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HYDROLOGY OF VARIOUS DELTA TYPES

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ABSTRACT

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The hydrology of deltaic regions is characterized by the interaction of fluviatile and marine changes in water level, by the small gradients that may cause extensive inundations, and by the influx of saline sea water into fresh surface- and groundwater.

Deltas possess a large development potential, both for agricultural and industrial purposes, provided water management and flood control is adequate. The measures taken may profoundly change the natural hydraulic environment. Several large deltas, in particular in Asia, still are in a primitive stage of hydrologic development, although they belong to the most productive and densely populated regions of the world.

Hydrological water management depends on the characteristics of the river basin (variable discharge, speed of flooding) and of the ocean (astronomical tides and storm surges). Agrohydrologically, the climate in a delta region is of prime importance. Examples are provided from deltas in the temperate (Rhine), arid (Nile) and humid tropical (Ganges, Irrawaddy and Mekong) climatic zones.

NATURAL HYDROLOGIC CONDITIONS

Typical features of hydrology of deltas

Deltas[2] are the meeting places of the rivers and the sea. They have been the stage of great events in human history.

Four ancient civilizations (Egypt, Mesopotamia, Indus and China) originated in deltas. Today many deltas range among the most densely populated and economically most significant parts of the crust of the earth. This may be attributed to the mystic attraction the sea has always exerted on Man, but the remarkable development of many deltas can also be explained by tangible factors. Indeed, deltas do possess a number of natural physical advantages which elsewhere are not found or do not occur to the same extent.

Delta soils are generally heavy with a high water-retention capacity, offering during dry periods a considerable amount of water to the crops. Furthermore the phreatic table is found at a shallow depth below the surface so that water may also be supplied to the root zone of the plants by capillary ascend. Deltas are level areas so that in case of paddy the depth of the surface water on the land or in case of dry crops the depth of the phreatic table below the surface can perfectly be controlled. Deltas are supplied with fresh water from the entire river basin and they present a network of water courses which never run dry and facilitate communications. Finally deltas are the outfalls of the hinterland and it is through the deltas that the inhabitants of the river basins communicate with overseas areas.

These natural advantages are partly offset by a number of inherent drawbacks. The soils may be so heavy that they are difficult to till and to drain. The level areas are exposed to flooding and even with extensive flood protection works the situation remains vulnerable. Harbours in deltas are liable to rapid silting up. Owing to the presence of thick formations near the surface with little bearing capacity foundation conditions are generally bad as will be set forth in other contributions to this symposium.

It is the apparent paradox of delta development that the serious drawbacks did not prevent an intensive economic development of many large and small deltas in the world. It seems that in order to have the full benefit of the high natural

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[2] In this paper a deltaic area of a river is defined as the system of river branches and land areas downstream from the apex, the point where a river starts branching off (Geikie, 1924).

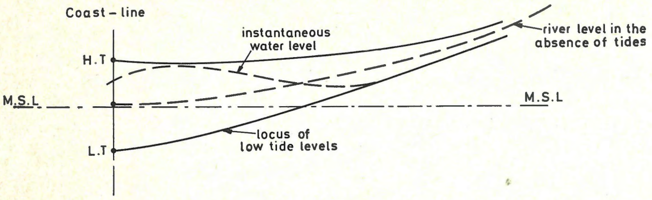

Fig. 1
Propagation of the astronomical tides into an estuary.

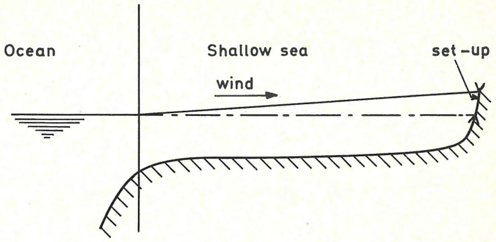

Fig. 2
Set-up of the water level caused by the drag of the wind over a water surface.

potential of deltas a certain threshold must be overcome. This may also explain the fact that many densely populated deltas are still in a first stage of technical development.

The statement that deltaic areas present unique features also applies to the occurrence and movement of water on the surface and in the subsoil which is the field of hydrology.

Hydrologic conditions of deltaic areas differ from those of the other portions of a river basin in that:

(1) the river stages and river flows are affected by the water levels at both ends of the area: the water levels of the recipient basin (ocean, sea or inland sea, lake or another river) and the water levels and discharges of the river upstream from the apex;

(2) the land and channel slopes of the delta are extremely small;

(3) under natural conditions the land areas of the delta are exposed to extensive flooding;

(4) the water courses and the soil in the delta are exposed to intrusion of saline water from the sea and the subsoil.

