DEPARTMENT OF WATER AFFAIRS
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PRECIPITATION

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PRECIPITATION

1. FORMATION

Four conditions must be met to produce rainfall:

1.1 Moisture supply

Sufficient water vapour must present - which implies that it must be constantly replenished. The precipitable water present at any moment in the air at any place depends on latitude, altitude, continentality, the general circulation of the atmosphere, and the short term local synoptic situation. As the saturation vapour pressure of the air is temperature-dependent, the precipitable water tends to be greatest in summer - but rarely much exceeds 25 mm. Thus a large net horizontal influx (known as convergence or advection) of moist air is a prerequisite for heavy and prolonged falls of rain.

1.2 Cooling

The quantity of water vapour that air can hold depends on its temperature.
If an unsaturated air mass is cooled sufficiently, its capacity to hold water vapour will decrease until it reaches a temperature - the dewpoint - at which it is saturated, whereupon excess water vapour can condense to form liquid droplets.

Air can be cooled by radiation, by contact with a colder surface, or by horizontal flow towards an area of lower pressure, but at best these processes can produce only fog or light drizzle. The only known mechanism whereby the temperature of large air masses can be lowered sufficiently to produce rain or other forms of precipitation in quantity is adiabatic cooling (also known as dynamic cooling) associated with the reduction in pressure when a pocket (generally known as a parcel) of air ascends. The processes whereby air masses can be so lifted forms the basis for typing rainfall (see 2)

1.3 Condensation

Lowering of the temperature of the air to below the dewpoint is in itself no guarantee that condensation will occur, for in the laboratory the temperature of air cleaned of all foreign particles can be cooled to well below the dewpoint, and thus far beyond 100% relative humidity, without condensation, the air remaining in a state of super-saturation. Condensation nuclei with an affinity for water must be present for condensation to occur. These microscopic particles are thought to be mainly of terrestrial origin - salt particles from seaspray, dust, combustion products and other atmospheric pollutants - although some may derive from meteorites, - and generally are present in sufficient numbers for condensation and cloud formation to occur when the temperature of the air falls below the dewpoint.

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1.4 Drop formation

Cloud droplets are so minute - only about 200 - 700 microns - that they remain in suspension, supported by the buoyancy of the air and vertical currents. Various theories have been advanced to explain how the droplets form rain or hail. The two dominant processes are thought to be the following:

1.4.1 In so-called "cold" clouds rising above the freezing altitude the water droplets can persist in a supercooled state, especially between 0°C and - 15°C, unless sufficient freezing nuclei are present around which ice crystals can form. In a 3-phase cloud in which water vapour, droplets and ice crystals co-exist, the lower saturation vapour pressure over ice compared with that over water at the same temperature causes the droplets to evaporate and the vapour so formed to condense on the ice-crystals which thus grow at the expense of the cloud droplets until they attain a mass that can overcome the buoyancy of air. They then fall, melt and grow further by collision.

1.4.2 Precipitation from "warm" clouds which lie wholly below the freezing altitude is thought to result mainly from the different rate of motion of droplets of different size, the larger drops overhauling and coalescing with the smaller ones.

2. COOLING MECHANISMS

The classification of rainfall types is based on the way in which air masses are lifted and cooled. Often these processes occur in combination.

2.1 Orographic lifting

This can occur when a mountain range or escarpment lying athwart the prevailing wind forces the air up the slope, whereupon it expands and cools due to the reduction in pressure with increase in elevation. The vertical velocity is a function of the angle of slope and of the horizontal wind velocity, and diminishes with height. Other conditions being equal, higher amounts and intensities of rain results from orographic than from frontal lifting (see 2.3) as mountain slopes are generally steeper than the angle of inclination of fronts, and fixed, so that cooling of the air tends to be more rapid and prolonged. Often the main rôle of orographic lifting is to trigger off latent instability originating in convective or cyclonic activity (see 2.4 and 2.3).

