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RAIN STORMS AND RIVER FLOODS IN ORISSA

By P. C. MAHALANOBIS.

INTRODUCTION.

The deltaic area in the province of Orissa has been subject to periodic floods for a long time. Since 1855 many special enquiries have been made with a view to prevent, or diminish these floods, and various recommendations have been made from time to time. In November 1927, an official committee of engineers was appointed by the Government of Bihar and Orissa[1] to prepare "an authoritative review of the flood problem as a whole." At the suggestion of the Orissa Flood Committee the Government of Bihar and Orissa asked me to conduct a special enquiry into the correlation of rainfall and floods in Orissa, and sent me a large mass of original records and papers for this purpose. I had also the opportunity of having several personal discussions in this connexion with Mr. E. L. Glass, Chief Engineer, Irrigation, Bihar and Orissa. In June, 1932 I submitted the bulk of my report to the Government of Bihar and Orissa, and some of my recommendations were accepted by the Government. A portion of the report was sent to the press but owing to various delays, partly due to my other preoccupations and partly due to the separation of the province of Orissa, it has not yet been published. On the 28th October, 1937, the Hon'ble Mr. Nityananda Kanungo, Minister in charge of Irrigation of the newly formed province of Orissa, visited the Statistical Laboratory; and two days later the Hon'ble Mr. Viswanath Das, Prime Minister of Orissa, the Hon'ble Mr. Nityananda Kanungo, and other members of the Orissa Government again came to the Statistical Laboratory to discuss this report. The Government of Orissa have decided to print this report ; but as this will take some time, I am publishing here a few notes on the subject.

THE DELTA OF ORISSA.

The delta of Orissa comprises roughly the three administrative districts of Cuttack, Puri and Balasore with a total population of over 4 millions, and lies approximately between 19°28′ and 21°57′ N and 85° and 87°29′ E. It is a narrow strip of alluvial soil formed by the deposit of silt brought down by a number of rivers some of which have their origin in Central India. The width of the delta never exceeds 60 or 70 miles, and at places is only from 15 to 20 miles wide. In the north and the west, the delta is overhung by the high lands of Orissa Tributary Mahals, which form a southerly projec-

[1] At that time Orissa formed a part of the province of Bihar & Orissa.

tion of the hills of Chota Nagpur. Some of the smaller rivers of Orissa have their origin in these hills, but others draw their main supply from huge tracts of undulating uplands on the further side of these ranges. In the south, the delta is bounded by the Chilka lake ; and in the east, by the sea.

The delta consists of three distinct zones each of which runs roughly parallel to the sea coast. Along the coast lies a narrow strip of salt tract from one to six miles broad, traversed by sluggish streams, full of swamps and morasses, and practically uninhabited and uncultivated. This is followed by an arable belt of level land about 40 or 50 miles broad lying betwen the salt tract and the hilly country on the west. The third belt is a submontane tract broken up by low hills some of which rise to 2,500 feet, and deep ravines and narrow valleys. The average level of the land lies between 250 and 500 feet ; the drainage slope is satisfactory and the country is immune from floods.

It is probable that the clusters of isolated hills, which dot the whole of Orissa, were once islands, and are the products of denudation. The fact that the whole country resembles an upraised archipelago suggests that the Bay of Bengal washed the western cliffs at a comparatively recent geological period.

RIVERS OF ORISSA.

The Orissa delta is traversed by a network of distributaries arising chiefly from the three rivers: Mahanadi, Brahmini, and Baitarini. All three rivers resemble one another in many ways. They all run roughly parallel ; all have their origin in the hilly countries of the Central Provinces or the Orissa Tributary Mahals ; and all run directly into the sea.

The *Mahanadi* (literally 'the Great River') rises near Sihawa in the extreme south-east of Raipur District in Central Provinces. After a course of about 470 miles, the Mahanadi pours down upon the Orissa delta from between two hills at Naraj about seven miles west of the city of Cuttack, the capital of the province. It traverses Cuttack district from west to east, and after throwing off numerous branches in a distance of about 50 miles to the sea, falls into the Bay of Bengal by several channels near False Point in 20°18′ N., 86°43′ E. The maximum discharge of the Mahanadi in high flood is over one and half million cubic feet per second, which approaches the flood discharge of the Ganges itself.

The *Brahmini* is formed by the junction of the South Koel and Sankh rivers in Gangpur State, and following a very winding easterly course is joined by the Baitarini (at 20°45′ N, 86°49′ E) and reaches the Bay of Bengal by the Dhamra estuary at 20°47′ N, 86°58′ E.

The *Baitarini* rises in the north-west of Keonjhar State, and flows first in a south-westerly and then in an easterly direction. It is joined by the Brahmini, and the united stream falls under the name of Dhamra into the Bay of Bengal.

The *Subarnarekha* rises near Ranchi and flows at first towards the north-east and then bends to the east and the south, and falls into the Bay of Bengal after a course of about 300 miles having drained an area of about 8,000 square miles.

RIVER FLOODS IN ORISSA.

The primary cause of floods in Orissa is the huge volume of water poured into the delta through the Mahanadi, the Brahmini, and the Baitarini during periods of excessive rainfall in the catchment area. In this paper I shall consider these three rivers primarily.

Compared with the main rivers of India they are all of a medium class. The length of the course, drainage area, and approximate discharge capacities are given below:

TABLE I. RIVERS OF ORISSA.

River	Length in miles.	Area in sq. miles Catchment	Area in sq. miles Delta	Discharge in cubic feet per second Maximum	Discharge in cubic feet per second Monsoon Normal	Discharge in cubic feet per second Minimum
Mahanadi	550	51000	2500	1,570,000	300,000	204
Brahmini	345	14000	700	650,000	90,000	130
Baitarini	142	4000		400,000	25,000	Small
Total		69000	3200		415,000	

Each river enters the Orissa delta in one single stream, and almost immediately divides into a great number of branches owing to deltaic action. During the monsoon season the rivers emerge from the hilly country with high velocities and laden with large volumes of silt. The velocity is suddenly reduced on reaching the plains, and the silt is deposited on the river beds. In this way the bed of the river rises and gradually a shallow ridge is built up, on the summit of which the river flows. But the gradient along the river channel decreases at the same time, which causes a further reduction of the velocity and consequently a greater deposit of silt, until the bed of the river is raised so high that the river bursts its banks and sends out branches into the valleys lying between two successive river ridges. Fresh ridges are formed by the deposit of silt along the channels of the new branches, and the whole process is repeated with the formation of more new branches. During heavy floods, water is spilled over either bank, and silt is deposited over the surrounding country which slowly raises the general level of the deltaic land. This action is, however, much slower than the raising of the river beds, so that the formation of new branches is a characteristic feature of all deltaic countries. Such deltaic action is very marked in Orissa, and we find that the Mahanadi, the Brahmini and the Baitarini have divided into about 15 main branches with innumerable minor streams about half way between the gorges and the sea. These branches are interlaced in a very intricate manner so that waters from the different rivers become inextricably mixed on their way to the sea.

Daily gauge readings are available practically at the head of the delta for the Mahanadi at Naraj since 1868, the Brahmini at Jenapore since 1875, and the Baitarini at Akhoyapada since 1874. Analysis of these gauge readings up to 1929 (discussed in detail in the Main Report) shows that the average height of the rivers at these places respectively have remained practically steady during the last 50 or 60 years. Deltaic action is, however, still at work in the plains which causes considerable fluctuations in the relative discharge through different channels from time to time.

THE FLOOD AREA.

Although the total area of the delta is about 8,000 square miles, from the point of view of floods the central area of about 3,000 square miles is the most important. The greater part of this central area, about 2,300 square miles in extent consists of the Mahanadi delta , while the north central area of about 800 square miles is watered by the distributaries of the rivers Brahmini and Baitarini. In the extreme north, a small portion is drained by the river Subarnarekha and some minor rivers.