When examining the hydrologic conditions of the various deltas in the world, a great diversity is found. This is caused by the external factors influencing these conditions (recipient basin, river regime and climate) and the geomorphological framework. There have been many proposals for delta classification (VOLKER, 1964) but rather than attempting in the presentation of the subject to use one of the existing classifications, an outline will be given of the factors determining the hydrologic conditions followed by an illustration with examples from various parts of the world with divergent conditions.

Especially in deltas where an intensive economic development has taken place the natural environment has been considerably changed by man. Large areas have been excluded from flooding by embanking and other hydraulic works, the distribution of the river discharge over the various branches has been modified, estuaries have been closed, wetlands have been drained etc. Therefore a distinction has to be made between the natural hydrologic conditions and the effects of human interference in the original system.

Water levels and discharges

The water levels and discharges in the river branches of a delta are affected by the boundary conditions at the downstream and the upstream ends of the area.

The downstream water levels depend on the nature of the recipient basin. The most frequent case is a sea or an ocean with astronomical tides. The tides penetrate into the river mouth and cause a tidal variation of the water levels in the estuaries and river branches.

Figure 1 indicates the levels which will be reached in a river branch for a given tidal range at sea and a given upland discharge. These levels are not reached simultaneously in all stations of the river branch because of the time lag involved in the propagation of the tidal variation. Thus the two lines do not represent water lines but loci of the high and low tide levels. The dotted line represents an instantaneous situation. It depends on the magnitude of the river flow (the 'upland discharge') to what distance from the coastline the tidal effect will be felt: the higher the discharge, the more the tidal penetration is pushed back to the sea.

In addition to the astronomical tides many sea and ocean coasts are exposed to storm surges causing abnormally high sea levels often many metres above the high springtide levels of the astronomical tides. These levels are caused by strong landward winds which exert a drag on the water surface producing a set-up of the sea level (Fig. 2). The wind effect is superimposed on the tidal movement (Fig. 3).

In the tropical and subtropical zones the storms appear as cyclones, typhoons and hurricanes on the coasts of the Bay of Bengal, the Pacific coast of Japan and the Gulf of Mexico. Extreme conditions occur along the coasts of West Bengal where there is evidence for wind effects leading to a set-up of the order of 6 to 9 metres.

In the temperate zone the wind effects are pronounced along the coasts of shallow seas, like the North Sea between England and the continent.

Finally, mention should be made of the tsunamis, long waves, generated by submarine earthquakes and landslides and travelling over considerable distances to hit coastal areas remote from the place of origin.

Along deltas in lakes or inland seas the tidal effects are either absent or too weak to be significant. The water level of the recipient basin may still fluctuate under the effect of winds.

As to the effect of the river on the hydrology and geomorphology of its delta the magnitude of the flow (the

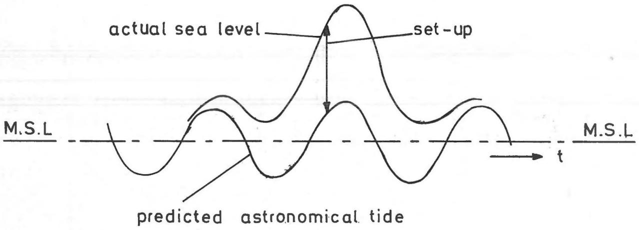

Fig. 3
Astronomical tide and wind effect.

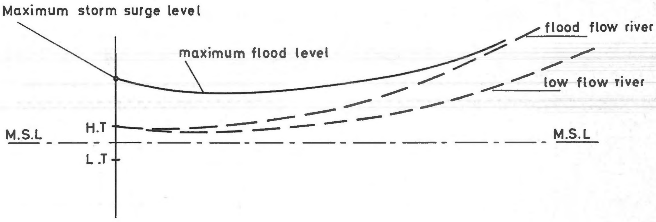

Fig. 4
High water levels reached during simultaneous occurrence of a sea flood and a river flood.

'upland discharge'), the variability of the discharge and the sediment load are obviously the prevailing factors. In this respect many similarities exist with upstream areas. Two specific aspects, however, should be mentioned here: the nature of the upstream floods and the conditions during periods of low flow.

The river floods reaching a delta depend on the rainfall and the physical characteristics of the river basin. The floods may be flashy, i.e. with quick rises to ralatively high and sharp peaks and rapid recessions, so that these floods are of short duration. Flashy floods may be generated in relatively small river basins with steep slopes and impervious soils exposed to short rains of high intensity. Quite the contrary are the gentle floods with gradually increasing discharges, relatively low and flat peaks and a slow recession. They are characteristic for large river basins with pervious soils and rainfall during long periods. In South-East Asia the rivers Ganges, Irrawaddy, Chao Phya and Mekong show floods of this type extending from June to November during the wet monsoon.

