the rate of intake of water is nearly independent of the soil-moisture. Moisture may be present in adequate quantities in adjacent soil after it has become exhausted to the wilting-point closely adjacent to plant-roots. Thereafter the roots can absorb moisture only as fast as it is transmitted by the slow process of capillary flow from more and more remote regions of the soil, and under these condi-
tions, which occur in dry periods, the transpiration-rate is materially diminished. Apparently the rate of transpiration-loss per unit of time, other things equal, is of the same order of magnitude in rainy and fair weather, except in extremely dry periods, when it is reduced. Evaporation from a soil-surface fully wetted takes place sensibly at the same rate as from a water-surface, other things equal. During fair weather, following rain, moisture close to the soil-surface becomes rapidly exhausted, so that the water-losses by direct evaporation from the soil will generally be much greater than during rain for a time after rain ends and thereafter will be less than during rain.

The preceding discussion relates chiefly to rates of water-loss per unit of time. The duration of rain is in general only a small percentage of the total time but the duration of conditions favoring rain, either on a given area or adjacent areas, is of the same order of magnitude as the duration of low-pressure areas on a given drainage-basin, or roughly one-fourth to one-third of the total time. All things considered, the rate of water-loss during conditions favoring rain is apparently not greatly different from and may sometimes exceed the average rate but the duration of conditions favoring rain is less than the duration of fair weather, so that the greater portion of the total water-losses occurs in fair weather under conditions such that vapor originating as water-losses is likely to be transported outside a given drainage-basin and either reprecipitated elsewhere or carried to the ocean.

The discussion thus far relates wholly to conditions during the warm or growing season. In the cold season, if there is snow-cover or, as is usually the case, the soil-surface is nearly saturated, direct evaporation from the soil occurs continuously at a rate governed by the evaporation-rate. Interception occurs much as in summer but there is no transpiration. The water-loss is in general considerably greater during and immediately following rain than in fair weather.

The chlorine-content of rain and runoff—Chlorine in runoff may occur as the result of carrying into solution from rock or soil of compounds containing chlorine or as the result of the precipitation of rain derived from ocean-vapor and containing salt-particles as condensation-nuclei. Where several types of nuclei are available, condensation takes place most rapidly on the larger particles and those having certain physical and chemical properties. Salt-particles are among the larger nuclei and are highly hygroscopic and, where available, they form the principal condensation-nuclei of cloud and rain-droplets. Along the coast salt-nuclei are derived from ocean-spray and from the breaking of waves on the shore-land are generally plentiful beyond condensation-requirements, and it may be assumed that nearly all vapor-particles derived from vapor passing inland from the oceans contain salt-nuclei.

The presence of excessive chlorine in potable waters is presumptive evidence of dangerous pollution. Extensive determinations of chlorine in runoff-waters have been made and, in addition to their use in interpretation of the quality of water, these data serve other purposes, as in the determination of the age of the Earth from the amount of sodium carried into the oceans by streams, and as a basis of determining sources of moisture in the study of air-masses and the interpretation of rainfall-maps.

In connection with the last-named problem the following notation is used, quantities of rainfall and runoff being expressed in inches depth and chlorine-content in parts by weight per million.

\[ P = \text{total precipitation} \]
\[ P_0 = \text{precipitation derived from ocean-vapor} \]
\[ P_g = \text{precipitation derived from vapor of land-origin} \]
\[ y = \text{total runoff} \]
\[ y_0 = \text{runoff derived from ocean-vapor} \]
\[ y_g = \text{runoff derived from land-vapor} \]
\[ C_y = \text{chlorine-content of the runoff} \]
\[ C_R = \text{chlorine-content of rain of oceanic origin} \]

Primes are added to the corresponding quantities to relate them to an inland location where the fractions of rain derived from ocean-vapor and land-vapor, respectively, are to be determined. In connection with land-areas the term "ocean-vapor" is used in the sense of vapor passing inland from the ocean. It may or may not all have originated as evaporation from the ocean; some of it may have been carried to the ocean from the land in air-masses, mixed with ocean-vapor and later returned to the land.