The rain is generally heaviest at the level of the cloud base, which may be below the summit. In contrast to the moist windward slope, there is often a pronounced dry "rain shadow" area to the lee, not only because the air has already shed most of its precipitable moisture but because

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in descending it is subject to an increase in pressure and thus to warming and a decrease in relative humidity.

Near the coast, orographic uplift can occur in the absence of a barrier if moist air moving inland is slowed down by frictional drag on the surface, and piles up.

2.2 Convergence

This term covers all processes that cause air to accumulate in a certain area, whether it be by divergence in the upper air, horizontal movement of air along a pressure gradient, funnelling of air down valleys, or momentum acquired in other latitudes. The congestion forces some of the air to rise, whereupon it cools as the result of the reduction in pressure, and expands. Convergence often operates jointly with other processes such as orographic and frontal lifting.

2.3 Frontogenesis

A front is a zone of discontinuity between converging dissimilar air masses which do not easily mix due to the difference in their density. Pronounced gradients in temperature, pressure, wind and water content can therefore occur across a front. The greater the contrast in these properties between adjacent air masses, the steeper the slope of the front and the greater the convergence, leading as a rule to heavier precipitation - although the latter is also influenced by the stability and water content of the air forced aloft. Not only the source but also the course of air massas converging along a front has a bearing on the subsequent weather, for cold air from high latitudes becomes unstable on reaching warmer areas, whereas the stability of warm equatorial air increases if it moves to colder regions.

A cyclone (also known as a dpression or low pressure system) is in effect a moving wave into which new air continuously flows to replace that already discharged during the period of some days in which the cyclone develops, intensifies and dies. In the forward sector of the extratropical (mid-latitudinal) cyclone, warm air overrides colder air to form a warm front with a slope of only about 1 : 100 to 1 : 400, which means that the highest cirrus clouds can be seen more than 1000 km ahead of the surface front, to be succeeded by altostratus and nimbostratus as the cloud deck descends with the advance of the surface front. Precipitation will tend to be light at first, then moderate, and fairly prolonged. Should the warm air aloft be unstable, uplift may trigger latent instability and lead to the development of some cumuliform clouds yielding heavier localised falls. The cold front which develops in the rear sector of the depression where a wedge of cold air forces the warm air forward and aloft, has a steeper slope of about 1 : 25 to 1 : 100. The rapid ascent and cooling of the warm air, especially if it is moist and unstable, generally causes deep cumuliform clouds to build up and yield pelting rain of fairly short duration along a comparatively narrow band, often accompanied by high wind. Unlike the warm front,

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the advent of a cold front is not heralded by advance cloud as the front slopes away from its direction of travel.

Whereas a fast moving depression tends to result in moderat rainfall over a large area, a stationary surface front accompanied by continuous upper air flow tends to give heavy rain over a small area.

Midlatitudinal depressions vary in size from minor waves of a few hundred square kilometres with a life of only a few hours, to gigantic systems extending over tens of thousands of square kilometres and lasting many days.

2.4 Turbulence

The passage of air over surface obstructions can create eddies whose upward motion can carry moist air aloft to the condensation level and cause shallow cloud to form.

Large scale turbulence results from atmosphere instability. The air is said to be stable if, when displaced, it is subjected to forces that tend to restore it to its original position, and unstable is the forces acting on the displaced air tend to move it still further from its original position Temperature differences or lapse rates serve as a measure of the stability of the air.

The air is largely transparent to incoming short wave solar radiation, and is primarily heated by long wave back radiation of heat from the earth's surface. The vertical temperature gradient - that is, the fall in temperature with increasing distance from the earth's surface - is about 0,6°C per 100 m.

When a pocket of unsaturated air is forced to rise, it expands, and the expenditure of energy on this expansion causes the temperature of the rising air to fall at the socalled dry adiabatic lapse rate (DALR) which is about 1°C per 100m. In the case of a rising parcel of saturated air, the cooling due to expansion is partially offset by the gain in latent heat of condensation so that the temperature of the rising air falls at the saturated adiabatic lapse rate (SALR) which averages about 0,55°C per 100 mm but varies inversely with temperature.