The central area is the most fertile and densely populated tract in Orissa, and the aim of most of the schemes of flood control developed so far has been to protect this patch of land. The problem of flood regulation is, however, one of peculiar difficulty owing to the fact that the land is extremely flat and practically without any slope throughout its breadth. The deltaic channels, in spite of their great number, are unable to carry away even half the water brought down by the rivers from the western mountains during high floods. Owing to the insufficient carrying capacity of the drainage channels, the flood water cannot quickly escape to the sea.

TIDAL ACTION.

The situation is greatly aggravated by obstruction to a free flow caused by canals and embankments constructed by men. In the lower reaches of the rivers another factor of some importance is the action of tides which at certain periods hold up the water and appreciably prolong the duration of floods.

Along the sea-coast of Orissa there exists a steady northward littoral sand drift. "This drift tends to form bars across the mouths of the rivers from south to north; a bar of this nature is often raised in the hot weather by the prevalent wind so as to form an unbroken sand dune across the mouth some 25 or 30 feet high above sea level. It is not uncommon to find a river pursuing a fairly straight course to the sea, there to be diverted parallel with the coast for several miles before it can succeed in obtaining an outlet." During heavy floods direct mouths are sometimes opened across the sand dunes, but such openings are again soon closed by the littoral drift. The Orissa Flood Committee of 1928 was of opinion that the shortness of the Orissa delta was very possibly due to this drift:—"Whereas the heads of the deltas of such rivers as the Ganges and Indus are situated about 400 miles from the sea, the deltas of the Mahanadi, Brahmini and Baitarani are little more than fifty miles long. It is probable that these rivers are continually striving, by deposit of silt, to form new land on the sea edge but that this silt is continually being forced towards the north by the littoral drift. We consider it likely that to this drift is due, on the one hand, the long shallow shelf which is shown on the charts as stretching into the Bay of Bengal in front of the Orissa rivers, and on the other, the progressive filling in of the Balasore Roads."

Tidal action extends to a considerable distance inland and causes marked variation in the level of all the rivers. During the monsoon season, water in the Bay of Bengal is headed up which raises the level of the water at the mouths of the rivers by some 2 or 3 feet or considerably more during storms.[2] Owing to the very small width of the Orissa delta (from 30 to 50 miles), this monsoon heading up and tidal action offer considerable obstruction to the flood discharge by appreciably reducing the slope of the water flowing down the rivers.

OBSTRUCTIONS CAUSED BY CANALS.

Finally, as already mentioned, the natural situation has been very seriously complicated by the erection of embankments for the protection of the arable tract from flooding and by the construction of canals for irrigation and navigation.

In Balasore District, the Orissa Coast Canal up to Charbatia runs parallel to and a few miles from the sea coast. It constitutes a barrier 60 miles long which prevents the free flow to the sea of the spill water from the numerous channels which cut it almost at right angles. The High Level Canal from Bhadrak to Cuttack, the Orissa Trunk Road, and more recently the Bengal Nagpur Railway line, all cut the main drainage channel practically at right angles, and thus complicate the flood sitution. In the Brahmini delta

[2] Report of the *Orissa Flood Committee*, 1928, p. 8.

a number of embankments (Uttikhan, Gajaria, Raj Kanika, Aul, etc.) seriously obstruct the flow of water.

In the area drained by the main channel of the Mahanadi and its branches in the Cuttack district a more stable regime has been reached by practically fully protecting the land from inundations by a system of embankments.

The situation, however, is very bad in the Puri District which is drained by the southern branches of the Mahanadi. These rivers are unable to carry even half the volume of water received during moderate floods from the main channel. In the Puri District, another important factor is the premature reclamation of land along the sea face. There are large areas only a few feet above the mean sea level which are protected from tides by salt embankments. Once they are flooded, rapid drainage is practically impossible. The premature reclamation also affects adversely the deterioration of estuaries which appears to be still in progress in this region.

In a deltaic country like Orissa, flooding is inevitable and is not an unmixed evil. The rivers of Orissa bring down both sand and silt, and if they cause injury by the deposit of sand, they also cause good by deposit of silt ; and the scouring action of high floods is on the whole beneficial. But serious damage is also done periodically by severe floods, and occasionally, one in fifteen or twenty years, great havoc is caused by catastrophic floods.

THE CATCHMENT AREA OF THE ORISSA RIVERS.

In this paper I shall describe some of the characteristic features of river floods in Orissa, and the rain-storms which give rise to them. I shall begin with a brief description of the catchment basins.

I have already mentioned that an enormous volume of water is brought into the delta by river channels, and that most of the inundations are caused by high floods in the rivers. In fact the total rainfall in the catchment area drained by the Orissa rivers is nearly thirty times as large as in the delta. A study of the precipitation in the catchment basins is therefore of fundamental importance in connexion with floods. In the Main Report I have studied the catchments separately. Working on maps of the series *Carte Internationale du Monde*, 1 : 1,000,000 (1 inch = 15·78 miles) published by the Survey of India, I separated the main catchments of the Mahanadi, the Brahmini, the Baitarini, the Subarnarekha and the minor rivers (that is, the respective areas drained by these rivers by carefully marking the watershed lines as shown in red dash-and-dots in the accompanying map.

THE MAHANADI CATCHMENT.

The Mahanadi Catchment was further subdivided into five sections, M-I, M-II, M-III, M-IV, and M-V, partly from meteorological and partly from hydrological considerations, the object being to make each section as homogeneous as possible in its rainfall characteristics as also in its topographical features. These sections are also marked separately in red dotted lines on the map.

This division into sections is convenient in many ways. Water from the nearer Sections M-I or M-II reach Naraj (which is situated about 7 miles above Cuttack, and where the main river gauge has been located for more than 70 years) within a short time. But there is an appreciable lag for the other sections, so that for the heavy rainfall in M-IV or M-V produce their maximum effect at Naraj after a considerable time. It is also possible to isolate each section at times of floods. Thus, if desired, M-V can be cut off by intercepting the flow along the river at one single place, and similarly for the other Sections.

In the same way Br-I and Br-II represent the lower and upper sections of the Brahmini catchment; and Sb-I and Sb-II those of the Subarnarekha catchment. The Baitarini basin which is only 4000 sq. miles in area and of a compact shape, has been left undivided.

EFFECTIVE LENGTH OF RIVER CHANNELS.

It is therefore desirable to obtain some idea of the average distance from Naraj of the different sections. For flood purposes we must of course take the distance along the river channels. But a complication arises as we have not one but many different channels in each section. It is therefore necessary to find out the average effective length of the channels within each section. Using a disc type of distance meter, the total length of river channels within each section was directly determined from the map Minor drainage channels which were not marked on the map were perforce neglected. But such channels must necessarily be small and extremely local in character, so that the excess run-offs most probably reach one or other of the channels printed on the map, within a short time, possibly within a few hours. I am also neglecting of course that portion of the rainfall which enters the sub-soil, or is held up in local retarding basins. In other words, I am considering here only the free excess flow through streams and river channels.

The following Table gives the basic data for the Mahanadi catchment: column (1) shows the Section; column (2) the area of the Section in square miles; column (3) the

TABLE 2. AREA AND EFFECTIVE LENGTH OF CHANNELS FOR DIFFERENT SECTIONS OF THE CATCHMENT BASIN OF THE ORISSA RIVERS.

Section of Catchment	Area in square miles	Name of End Station	Distance from Head of Delta in miles	Within each Section: Number of Channels	Total length of Channels	Average length in miles	Average distance from Head of Delta
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		MAHANADI CATCHMENT					
Mahanadi-I	6400	Naraj (Hd. of Delta)	—	87	8352	96	96 miles
Mahanadi-II	12400	Sonepur	131	83	5727	69	200 ..
Mahanadi-III	14300	Sambalpur	180	143	18304	128	308 ..
Mahanadi-IV	6600	Seorinarayan	282	43	1548	36	318 ..
Mahanadi-V	11300	Changori	296	81	9072	112	408 ..
Mahanadi Total	51000		—	437	—	—	265 ..
		BRAHMINI CATCHMENT					
Brahmini-I	5600	Jenapore (Delta)		90	9360	104	104 ..
Brahmini-II	8400	Bonaigarh	150	118	14750	125	275 ..
Brahmini Total	14000	—	—	208	—	—	156 ..
		BAITARINI CATCHMENT					
Baitarini	4000	Akhoyapada (Delta)	—	63	6300		100 ..

name of the station situated at the extreme end of each Section nearest to delta; column (4) the distance from delta in miles; column (5) the total number of channels; column (6) the total length of all the channels in miles; column (7) the average length of the path within each Section in miles ; and finally in column (8) the average effective length of the drainage channels for each Section up to the head of the delta.