Along the coast the solutional chlorine in runoff is usually small relative to the chlorine derived from rain and may for the present be neglected. Then for coastal conditions
At the interior location \( x \) it may be assumed that all the chlorine \( C_y \) in runoff is derived from that in the fraction \( P_0' \) of the rainfall at \( x \). This assumption will only be true if the solutional chlorine is first deducted or is negligible in amount. That it will then be true is evident from the fact that part of the rain of oceanic origin and containing chlorine goes directly into the runoff, while the remainder is evaporated and the chlorine remains behind and sooner or later appears in the runoff. Under these conditions

\[
C_T P_0' = C_y y'
\]

and

\[
(P_0'/P') = (C_y/C_T) (y'/P')
\]

Substituting the value of \( C_T \) from (9) in (10) and (11) gives

\[
(P_0'/P') = C'_y/C_T \ (P/y) (y'/P')
\]

and

\[
(P_0'/P') = [1 - (C_y/C_T) (P/y) (y'/P')]
\]

Equations (12) and (13) show, respectively, the fractions of precipitation at \( x \) derived from vapor originating over the ocean and land. This analysis takes into account the effect of differences of rainfall and water-losses at the coast and at the inland location, respectively, on the concentration of chlorine and runoff. If a map of chlorine-content of waters at the coast and at the location \( x \), together with data of rainfall and runoff, are known for the two locations, then the fractions of rain derived from ocean- and land-vapor, respectively, can be determined.

On the Atlantic Coast, in the vicinity of New York City, \( P = 45 \) inches, \( y = 22.5 \) inches, and \( C_y = 6.0 \). In the lower Genesee River Valley, in western New York, about 300 miles from New York City, \( P' = 30 \) inches, \( y = 12 \) inches, and \( C_y' = 0.3 \). From equation (4), \( (P_0'/P') = 0.04 \), or about four per cent of the rain is derived from oceanic vapor and 96 per cent from vapor originating over land. Even this result is somewhat too large, as a part, apparently about 0.1 part per million (ppm) of the chlorine-content of runoff in the Genesee Valley, 0.3 ppm, is solutional chlorine. In this case if the ratio of runoff to rainfall had been the same in the two cases, then the fraction of rain derived from ocean-vapor would be five per cent.

Professor DANIEL D. JACKSON [6] published a map showing the isochlors or normal quantity of chlorine-content in unpolluted waters, in ppm, in New York and the New England States. In this region there are few local sources of chlorine in unpolluted runoff and the quantity of solutional chlorine is small—apparently not exceeding 0.2 ppm. Figure 2 shows a chlorine-profile derived from Jackson's map, along the Hudson and Champlain valleys, together with the rain-profile.
Subject to the effect of local variations of rainfall and runoff, the chlorine-content of surface-runoff is quite closely represented by the equation given in Figure 2. It will be noted that at a distance exceeding 300 miles from the coast-line, only solutional chlorine is contained in the runoff. This indicates that in this region rain derived from oceanic vapor is limited to a coastal belt about 300 miles in width. Within this belt the fraction of rain derived from oceanic vapor decreases in accordance with an inverse exponential law, as would be expected from the fact that processes of exhaustion are involved, the amount of rain derived from oceanic vapor being proportional to the amount of oceanic vapor remaining in the air-currents producing rain. The width of the coastal belt in which rain is derived from oceanic vapor diminishes in case there is a mountain mass adjacent to the coast-line. Such mountain masses exist throughout nearly the whole length of the Pacific coast-lines of North America. The oceanic vapor is precipitated more rapidly as a result of orographic effects than would be the case if the land rose gradually and uniformly proceeding away from the coast-line, as happens in the lower Mississippi Valley.