Thus a rising parcel of unsaturated air cools at the DALR until its temperature falls to the dewpoint, and at that altitude condensation may ensue and form a cloud whose base will mark the condensation level. The rising air will now continue to cool, but at the SALR, until its temperature is the same as that of the surrounding air, whereupon its ascent will cease.

Unsaturated air is said to be stable if its temperature lapse rate is less than the DALR, and unstable if its lapse rate is greater than the DALR. Similarly saturated air is stable if its lapse rate is less than the SALR, but if it is greater it is unstable.

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The following can cause instability and thus turbulence in an initially stable air mass:

2.4.1 Basal heating

can result from strong local heating of the soil surface on a hot day, giving rise to powerful vertical convection currents, and to short duration, high intensity rainfall, or from the horizontal influx of cool air (generally from higher latitudes) over a warmer area.

2.4.2 Upper cooling

occurs when the upper part of an air mass is drier than the lower layers, and radiates heat more quickly. This can cause a cloud to develop into a thunderstrom at night.

2.4.3 Conditional instability

when the lapse rate is between the DALR and the SALR, can turn to instability if triggered by orographic or frontal lifting.

2.4.4 Lifting

can trigger latent instability in an air mass which is moist at its base and dry aloft.

3. POINT INTENSITY MEASUREMENTS

The design as well as the operation and/or efficiency of a hydraulic structure requires knowledge of

- the volume of rain falling on the contributory catchment at the frequency constituting one of the design criteria,
- the spatial distribution of that rain, and
- variations in the time distribution of such rain.

All such information on depth - area - duration - frequency relationships has to be derived from point intensity measurements yielded by the network of recording raingauges. In South Africa the network administered by the Weather Bureau is still rather sparse, numbering only about 100+ gauges, few of which are located in the hydrologically important high - rainfall mountainous areas.

The smaller the catchment, the more adequately does point rainfall represent the mean rainfall over the catchment, the more tenable is the assumption that the rainfall is evenly distributed over the catchment in both space and time, and the less does catchment response vary for a given rainfall.

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3.1 Frequency-distribution

For design purposes it is necessary to analyse point rainfall data to determine the return period (Tr), also known as the recurrence interval or incidence frequency, of a given event X (such as 24-hour rainfall total), this being the average number of years between events equal to or greater than X.

Analogous to this is the N-year event, this being the event which can be expected to occur once every N-years.

It should be noted that both the return period and the N-year event refer merely to the expected average frequency of occurrence, and that there is no assurance that an event of given magnitude will recur regularly at stated intervals of N-years.

3.2 Maximum rainfall

A rainfall station record covering, say 60 years will yield reasonably accurate estimates for small values of X and N, but is too short, and thus too small a statistical sample, to represent random rare events adequately. In these cases recourse must be hand to various statistical theories of extreme values, a double exponential distribution (known as the Gumbel distribution) being often used. The maximum precipitation likely to occur for a given duration and return period is an important design criterion, hence the importance attaching to estimates of rare events. (that is, extreme values).

It is customary to summarise rainfall intensity data in the form of a family of curves. showing, for a given return period, the maximum mean rainfall intensity for each of a number of durations.

Data on extreme rainfall are contained in two publications issued by the Weather Bureau, viz.: "Maximum 24-hour rainfall" (1956) and "Extreme values of rainfall, temperature and wind for selected return periods" (1974), the latter containing estimates of the expected maximum point rainfall for durations of 15, 30, 45 and 60 minutes and 24 hours, and for return periods of 25, 50 and 100 years. The Hydrological Research Unit (University of the Witwatersrand) has produced a co-axial diagram from which the point rainfall likely to be equalled or exceeded in return periods up to 100 years can be estimated for any place in South Africa, for durations up to 24 hours. The Unit has also produced a diagram comprising a series of envelopes delimiting the highest point precipitations of various durations yet recorded in various parts of South Africa, together with comparative world extremes.