An example will make the position clear. In Section M-V, the station situated at its extreme end is Changori and its distance from Naraj is 296 miles. The number of channels within this Section is 81, and the total length of these 81 channels each measured up to Changori was found to be 9,072 miles. The average length of drainage channels in this section up to Changori is therefore 112 miles. Adding to this, 296 miles—the distance between Changori and Naraj—we get the effective average distance of the equivalent drainage channel from Section M-V to Naraj as 408 miles. The length of the effective drainage channel for the Mahanadi Catchment as a whole up to Naraj is simply the weighted average of the sectional figures and is equal to 265 miles.

The physical conditions in the different Sections are not of course identical, and the average velocity in different Sections will therefore be different. Still the effective distances given in the above table may be used to give a rough idea of the time lag for the different Sections. Very little information is available regarding the gradients. We know, however, that the fall from Sambalpur to Naraj is about 375 feet in 180 miles, that is, about 25 inches per mile.

Normal Rainfall in the Catchment Area.

The average rainfall in each Section of the Mahanadi Catchment during different seasons was determined from primary rainfall records[3] and is shown in Table 3. These averages are based on data for individual rainfall stations a list of which is given in

Table 3. Normal Rainfall in the Catchment Basin.

Section of Catchment	Number of Rainfall Stations	Normal Rainfall in Inches					Monsoon Rainfall	
		Winter Dec. to Feb.	Summer March to May	Monsoon June to Sept.	Autumn Oct. to Nov.	Annual Jan. to Dec.	Percentage of Total	Adjusted Normal Precipitation in Kilocusecs
Mahanadi-I	10	1·72	5·23	42·73	5·31	54·99	77·71	75
Mahanadi-II	6	1·49	3·06	47·49	2·78	54·82	86·63	161
Mahanadi-III	7	1·81	2·15	52·96	2·58	59·50	89·01	208
Mahanadi-IV	3	1·65	2·62	45·78	3·09	53·14	86·15	83
Mahanadi-V	13	1·91	2·19	40·83	2·66	47·59	85·80	126
Mahanadi Total	39	1·76	3·13	44·90	3·38	53·17	84·45	— 650
Brahmini-I	7	1·80	4·93	45·80	4·56	57·09	80·22	70
Brahmini-II	9	2·52	3·52	49·10	3·38	58·52	83·90	113
Brahmini Total	16	2·21	4·14	47·66	3·90	57·91	82·31	— 180
Baitarini	6	2·08	7·06	38·84	5.60	53·58	72·49	— 48
Delta	12	1·80	6·35	43·15	8·37	59·67	73·31	— 30

[3] For the period 1891-1928 given in the Annual Rainfall volumes published by the Indian Meteorological Department. Two different methods were used for calculating the normal rainfall. The numerical method is based on the average of all the rainfall stations included within each Section. Independent estimates were also made by drawing lines of equal rainfall, and measuring the area enclosed within each pair of such lines directly by a planimeter. In the case of monthly normals, the discrepancy between the two methods was found to be of the order of 3·5 per cent.

Appendix I. The normal rainfall during the monsoon months (June, July, August, and September) and during the whole year for each rainfall station is shown in Appendix II.

The distribution of the monsoon rainfall is shown in the accompanying map. The precipitation is larger over the catchment area than the delta. There is at first a slight rise near the hills on the western edge of the delta, and a much sharper and more pronounced increase in the rainfall near the mountainous region of the Feudatory States and Tributary Mahals. The monsoon rainfall jumps from 42 inches near Phulbani, Chendipara, or Chakradharpur to over 56 inches at Pal-Lahera or Deoghar within a distance of about 20 miles. The maximum rainfall occurs over the northern portions of the Brahmini catchment and the south-eastern portions of the Mahanadi catchment. Further west the rainfall decreases gradually with a closed minimum in Section M-V near Kawardha and Chuikhadan.

It will be seen that not only the gross rainfall but the percentage rainfall is greater over the catchment area during the monsoon period. In the delta only about 72 per cent of the total annual precipitation occurs during the monsoon; while the corresponding percentage is 82 in the Brahmini basin and 85 in the Mahanadi catchment area (varying roughly between 78 and 89 in the different sections). We may say, therefore, that about four-fifths of the total annual rainfall occurs in the river basins during the four monsoon months.

For flood purposes it is convenient to convert rainfalls into rates of precipitation. As one inch of rainfall in one day represents 26.8 cubic feet per second per square mile, we can easily get the rate of precipitation in cusecs in each Section by multiplying the area of each Section (given in column (2) of Table 2) by the corresponding normal rainfall in inches (column (7) of Table 3) multiplied by the factor 26.8. The adjusted rates of precipitation in kilocusecs (in round numbers allowing for the margin if error in the calculations) is given in the last column of Table 3. It will be seen that the monsoon precipitation (July to September) is of the order of 650 kilocusecs in the Mahanadi catchment, 180 kilocusecs in the Brahmini catchment and about 40 kilocusecs in the Baitarini basin, or a total precipitation of about 870 kilocusecs in the river basins against only 30 kilocusecs in the corresponding delta.

The South-West Monsoon.

The months of June, July, August and September comprise the period of the south-west monsoon. For the present study, this is the most important season as about four-fifths of the annual rainfall is concentrated in these months. In years of normal monsoon, the distribution of the rainfall controls the crop-yield; in years of drought the failure of the rains causes scarcity or famine; and finally in years of excessive rainfall the amount and distribution of the precipitation determine the nature and intensity of the floods. A brief description of weather conditions during this season will not therefore be out of place.

The rapid increase of temperature during the months of March, April, and May reduces the surface pressure of the atmosphere over northern India, so that by the beginning of June, the winter high pressure area is replacd by a deep low pressure area extending in India from Sind and Western Rajputana to Bengal.

The lower monsoon current may be considered to be a part of the large circulation round the Asiatic low pressure area.[4] A steady indraught of moisture-laden winds from

[4] *Ind. Met. Mem.*, Vol. XXIV, Part VIII, page 268.

the oceanic area blowing roughly from the south-west in the Arabian Sea and the Bay of Bengal constitutes the south-west monsoon in the lower levels. The Arabian Sea branch of the monsoon usually sets in in Bombay in the first week of June, a few days before the Bay current reaches Bengal.

Although a certain amount of rainfall occurs in Orissa and the catchment areas without being associated with any large change in the barometric pressure, the heavier and more concentrated falls occur at intervals along the tracks of depressions and cyclonic storms which originate in the Bay of Bengal. Periods of heavy rainfall alternate with periods when the rain is confined to the coast districts and to scattered local thunderstorms. The front of an advancing current of monsoon in the Bay of Bengal is usually an area of disturbed weather, strong winds, and rain squalls. A characteristic feature is the formation of cyclonic storms and depression.

The Track of Rain Storms across the Catchment Area.

The heaviest rainfall in the catchment area of Orissa rivers is given by such storms[5] and depressions which move inland from the Bay of Bengal during the monsoon season. I have therefore made an attempt to chart the average track of such storms across the Orissa delta and the catchment areas of the Orissa rivers.

The actual tracks of all storms which entered the land area lying between 19° and 24°N, and between 81° and 88°E were indexed separately for the months May to

Table 4. Track of Individual Storms : September.