Results similar to those obtained for New York and New England are certainly applicable to the Pacific coastal mountain regions as regards inland distribution of rain derived from oceanic vapor. Precise calculations cannot be made for the reason that there are local sources of solutional chlorine, particularly in case of storm-runoff from playas and alkaline soils on or into which large quantities of salts have been deposited by evaporation, thus making it impossible to determine the normal chlorine-content of unpolluted waters from the data presently available. In the case of the Mississippi Valley the slope is gradual proceeding inland. Low-pressure areas crossing central and northern United States from the Pacific toward the Atlantic carry with them oceanic vapor containing chlorine, some of which still remains in the dryer air descending onto the plains east of the Rocky Mountains. Air-currents from the Gulf of Mexico containing chlorine tend to flow into low-pressure areas crossing the United States, the amount decreasing with the distance inland. Some chlorine of oceanic origin reaches the upper Mississippi and Missouri River valleys from one or both of these sources.

Records of chlorine (as chlorides) in rain and snow at Mt. Vernon, Iowa, have been given as in Table 3 by HENDRICKS [7]. The weighted average amount of chlorine in 28.37 inches of precipitation in 42 storms analyzed during the seven-month period, November, 1926, to May, 1927, was 3.95 ppm. Seventy per cent of the chlorine was contained in two snowstorms in January, 1927. Omitting these the weighted average chlorine in 40 storms was 1.17 ppm and in one-half of these rains no chlorine occurred. Taking the normal coastal chlorine in coastal rain as six ppm it appears that in the central Mississippi Valley about one-fifth of the rain is normally precipitated from ocean-vapor, chiefly in winter, but exceptional storms may occur in which as much as two-thirds of the precipitation is from vapor of oceanic origin. In the region referred to this presents a large proportion of the winter precipitation. In one-half of the rains there was no chlorine indicating that the vapor producing the rain was wholly of non-oceanic origin. If chlorine occurred it was likely to be found to the extent of several parts per million.

Table 3--Chlorides in precipitation, Mt. Vernon, Iowa

<table>
<thead>
<tr>
<th>No.</th>
<th>Amount precipitation</th>
<th>Chlorine</th>
<th>No.</th>
<th>Amount precipitation</th>
<th>Chlorine</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>12.0</td>
<td>0.71</td>
<td>21</td>
<td>6.0</td>
<td>17.04</td>
</tr>
<tr>
<td>23</td>
<td>6.0</td>
<td>120.7</td>
<td>24</td>
<td>3.0</td>
<td>77.38</td>
</tr>
</tbody>
</table>

Rain-profiles--Because of the complexity of the conditions it is difficult to arrive at reliable conclusions as to the composition of rain with respect to moisture-sources from considerations of storm-periods and water-losses. Better results can be obtained from a study of the chlorine-content of rain where such data are available. If their forms are not too much disturbed by orographic conditions it will be found that rain-profiles proceeding inland from the coast can often be quite accurately represented by an equation of the form

\[ P = ae^{-k_1x} + b (1 - e^{-k_2x}) \]

where \( P \) is the precipitation-depth, \( x \) the distance inland in miles, and \( k_1, k_2, a, \) and \( b \) are constants for a given profile. Figure 3 shows such a profile for the Hudson Valley. North of the mountain barrier at Storm King the profile follows the equation given by Figure 3 except for some topographic
eq 1

\[
P = 52 \left[ \epsilon^{-0.92x} + \frac{2}{3} (1 - \epsilon^{-0.92x}) \right]
\]

where \( x \) = distance inland from "a" in 40-mile units.

effects at the divide between the Hudson and Champlain valleys. The first term in the equation apparently represents precipitation from vapor derived from the ocean. The value of this term approaches zero as \( x \) increases. The second term in the equation apparently represents precipitation from vapor of inland origin and this term increases with \( x \), approaching a limit \( b \). In case of other rain-profiles the second or reprecipitation-term of the equation is often sensibly constant.