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It is important to note that a given input in the form of rainfall of a given return period, will not necessarily produce an output, in the form of run-off, of the same return period as the input, for the probability of occurrence of the output is the joint (product) probability of occurrence of the input and of the state (notably the storage capability) of the catchment at the time of the input.

4. AREAL DISTRIBUTION

The catch in a raingauge represents an infinitesimal sample of the total volume of rain falling on an extensive catchment, and as its distribution is irregular and the raingauge network sparse, precautions must be exercised in estimating the average depth of rain over a catchment from point rainfall.

Rainfall decreases away from a storm centre.

4.1 Formulae

Formulae for estimating the average rainfall ($\overline{R}$) over a given area (A), for a given duration and recurrence interval, from point rainfall at the focus (R_o) are generally of the form

$$\overline{R} = R_o e^{-kA^n}$$

where k and n are constants for a given storm, or generic values for storms of given duration.

4.2 Depth-area curves

The reduction in average depth of rainfall with increasing area can conveniently be depicted by means of depth-area curves.

In cases where the focus is a storm centre, the depth-area curves are steeper than those derived from a fixed network of raingauges to which storm centres are randomly related.

In general, the difference between the rainfall over an area, relative to point rainfall at storm centre
- increases with an increase in storm area
- decreases with an increase in storm duration
- decreases as the total depth of rainfall increases
- is greater for orographic and convectional rain than for cyclonic and other frontal rain.

The decrease in average precipitation with increasing area is less if derived from a fixed raingauge network than from a storm centre.

Generally the reduction factor used to convert point rainfall to areal rainfall varies mainly, with the size of the area and with storm duration, and only to a slight degree with the return period of the storm.

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The Hydrological Research Unit (University of the Witwatersrand) has curves portraying the depth-area-duration relationship for areas up to 30 000 km^2.

4.3 Estimation of average rainfall from rainguage networks.

Methods include

- the arithmetic mean of point values,
- aerial weighting of point values by means of Thiessen polygons,
- triangulation,
- linear and subjective interpotation of isohyets,
- other methods of weighting.

5. TIME DISTRIBUTION

5.1 Chronological sequence

Histograms or graphs are used to show the time sequence of point rainfall. Moving averages are sometimes used to smooth out fluctuations and extremes so as to reveal trends, but should be used with cautinn as the inclusion of extreme values in successive averages may induce spurious trends.

5.2 Temporal distribution

The time distribution of rainfall can be depicted as a mass curve of cumulative rainfall against storm duration. This can also be used to derive a hyetograph on which rainfall intensity in mm/hour is plotte against the time spells during which the intensity occurred.

The data can also be presented in dimensionless form as a double mass plot of percentage of storm rainfall against percentage of storm duration. Such storm profiles facilitate comparison between storms of varying durations and precipitation depth, and have been used in the U.S.A. to demonstrate that thunderstorms of 25-50 mm/hour intensity show a marked peak at the beginning of the storm, this becoming less pronounced as the 1 hour intensity increases. Storms of 6-24 hour duration have very similar profiles, all exhibiting a tendency for the most intense rain to occur during the third quartile. Profiles for intermediate durations of up to 24 hours, prepared by the Hydrological Research Unit (University of the Witwatersrand) are not dissimilar. In an analysis carried out in Britain, storm profiles were found to vary mainly with the individual character of storms rather than consistently with storm size or duration, or return period.

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6. DEPTH-AREA-DURATION-FREQUENCY RELATIONS

The Hydrological Research Unit (Dept. of the Witwatersrand) has produced for each of 29 regions and sub-regions into which South Africa has been divided, a co-axial diagram interrelating depth, duration, area and return period of extensive storms. This enables the designer to synthesize a storm for any part of South Africa, of any extent, duration and return period of more than 5 years.

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