Year	Date	92°	91°	90°	89°	88°	87°	86°	85°	84°	83°	82°	81°	80°	79°	78°	[E
1893	(2–4)–5			*	88·7 19·4	→ 20·6	21·2	21·7	22·3	22·7	23·0	23·2	23·6	24·0	→ 24·8	78·3 26·0	‡
	9–(10–13)	*	90·3 17·7	→ 18·4	20·3	21·1	21·7	22·0	22·4	22·6	23·0	23·4	24·0	‡			
	21–(22–24)–26		*	89·4 16·4	→ 17·6	19·0 ‡	19·8 27·5	20·4 27·1	21·0 26·4	→ 21·6 25·3 ←	83·3 23·0	↓					
1894	(24–30)–1st Oct			*	88·5 19·3	→ 19·4	19·7	20·3	20·6	20·8	21·1 ‡	21·3 25·3	21·6 24·7	→ 22·3 23·7 ←	↓		
1895	16–(18–19)–20		*	→ 18·0	20·0	21·0	22·0	23·4	24·5	25·3	26·0	27·0	‡				
	30–1st Oct.)–20th Oct	→ 24·8	23·7	22·8	21·5	20·5	‡										
1896	13–(15–16)–19	*	90·6 19·9	→ 20·0 ‡	20·3 25·1	20·7 24·7	→ 22·0 23·8 ←	↓									

[5] In the Main Report I have given a detailed narrative record (which was compiled from the Daily Weather Charts issued by the Calcutta Meteorological Office during the period 1890—1926) showing the conditions in the Bay for about a fortnight preceding the days of highest level of the Mahanadi at Naraj.

November for the period 1891—1928 from the publications of the India Meteorological Department.[6] The track of each individual storm was tabulated showing the latitude position of the centre of the storm for each degree of longitude. A small portion of the tabulated tracks given in the main report is reproduced in Table 4.

For example, in the case of the storm of September 21—26, 1893, the centre was lying at latitude 16·4°N on longitude 90°E; at latitude 17·6°N on longitude 89°E; at latitude 19°N on longitude 88°E, etc. The origin of the storm (where determinate) is shown by a star mark. The direction of the storm is usually from left to right as shown in the table; that is, from east to west or from higher to lower longitudes. In a few cases the storms curved back moving from west to east. In such cases the approximate longitude where the storm turned back is indicated by a vertical arrow, and the reverse track is given in the second line of figures. Thus the present storm turned back at 23°N and 83·3°E, and the position of the reverse track is given in the second line of figures, namely, the latitude positions of 25·3°, 26·4°, 27·1°, and 27·5°N corresponding to 84°, 85°, 86°, and 87°E. respectively.

Table 5. Mean Position of Track of Storms (in North Latitude corresponding to each degree Longitude East) together with Standard Errors.

East Longitude Degrees	July		August		September	
	No. of Storms	Mean ± S.E.	No. of Storms	Mean ± S.E.	No. of Storms	Mean ± S.E.
E 90°	—	—	8	20·86 ± ·46	20	18·43 ± ·46
89°	—	—	19	21·36 ± ·30	22	19·81 ± ·34
88°	34	21·47 ± ·22	30	21·26 ± ·25	26	20·44 ± ·28
87°	40	21·51 ± ·19	34	21·11 ± ·25	29	20·61 ± ·34
86°	41	22·04 ± ·22	39	21·30 ± ·31	33	21·13 ± ·41
85°	38	22·15 ± ·19	37	21·97 ± ·28	30	21·74 ± ·45
84°	36	22·35 ± ·19	35	22·31 ± ·25	28	21·69 ± ·45
83°	35	22·58 ± ·19	34	22·79 ± ·19	26	21·87 ± ·41
82°	34	22·84 ± ·21	32	23·31 ± ·21	25	22.24 ± ·42
81°	33	23·12 ± ·22	29	23·62 ± ·21	24	22·77 ± ·37
80°	31	23·68 ± ·31	25	24·07 ± ·27	22	23·02 ± ·42
79°	28	23·89 ± ·31	21	24·14 ± ·27	17	23·44 ± ·33
78°	22	23·90 ± .33	19	24·40 ± ·48	10	23·87 ± ·45
77°	15	23·89 ± ·41	12	23·83 ± ·61	9	24·11 ± ·63
76°	11	24·01 ± ·48	11	23·94 ± ·69	6	24·38 ± ·70
75°	11	24·36 ± ·52	8	24·06 ± ·96	—	—
74°	8	23·40 ± 1·02	4	24·18 ± ·31	—	—

Taking the average of these latitude positions we can find the mean latitude position of the storm track corresponding to each longitude. These mean tracks with

[6] In calculating the mean track of storm I did not however take depressions into consideration although the distinction between storms and depressions is purely conventional. The India Meteorological Department tries to limit the use of the work "depression" to those "cyclonic circulations in which the wind does not reach gale force, i.e. of force 7 or less on the Beaufort scale" (which corresponds to 28-33 miles per hour). A "depression" becomes a "storm" when the wind in a part of the cyclonic area reaches gale force, Beaufort scale 8 (or 34-40 miles per hour), and is called severe when the wind rises to force 10 (or 49-56 miles per hour).

corresponding standard errors are shown in Table 5 and the actual position of the mean storm track is shown on the accompanying map by the thick red line with arrow-marks. The two parallel lines in red dashes on either side show the spread of the standard error of the mean position of the storm-tracks. The mean track given here represents average conditions for 37 years; if the mean track is calculated for another period of 37 years, the chances are 2 to 1 in favour of the new track lying between the two dashed lines in red which mark off the spread of the standard error. Considering the nature of the material the mean track of rain-storms appear to be confined within a comparatively narrow strip in the river basins. It will be noticed that the region of heaviest rainfall is determined to a great extent by the position of the mean track of storm across the area under consideration.[7]

Velocity of Movement of Rain-Storms.

The average velocity of the rain-storms across the catchment area is of considerable importance in connexion with flood studies. As the position of the centre of the rain-storms on each day at 8-0 A.M. is given in the Daily Weather Chart published by the Meteorological Department, it was easy to measure directly the distance moved on each day for about 27 storms which crossed Orissa during the months of July, August and September between 1891—1928. It was found that the storms usually moved across the area under consideration in about two days ; and the velocity of movement was found to be about the same on both days, and equal to roughly 200 miles per day or 8·5 miles per hour approximately.

We know that the width of the delta is about 50 miles from the coast ; the average time taken by the storm to reach the head of the delta near Naraj will be thus about 6 hours from the time of crossing the coast.

Table 6. Interval between Rainfall and different Sections of the Mahanadi Catchment.

Position of Rainfall (Centre of Section)	Distance from Coast (in miles)	Lag of heavy Rainfall in hours on				
		Coast	Delta	Naraj	Mahanadi Section I	Mahanadi Sections II & III
Delta	25	3·0	0	—	—	—
Naraj (Head of Delta)	50	6·0	3·0	0	—	—
Mahanadi-Section I	122	14·5	11·5	8·5	0	—
Mahanadi-Sections II & III	234	27·5	24·5	21·5	13·0	0
Mahanadi-Sections IV & V	354	41·7	38·7	35·7	27·2	14·2
Extreme end of Section V	414	48·7	45·7	42·7	34·2	21·2

[7] The storm tracks show a close connexion with the winds at the Cirrus level. In fact in the middle of the monsoon, storms from the Bay generally follow the direction of the wind at the Cirrus level across the head of the peninsula, and curve round towards north and north-west in the region of the south-west upper winds over north-west India. (*Ind. Met. Mem.* Vol. XXIV, Parts VII & VIII, page 270).

The distance of the approximate position of the centres of different Sections of the Mahanadi catchment from the coast are given in column (2) of Table 6. Dividing these distances by 8.5, we get the time taken by the storm to reach the different Sections of the catchment shown in the next column of the same Table. The lags or time differences between various Sections are also shown in other columns.

We may assume, further, that the locus of heavy rainfall moves with approximately the same velocity as the centre of the storm itself. The sequence of events may be now described. Heavy rain first falls in the delta ; about 11 or 12 hours later in Mahanadi Section I, Brahmini Section I, and in the catchment of the Baitarini and other minor rivers ; about 24 hours later in Mahanadi Section II and III, and Brahmini Section II, and finally about 40 hours later in Mahanadi Sections IV and V. It will be noticed that the average duration of the storm within the area under consideration is only about 48 hours.