Determination of runoff from vapor-exchange--The quantity of runoff is almost wholly unknown for nearly all oceanic islands on the Earth and for a large portion of the areas of the continents. To determine the average runoff from an island like Madagascar, having over 20 large rivers entering the ocean and 2,000 miles of coast-line, with mostly direct drainage, would require years of observation and at many gaging-stations. It appears possible to determine approximately the runoff from an oceanic island from the simple fact that the average runoff is equal to the net vapor-exchange between the surrounding ocean and the island. Navigation-maps are available giving surface wind-directions and wind-velocities, temperatures, relative humidities, and other data from which the vapor-content of the air near the surface can be determined. While the method has apparently never been used, it appears possible, using known relations between the average vapor-content of a vertical air-column at different heights, and the vapor-content at the ground-surface, together with relations of average velocities and directions of wind at different heights to those at the surface, to determine the average inflow to and outflow of vapor to the atmosphere over a given island, month by month or for average conditions, and from these data to determine the net vapor-exchange and consequently the runoff. The accuracy of the result would depend on the accuracy with which known data for surface-conditions can be translated into average data for the air-prism up to the height--usually a few thousand feet at most--above which the vapor-content of the air becomes negligible. The computations involved in this arm-chair method of determining runoff would no doubt be laborious if carried out in detail but the method appears capable of giving results of the right order without the long delay which is unavoidable in determining average runoff by direct gagings.

Summary

(1) The storage-equation provides a basis for determining the net vapor-exchange between lands and oceans but not for determining the relative amounts of precipitation derived from moisture from different sources. For any land-area, large or small, coastal or inland, producing
runoff to the ocean, the net vapor-exchange between the area and the ocean is equal to the runoff from the area. This is true for the peripheral land-surfaces of the Earth as a whole. For the United States the runoff from the peripheral land-areas is roughly 11 inches or about 33 per cent of the precipitation, and the net vapor-exchange is equivalent to this amount.

(2) It is also true that for the world as a whole the total precipitation on the lands and oceans is, for steady conditions, equal to the water-losses from the lands plus the evaporation from the oceans. Water-losses from the lands in the United States are about 67 per cent of the rainfall and a similar figure apparently applies to the Earth as a whole. Consequently the evaporation from the oceans must exceed the precipitation on the oceans by an amount equal to the runoff from the peripheral areas of the Earth, expressed in inches depth on ocean-surfaces.

(3) Vapor-exchange may take place through intermediate steps or barter, and little or no vapor of truly oceanic origin may ever reach small tributary-areas at the headwaters of large rivers.

(4) Adjacent to the coast-line the actual precipitation of rain from vapor imported from the ocean may exceed the net vapor-exchange between the land and ocean, the hydrologic balance being maintained by transfer of native vapor to the ocean and which is precipitated thereon.

(5) There is a seasonal cycle of gain and loss of storage on a given drainage-basin and a corresponding cycle of exchange of storage between the drainage-basin and the ocean. In the warm season the water-content of the drainage-basin decreases and that of the ocean increases. The converse occurs in the cold season. This has the effect of increasing cold-season precipitation and decreasing warm-season precipitation on land without changing the total annual precipitation.

(6) A similar effect occurs during wet and dry periods and tends to concentrate rain on the land in a smaller number of heavier showers and to aid in producing beneficial soaking rains.

(7) The rates of water-losses from land-areas in wet and dry periods in the warm season is the converse of the relative rates of occurrence of evaporation from broad water-surfaces under the two conditions.

(8) Light is thrown on the composition of rain in terms of vapor-sources from a consideration of the chlorine-content of rain and from the equations of rain-profiles proceeding inland from the coast.

(9) It appears to be possible to make an approximate determination of the runoff from a given area, such as an oceanic island, from a study of net vapor-transfer between the atmosphere above the area and the surrounding region.

References


Voorheesville, New York