In view of the importance of the above results I tried to check them by an altogether independent method. The average daily rainfall in the different Sections of the Mahanadi during each rain-storm were calculated and are given in the Main Report. By a careful scrutiny of these daily values, it is possible to locate the exact date of the maximum rainfall in each Section. Hence it is also possible to determine the time interval (in day) between the occurrence of maximum rainfall in any two Sections. This was done for 34 different storms for the two Sections I and V ; and it was found directly that the interval was 1·15 day or 27·6 hours. From Table 6 we find the lag to be 27·2 hours ; the agreement is almost perfect, and is, of course, partly fortuitous. It gives us confidence, however, in accepting the average velocity of 8·5 miles per hour as fairly reliable.

THE LAG BETWEEN RAINFALL IN THE CATCHMENT AND THE OCCURRENCE OF FLOODS AT NARAJ.

In the case of a large catchment basin like that of the Mahanadi it takes some time for the water to run down to the delta, so that there is a time lag between the occurrence of heavy rainfall in the catchment and that of a high flood at Naraj. It is essential to gain some idea regarding this time lag in order to attempt any kind of flood forecast.

Tables were prepared for this purpose showing the actual dates of high flood at Naraj and the last date of the rainfall period. The interval between these two dates give the lag between the rainfall and the occurrence of a maximum flood. This was done for rainstorms of different durations namely, 3, 4, 5, 6, and 10 days, and the results are shown below :

TABLE 7. INTERVAL BETWEEN RAINFALL AND FLOOD AT NARAJ.

Period of Rainfall in days	LAG IN DAYS IN THE OCCURRENCE OF A MAXIMUM FLOOD AT NARAJ	
	From end of Rainfall Period	From centre of Rainfall Period
3	2·30	3·80
4	2·16	4·16
5	1·67	4·17
6	0·48	3·48
10	0·04	—

It would appear from the figures for the centre of rainfall period, that the maximum flood at Naraj occurs about 3 or 4 days later than the day of the heaviest precipitation in the catchment. This is encouraging ; it leaves time for prediction. Had there been no appreciable lag between raifall and flood, forecasts of any kind would have been quite impossible.

In view of the importance of the question I have analysed the data separately for the different Sections. The interval between the date of occurrence of the single day maximum rainfall in each Section of the Mahanadi catchment and the date of occurrence of the corresponding maximum level at Naraj was recorded separately for all the Sections for each month separately and for the whole monsoon period, and is given in the Main Report. The average values of the intervals for each month separately and for the whole monsoon period are shown in Table 8, together with the size of the sample in each case.

TABLE 8. INTERVAL BETWEEN DATE OF MAXIMUM RAINFALL AND OCCURRENCE OF MAXIMUM FLOOD AT NARAJ.

Section of Catchment	July		August		September		Monsoon Period (July—Sept.)		
	No.	Days	No.	Days	No.	Days	No.	Days	Hours
Mahanadi-I	28	1·1	31	1·3	16	1·0	75	1·16	27·8
Mahanadi-II	48	1·2	59	1·6	30	1·3	137	1·38	33·1
Mahanadi-III	54	2·6	46	2·5	21	2·3	121	2·50	60·0
Mahanadi-IV	34	2·8	55	2·7	21	2·6	110	2·70	64·8
Mahanadi-V	27	3·4	21	3·3	12	4·0	60	3·50	84·0
Whole Catchment ...	191	2·18	212	2·21	100	2·06	503	2·18	52·1

The rainfall readings refer to the period of 24 hours ending at 8-0 A.M. and should be centred at 8-0 P.M. of the previous day. Most of the gauge readings represent the average of three readings taken at 6-0 A.M., 12-0 noon and 6-0 P.M., and should be centred at 12-0 noon. For readings on the same day, that is, for a nominally zero interval, the real lag is thus 16 hours. Making this correction, the adjusted values are shown in column (3) of Table 9.

TABLE 9. VELOCITY OF THE FLOW OF FLOOD WATER.

Section of Catchment (1)	Lag in hours: Nominal (2)	Lag in hours: Adjusted (3)	Distance from Naraj (4)	Velocity of Flow: Miles per hour (5)	Velocity of Flow: Feet per Second (6)
Mahanadi-I	27·8	43·8	96 miles	2·19	3·21
Mahanadi-II	33·1	49·1	200 ,,	4·07	5·97
Mahanadi-III	60·0	76·0	308 ,,	4·05	5·94
Mahanadi-IV	64·8	80·8	318 ,,	3·95	5·79
Mahanadi-V	84·0	100·0	408 ,,	4·08	5·98
Whole Catchment ...	52·1	68·1	265 ,,	3·89	5·70

VELOCITY OF THE FLOW OF FLOOD WATER.

Using the above estimates of the average time taken by the rainfall to reach Naraj, we can now calculate the average velocity of flow of the run-off as we already know the average equivalent length of the channels for each Section of the catchment (which are quoted in col. (4) of Table 9 for ready reference).

The results are shown in columns (5) and (6) of Table 9. It will be noticed that, excepting in Mahanadi Section I, the mean velocity is everywhere of the order of 4 miles per hour or about 6 feet per second. The agreement between the different Sections is quite striking, showing that the estimated value of 4 miles per hour is fairly reliable. The average velocity is, however, only 2.2 miles per hour in Section I, but this is easily explained by the fact that the gradient in this Section is very small.

VELOCITY OF FLOOD FLOW FROM CORRELATIONAL STUDIES.

I have calculated the velocity of flood flow by an altogether independent method Daily readings of the height of the Mahanadi are available for Naraj, and also for Sambalpur which is situated about 180 miles above Naraj. A detailed study of the correlation between the daily gauge-readings at these two stations is given in the Main Report, and here I shall simply give relevant extracts bearing on the present problem.

The correlation between the level of the Mahanadi at Naraj and Sambalpur on the same day is fairly high, and equal to about +0·78, +0·74, and +0·73 for July, August, and September respectively, the pooled value for the monsoon period of July—September being +0·745 (based on 1914 pairs of daily reading). The correlation between the level of the river at Naraj on one day and the level at Sambalpur on the previous day is still higher and equal to +0·83, +0·88, +0·85 respectively in July, August and September, and +0·86 for the whole monsoon period. The physical explanation is obvious. The water at Sambalpur takes some time to reach Naraj, and hence the lag of one day leads to a significant increase in the correlation.

Correlations with a lag of two days were also calculated. For convenience of comparison the pooled correlations[8] are shown in Table 10.

TABLE 10. CORRELATION BETWEEN GAUGE READINGS OF THE MAHANADI AT SAMBALPUR AND NARAJ.

Period		Same day		Lag of 1 day		Lag of 2 days	
		n'	r	n'	r	n'	r
July	1—10	177	·726	177	·736	178	·756
	11—20	187	·762	189	·814	190	·859
	21—31	219	·818	199	·795	218	·845
August	1—10	218	·764	220	·935	219	·875
	11—20	211	·695	212	·838	218	·917
	21—31	234	·745	241	·848	241	·752
September	1—10	242	·687	242	·857	243	·902
	11—20	234	·742	233	·828	234	·854
	21—30	189	·747	180	·873	159	·855
July	1—31	583	·776	565	·834	586	·826
August	1—31	663	·736	673	·884	678	·860
September	1—30	665	·726	655	·846	636	·874
July 1—Sept. 30		1911	·745	1893	·860	1900	·856

[8] Unfortunately records for Sambalpur were not complete, and each of the figures given in the above Table is a pooled estimate based on the data for three different periods 1883-86, 1907-16, and 1920-29. The pooled estimates were calculated with the help of R. A. Fisher's z-transformation, and the residual degrees of freedom for the pooled values of z are shown under the column heading n':

The evidence is rather conflicting. In about half the cases the correlation with a lag of one day is higher; while in the other half, the correlation with a lag of two days is higher. On the available evidence, namely, practically an equal division of the highest correlations between lags of one day and two days, it is plausible to assume that the optimum lag would be given by a value lying midway between one and two days. The gauge reading at Naraj is the average of three observations at 6-0 A.M., 12-0 noon, and 6-0 P.M., and may therefore be centred at 12-0 noon. Assuming that the gauge readings at Sambalpur were at 8-0 A.M., a lag of one day represents an interval of 28 hours,[9] and a lag of two days an interval of 52 hours. The mean value is 40 hours. This then is the time taken by the water at Sambalpur to exert its greatest effect at Naraj which lies 108 miles lower down. The average velocity thus works out at 180 miles in 40 hours, or 4·5 miles per hour as compared with the average value of just over 4 miles per hour found previously.

For a closer study of the problem I selected readings greater than 23·7 feet at Sambalpur (which corresponds to high floods), and found the correlations with the level at Naraj for various lags. The results, with the size of the sample, are given in Table 11.

TABLE 11. CORRELATION BETWEEN HIGH GAUGE READINGS OF THE MAHANADI AT SAMBALPUR AND NARAJ.

Sambalpur on first day at 8-0 A.M.			Lag in hours	July		August		September	
				n	r	n	r	n	r
Naraj on successive days	2nd day	12-0 noon	28	87	+ ·471	168	+ ·581	37	+ ·419
		6-0 P. M.	34	61	·485	109	·642	37	·467
	3rd day	6-0 A. M.	46	63	·486	162	·634	50	·669
		12-0 noon	52	87	·458	168	·716	50	·788
		6-0 P. M.	58	51	·357	163	·531	37	·428
	4th day	12-0 noon	76	87	·362	166	·453	37	·274

For this selected data the magnitude of the correlation is smaller which is, of course, to be expected. The optimum lag in July comes out about midway between 34 and 46 hours, with a mean value of 40 hours as before. A more interesting result is the tendency for the maximum correlation to occur with a longer lag of 52 hours in August and September. This leads to an appreciably lower flood velocity of about 3·5 miles per hour. If this is a real effect, and it does look like one, it indicates a retardation of the flood flow in August and September when the river is full owing to a decrease in the effective fall of the river level.

It is satisfactory to note, however, that the velocity of flood flow from correlational studies varies between 3.5 and 4.5 miles per hour which is quite consistent with the average vlaue of 4 miles per hour found by an altogether different method.

INTENSITY OF RAINFALL IN THE PERIOD PRECEDING RIVER FLOODS.

We may now consider the rainfall during and just preceding high floods in the river. By a careful scrutiny of the rainfall records and gauge readings, it is usually possible to locate the patch of rainfall preceding (and presumably causing) particular floods. This was done for 39 floods which occurred during the period 1874—1926, and

[9] This point has been discussed in detail in the Main Report.

the detailed data are given in the Main Report in the form of the daily average intensity of rainfall in the Mahanadi catchment for each successive day for a period of 9 consecutive days immediately preceding the occurrence of floods at Naraj. In this analysis, the stations above and below Sambalpur were grouped separately. The mean values for 30 floods are shown in Table 12.

Table 12. Average Intensity of Rainfall (in inches per day) on Nine Successive Days preceding Floods at Naraj.

Section of Catchment	Day of flood	Days of rainfall preceding the floods								
		1st day	2nd day	3rd day	4th day	5th day	6th day	7th day	8th day	9th day
Above Sambalpur	0·45	0·78	1·13	1·33	1·13	0·72	0·48	0·54	0·63	0·66
Below Sambalpur	0·31	0·69	1·31	1·78	1·41	1·02	0·66	0·52	0·54	0·56
Whole Catchment	0·38	0·74	1·22	1·56	1·27	0·87	0·57	0·54	0·59	0·63

It will be noticed from the above table that the precipitation beyond the sixth day preceding the occurrence of a high flood in the Mahanadi is practically normal. It is usually the rainfall which occurs between the fifth and the second day preceding a flood which is effective. Usually there is patch of about three consecutive days of heavy rainfall of over one inch per day. The rainfall however falls off just before the occurrence of the flood, which merely shows that it takes some time for the flood water in the catchment to come down to Naraj.

It will also be noticed that the patch of heavy rainfall occurs about a day earlier (fifth day preceding a flood) in the area below Sambalpur. This is, of course, quite natural, since most of the pre-flood rainfall is given by the rain-storms which move across the catchment roughly from east to west, *i.e.*, from below Sambalpur to above.

Similar material was tabulated in a different way separately for short floods (during which the height of the Mahanadi remained above danger level at Naraj for one or two days), and long floods (during which the river level was above danger level for three or more days). Averages for short floods and long floods are given in the following Table 13.

Table 13. Average Intensity of Rainfall (in inches per day) preceding Floods at Naraj.

Nature of floods	Day of flood	Days preceding the floods								
		1st day	2nd day	3rd day	4th day	5th day	6th day	7th day	8th day	9th day
Short Floods	0·18	0·40	1·07	1·44	1·10	0·73	0·47	0·56	0·52	0·70
Long Floods	0·44	1·03	1·52	1·97	1·61	1·12	0·74	0·61	0·66	0·66
All Floods	0·29	0·66	1·26	1·66	1·32	0·89	0·58	0·57	0·58	0·68

We notice that, naturally enough, long floods were preceded by much heavier rainfall than short floods. We also find that, in the case of long floods, there is heavy rainfall exceeding one inch per day for five consecutive days up to the day previous to the occurrence of the maximum height of the river at Naraj. For short floods, there is heavy rainfall for about three days on the fourth, third and second day preceding the date of the flood. On an average, at least three consecutive days of heavy rainfall exceeding one inch per day are required to cause short floods, and five consecutive days of heavy rainfall to cause long floods. In the case of short floods, the level of the river reaches its greatest height usually two days after the cessation of heavy rainfall ; and in the case of long floods, the maximum flood occurs usually one day after the cessation of heavy rainfall.

The Rise of the Mahanadi during Floods.

We have just seen that the flood rainfall occurs in heavy patches (over 1″ per day) exceeding over 3 or 4 days, and moderate patches (over 0·5″ per day) over 6 or 7 days. How long does the effect of the rainfall persist at Naraj ? In order to study this question, a table was prepared showing the actual rise of the river on the 1st day, 2nd day, etc. up to the 10th day beginning from the day of the sharp rise due to heavy rainfall for 106 periods of such heavy precipitation. The average values are given in Table 14.

Table 14. Average Rise (in feet per day) of the Mahanadi on Successive Days of Floods.

Successive Days of Floods	Rise of the river		Successive Days of Floods	Rise of the river	
	Per day	Accumulated Total		Per day	Accumulated Total
1st Day	+ 1·83 ft.	1·83 ft.	6th Day	− 0·41 ft.	4·30 ft.
2nd ,,	+ 2·30 ,,	3·13 ,,	7th ,,	− 0·33 ,,	3·97 ,,
3rd ,,	+ 1·48 ,,	4·61 ,,	8th ,,	− 0·30 ,,	3·67 ,,
4th ,,	+ 0·42 ,,	5·03 ,,	9th ,,	− 0·29 ,,	3·38 ,,
5th ,,	− 0·32 ,,	4·71 ,,	10th ,,	− 0·19 ,,	3·19 ,,

It will be seen from the above table that the river rises on an average by about 22 inches in the first day, nearly 28 inches on the second day, and about 18 inches on the third day; the rise on the fourth day is small and only about 5 inches.

The level begins to fall slowly from the fifth day, and continues to do so at a more or less steady rate of 4 or 5 inches per day until on the tenth day the height is about the same as that on the second day. We may say, therefore, that the first and immediate effect of the rainfall persists for about five or six days, but the river often continues to remain high for a few days more.

General Description of Floods in the Mahanadi.

A typical picture of floods in the Mahanadi can now be constructed. The river floods are caused by the heavy rain given by storms and depressions which have their origin in the Bay of Bengal, and which move across the Orissa delta and the river basins in an approximately west-north-westerly direction with an average velocity of about 8·5 miles per hour along the track shown in red in the accompanying map.

The rainfall in the period immediately preceding floods usually occurs in well-marked patches of very heavy rain of intensity considerably over one inch per day for about three consecutive days, and moderately heavy rain of over three-quarters of an inch per day for about five consecutive days. Heavy rain first occurs in the delta, and then gradually moves across the catchment area of the Mahanadi, occurring usually about 12 hours later in Section I, about 24 hours later in Sections II and III, and finally about 40 hours later in Sections IV and V of the Mahanadi basin.

It takes some time for the flood water in the basin to reach Naraj. The average velocity of flow is about 4 miles per hour or 6 feet per second, except in Section I where owing to the low gradient the velocity is about 2.2 miles per hour or 3.2 feet per second. It usually takes about 44 hours for the flood water from Section I to exert its greatest effect at Naraj ; and 50 hours, 76 hours, 81 hours, and 100 hours for the water from Sections II, III, IV and V respectively. This lag between rainfall and flood makes it possible to issue flood forecasts sufficiently in advance of the actual occurrence of floods.

As regards the level of the Mahanadi at Naraj we found that usually there is a steady rise at first, which is maintained for about three days ; the rise on the fourth day, as the river level approaches the maximum, being comparatively small. Ordinarily the river begins to fall slowly from the fifth day, but the river level remains quite high for several days longer.

LEGEND TO THE MAP.

In the accompanying map areas situated at levels higher than 3.280 feet (1000 metres) above sea level are shown in deep brown colour; areas between 1,640 – 3 280 feet (500 – 1000 metres) in brown colour; areas between 656 – 1.640 feet (200 – 500 metres) in light brown colour; and levels between 328 – 656 feet (100 – 200 metres) in pale blue colour; land immediately adjacent to the sea and below 328 feet (100 metres) is shown in blue; and important rivers and lakes in deep blue.

The main watersheds for different rivers are separated by red dash-and-dot (— · — · — · —) lines; and sub-divisions within the catchment basin of the same river are shown in red dotted (. . . . . .) lines. The mean track of storms during the monsoon period (July-September) for the period 1891-1928 is shown in a thick red line with arrow marks; and the corresponding spread of the standard error of the mean track is indicated by two parallel lines in red dashes (-- — — — —) on either side of the mean track. The isohyetal lines (from 40 to 60 inches) at intervals of 5 inches for the total rainfall during the four months June to September are shown in black lines. The area subject to floods is shown by slanting hatched lines.

The actual position of the rainfall stations are shown by red dots together with a serial number in black figures which correspond to the serial number given in the first column of Appendices I and II. In Appendix I, col. (2) gives the full name of the rainfall station grouped under the appropriate catchment basins; col. (3) the year from which rainfall records are available; the last two columns show the latitude and longitude of of the stations.

In Appendix II the first two columns show the serial number and the name of the station; col. (3) the normal annual rainfall in inches; col. (4) the normal monsoon rainfall in inches; and col. (5) the monsoon rainfall expressed as a percentage of the annual rainfall.

APPENDIX I. LIST OF RAINFALL STATIONS WITH LATITUDE AND LONGITUDE

No.	Name and Catchment	Year of Starting	Latitude	Longitude
	Mahanadi I			
1	Udaigiri	1876	20°08′	84°22′
2	Phulbani	1881	20°30′	84°14′
3	Banki	1883	20°22′	85°32′
4	Kunjabangarh	1883	20°21′	84°51′
5	Narsingpur	1887	20°28′	85°05′
6	Baramba	1890	20°26′	85°20′
7	Nayagarh	1894	20°08′	85°06′
8	Tikerpara	1901	20°36′	84°47′
9	Rampur	1902	21°04′	84°20′
10	Band	1903	20°50′	84°19′
11	Balandapara	1905	20°46′	84°04′
12	Athgarh	1906	20°32′	85°38′
13	Bolgarh	1915	20°10′	85°16′
	Mahanadi II			
14	Bargarh	1867	21°20′	83°37′
15	Padampur	1902	21°00′	83°05′
16	Bhowanipatna	1902	19°55′	83°10′
17	Bolangir	1902	20°43′	83°30′
18	Sonepur	1902	20°50′	83°55′
19	Saraipali	1902	21°20′	82°52′
20	Deobhog	1906	19°53′	82°40
21	Khariar	1906	20°17′	82°46
22	Binka	1915	21°02′	83°48
23	Dhama	1920	21°16′	83°55
24	Bijepur	1920	21°12′	83°28′
	Mahanadi III			
25	Sambalpur	1865	21°28′	83°59′
26	Janjgir	1866	22°01′	82°34′
27	Korba	1880	22°21′	82°42′
28	Raigarh	1880	21°53′	83°24′
29	Sarangarh	1880	21°36′	83°05′
30	Gangpur	1883	22°07′	84°02′
31	Sakti	1902	22°02′	82°57′
32	Dharmajaigarh	1906	22°28′	83°13′
33	Pasan	1912	22°51′	82°06′
34	Baikunthapur	1913	23°16′	82°34′
35	Katghora	1916	22°31′	82°33′
36	Jharsuguda	1920	21°51′	84°02′
37	Ambhabhona	1920	21°35′	83°29′
	Mahanadi IV			
38	Dhamtari	1866	20°42′	81°33′
39	Kankar	1902	20°16′	81°30′
40	Gariabund	1903	20°38′	82°04′
41	Arang	1905	21°12′	81°57′
42	Rajim	1905	20°57′	81°52′
43	Mahesamund	1906	21°07′	82°05′
44	Kurid	1906	20°50′	81°43′
45	Pithora	1917	21°15′	82°31′
46	Nowapara	1918	20°15′	81°50′
	Mahanadi V			
47	Bilaspur	1866	22°05′	82°10′
48	Drug	1866	21°11′	81°17′
49	Raipur	1866	21°14′	81°38′
50	Simga	1866	21°38′	81°42′
51	Mungeli	1866	22°03′	81°40
52	Pendra	1880	22°47′	81°57′
53	Pendaria	1897	22°13′	81°25′
54	Kowardha	1902	22°00′	81°14′
55	Chhuikhadan	1902	21°32′	81°00′
56	Khairagarh	1902	21°25′	80°58′
57	Dongargarh	1902	21°12′	80°45′
58	Nandagaon	1902	21°06′	81°02′
59	Boladabazar	1903	21°39′	82°10′
60	Chowki	1905	20°45′	80°47′
61	Sanjari	1906	20°51′	81°01′
62	Bemetara	1905	21°43′	81°32′
63	Gondai	1906	21°39′	81°07′
64	Pondi Lafa	1906	22°07′	81°16′
65	Kusrangi	1906	21°21′	82°00
	Baitarani			
66	Keonjhar	1883	21°37′	85°35′
67	Akhoyapada	1885	20°55′	86°16′
68	Anandapur	1893	21°13′	86°07′
69	Karanjia	1905	21°53′	85°59′
70	Bonth	1905	21°07′	86°19′
71	Korai	1912	20°59′	86°08′
72	Champua	1922	22°04′	85°40′
	Nilgiri			
73	Baripado	1879	21°56′	86°44′
74	Nilgiri	1905	21°28′	86°46′
75	Turigaria	1908	21°17′	86°36′
	Brahmini I			
76	Angul	1881	20°51′	85°07′
77	Dhenkanal	1881	20°40′	85°36′
78	Talcher	1881	20°57′	85°14′
79	Pal-Lahera	1892	21°27′	85°11′
80	Chhendipara	1901	21°05′	84°53′
81	Deagarh	1903	21°32′	84°43′
82	Hindol	1903	20°37′	85°12′
83	Sukinda	1915	20°58′	85°55′
84	Barchana	1915	20°40′	86°06′
85	Jarpara	1917	20°53′	84°52′
	Brahmini II			
86	Jashpur	1883	22°53′	84°08′
87	Lohardaga	1884	23°26′	84°41′
88	Chainpur	1894	23°07′	84°14′
89	Palkot	1894	22°52′	84°38′
90	Gailkura	1896	22°31′	85°22′
91	Manoharpur	1896	22°23	85°13′
92	Kurdeg	1900	22°33′	84°08′
93	Bano	1900	22°40′	84°55′
94	Gumla	1903	23°02′	84°32′
95	Jagannathpur	1904	22°13′	85°38′
96	Bonaigarh	1906	21°49′	84°57′
97	Simdega	1919	22°36′	84°29′
	Subarnarekha I			
98	Jellasore	1873	21°48′	87°14′
99	Bharogora	1887	22°17	86°43′
100	Silda	1909	22°37′	86°49′
101	Kultikri	1910	22°07′	87°08′
	Subarnarekha II			
102	Ranchi	1864	23°22′	85°19′
103	Chaibassa	1870	22°33′	85°48′
104	Ghatsila	1886	22°34′	86°28′
105	Jhalda	1886	23°22′	85°58′
106	Silli	1887	23°21′	85°50′
107	Chakradharpur	1887	22°40′	85°37′
108	Kalikapur	1893	22°37′	86°17′
109	Tamar	1895	23°03′	85°38′
110	Seraikella	1901	22°42′	85°55′
111	Kharswan	1901	22°47′	85°49′
112	Khunti	1907	23°05′	85°16′
113	Piska	1922	23°20′	85°12′
114	Sonahatu	1922	23°11′	85°42′
	Delta			
115	Cuttack	1870	20°28′	85°52′
116	Hukitola	1870	20°25′	86°48′
117	Bhadrak	1870	21°04′	86°31′
118	Balasore	1870	21°30′	86°56′
119	Puri	1870	19°48′	85°49′
120	Kendrapara	1871	20°30′	86°25′
121	Jajpur	1871	20°50′	86°20′
122	Khurda	1871	20°11′	85°37′
123	Jagatsingpur	1872	20°15′	86°10′
124	Chandbally	1873	20°46′	86°45′
125	Banpur	1879	19°47′	85°10′
126	Ranpur	1893	20°05′	85°20′

Appendix II. Annual and Monsoon Rainfall

Serial No.	Name of Station	Annual Normal	Monsoon Actual	Monsoon p.c.
	Mahanadi I			
1	Udaigiri	54·45	40·46	74·3
2	Phulbani	52·58	43·88	83·5
3	Banki	52·82	42·25	80·0
4	Kunjabangarh	51·27	41·05	80·1
5	Narsinghpur	48·38	39·27	81·2
6	Baramba	53·01	42·30	79·8
7	Nayagarh	51·89	41·26	79·5
8	Tikerpara	47·59	38·90	81·7
9	Rampur	60·93	54·14	88·9
10	Band	51·23	43·76	85·4
11	Balandapara	73·74	64·33	87·2
12	Athgarh	53·71	63·11	80·3
13	Bolgarh	53·89	39·26	72·9
	Mahanadi II			
14	Bargarh	53·67	47·86	89·2
15	Padampur	52·57	44·98	85·6
16	Bhowanipatna	57·65	48·63	84·4
17	Bolangir	56·45	48·06	85·1
18	Sonepur	55·10	48·25	87·6
19	Saraipali	53·63	47·21	88·0
20	Deobhog	53·84	45·01	83·6
21	Khariar	53·27	43·88	82·4
22	Binka	71·56	61·97	86·6
23	Dhamka	...	...	...
24	Bijepur	...	...	...
	Mahanadi III			
25	Sambalpur	70·22	63·38	90·3
26	Janjgir	51·49	46·01	89·4
27	Korba	57·10	50·47	88·4
28	Rajgarh	62·23	56·45	90·7
29	Sarangarh	53·24	47·06	88·4
30	Gangpur	61·57	53·35	86·6
31	Sakti	60·64	54·00	89·1
32	Dharmajaigarh	64·94	57·32	88·3
33	Pasan	48·10	42·04	87·4
34	Baikunthapur	61·45	52·71	85·8
35	Katghora	64·51	56·06	86·9
36	Jharsuguda	...	...	...
37	Ambhabhona	...	...	...
	Mahanadi IV			
38	Dhamtari	50·72	45·13	89·0
39	Kankar	51·28	42·96	83·8
40	Gariabund	57·45	49·27	85·8
41	Arang	55·21	48·86	88·5
42	Rajim	56·04	48·78	87·0
43	Mahesamund	62·85	55·43	88·2
44	Kurid	48·91	43·63	89·2
45	Pithora	...	...	...
46	Nowpara	...	...	...
	Mahanadi V			
47	Bilaspur	49·63	43·36	87·4
48	Drug	48·23	42·80	88·7
49	Raipur	50·43	44·42	88·1
50	Simga	44·64	40·22	90·1
51	Mungeli	45·33	39·65	87·5
52	Pendra	51·58	43·43	84·2
53	Pendaria	43·65	36·77	84·2
54	Kowardha	40·72	32·90	80·8
55	Chhuikhadan	42·79	35·25	82·4
56	Khairagarh	45·70	38·14	83·5
57	Dongargarh	50·85	43·09	84·7
58	Nandagaon	52·39	44·07	84·1
59	Boladabazar	53·89	46·72	88·3
60	Ambachowki	55·25	47·99	86·9
61	Sanjari	53·21	45·33	85·2
62	Bemetara	47·79	41·66	87·2
63	Gondai	42·60	35·82	84·1
64	Pondi Lafa	57·55	51·43	89·4
65	Kusrangi	51·25	45·85	89·5
	Baitarani			
66	Keonjhar	47·98	36·47	76·0
67	Akhoyapada	58·23	42·83	73·6
68	Anandpur	54·86	40·02	72·9
69	Karanjia	61·14	46·70	76·4
70	Bouth	54·13	38·55	71·2
71	Korai	52·15	39·50	75·7
72	Champua	...	...	...
	Nilgiri			
73	Baripado	62·93	46·74	74·3
74	Nilgiri	68·15	46·18	67·8
75	Turigaria	60·20	42·29	70·2
	Brahmini I			
76	Angul	48·92	37·63	76·9
77	Dhenkanal	57·58	44·77	77·8
78	Talcher	51·61	41·24	79·9
79	Pal-Lahera	67·98	56·76	83·5
80	Chhendipara	51·10	41·35	80·9
81	Deogarh	67·29	57·10	84·9
82	Hindol	55·26	41·77	75·6
83	Sukinda	65·18	47·31	72·6
84	Barchana	64·66	47·04	72·7
85	Jarpara	...	...	...
	Brahmini II			
86	Jashpur	65·00	54·38	83·7
87	Lohardaga	51·36	42·20	82·2
88	Chainpur	54·46	44·67	82·0
89	Palkot	59·68	50·09	83·9
90	Gailkura	61·12	50·44	82·5
91	Monoharpur	61·42	51·51	83·9
92	Kurdeg	60·36	53·35	88·4
93	Bano	59·11	51·16	86·6
94	Gumla	54·22	44·12	81·4
95	Jagannathpur	53·77	43·39	80·7
96	Bonaigarh	66·31	57·14	86·2
97	Simdega	...	...	...
	Subarnarekha I			
98	Jellasore	58·78	43·43	73·9
99	Bharogora	57·38	44·40	77·4
100	Silda	56·18	41·07	73·1
101	Kultikri	56·28	39·27	69·8
	Subarnarekha II			
102	Ranchi	54·72	45·30	82·3
103	Chaibassi	52·95	41·83	79·0
104	Ghatsila	57·56	45·63	79·3
105	Jhalda	54·98	44·82	81·5
106	Silli	51·38	42·78	83·3
107	Chakradharpur	51·99	41·91	80·6
108	Kalikapur	62·34	49·77	79·8
109	Tamar	51·07	42·36	82·9
110	Seraikella	49·54	38·90	78·5
111	Kharswan	56·07	45·12	80·5
112	Khunti	66·58	55·59	83·5
113	Piska	...	...	...
114	Sonahatu	...	...	...
	Delta			
115	Cuttack	60·66	45·93	75·7
116	Hukitola	65·26	44·80	68·6
117	Bhadrak	60·14	42·86	71·3
118	Balasore	63·82	45·20	70·8
119	Puri	53·99	37·89	70·2
120	Kendrapara	59·47	43·22	72·7
121	Jaipur	59·90	43·98	73·4
122	Khurda	59·29	44·91	75·7
123	Jagalsingpur	60·71	44·35	73·1
124	Chandbally	60·98	42·96	70·4
125	Banpur	53·83	39·07	72·6
126	Rampur	57·06	42·62	74·7