The distinction between flashy and gentle floods is significant for the difficulties involved in protecting the land areas by embanking from being flooded and for the possibilities of utilization of non-protected deltas in the humid tropical zone for growing a crop of rice.

Many deltas are exposed to floods from two sides: the sea and the river. Maximum flood levels are reached when both floods coincide (Fig. 4).

The hydrologic conditions during periods of low flow will be discussed in relation to the phenomenon of salt-water intrusion.

Geohydrology

The subsoil of deltaic areas, especially the larger ones, is characterized by the presence of thick layers of unconsolidated deposits of fluviatile and marine origin. The deposits consist of pervious material (sand, gravel) forming aquifers and semi-pervious material (clay, loam, peat) offering a considerable resistance against the passage of water.

The total thickness of aquifers and semi-pervious strata may be more than 300 m like in the delta of the Nile river. Here solid rocks form an impervious base; in other deltas the base is formed by thick layers of clay, often of marine origin, like in the delta of the Rhine river.

The built-up may be simple like in figure 5a with a single aquifer (the 'Dutch profile') and a single impervious base or more intricate like the one in figure 5b with many interbedded semi-pervious layers. In this way the subsoil offers a good possibility for the passage of water from one area to another with different levels of the surface water.

The seepage flow in such confined systems has been extensively studied. The general law was formulated by Darcy in 1856 and the fact that the relation between velocity and hydraulic gradient is a linear one made a mathematical analysis quite accessible. The built-up of subsoil is such that a horizontal flow in the aquifers can be assumed and that the vertical resistance in these strata can be neglected compared with the resistance in the horizontal direction. As to the flow through the semi-pervious layers, a vertical flow direction can be assumed (Fig. 6).

If the geotechnical parameters are known, the seepage flow can be computed for given boundaries. These parameters refer to the so-called transmissivity of the aquifers (the product kD of the permeability coefficient k and the thickness D) and the resistance C of the semi-pervious layers.

Various methods are available to determine these parameters like permeability tests on samples, pumping tests, propagation of the tidal movement and others, but they are not always conclusive. Especially the resistance C which is highly affected by inhomogeneities in the semi-pervious layers is difficult to determine. The most dependable method for determining the parameters is found in the analysis of large-scale existing ground-water flows as exist along the land-side of deltas where groundwater is flowing out from recharge areas, hills with infiltrating rain water. Sometimes low-lying reclaimed areas can be used by way of huge pumping tests yielding results which are representative for large areas.

Seepage flow in deltas between areas of different elevation of the surface water may cause considerable difficulties in the water management. The lower areas may be exposed to excessive supply of water and become water logged where the higher areas may suffer from almost permanent drought.

There is another circumstance which still aggravates the problem. That is the fact that in almost all deltas the pore water contained in the aquifers is saline or brackish at least under a certain portion of the delta area.

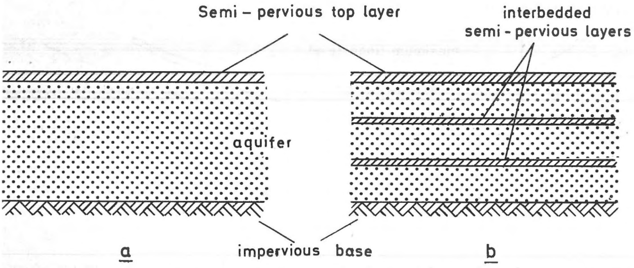

Fig. 5
Built-up of the subsoil.

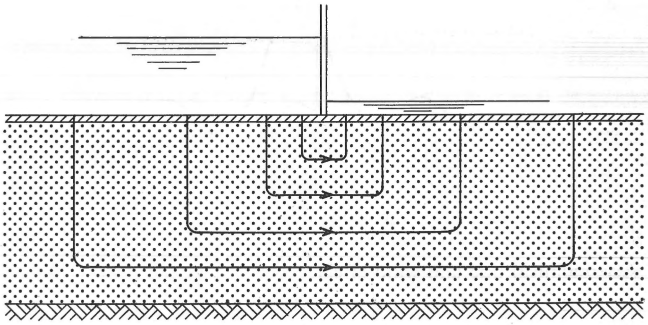

Fig. 6
Seepage flow.

Various hypotheses have been advanced to explain the origin of the brackish groundwater under deltas. There is some evidence (VOLKER, 1961) that the brackish water under the delta of the Rhine river dates from the various periods of marine transgression that occurred during the deposition of the impervious base and it is likely that something similar occurred in other deltas. The salinity of the groundwater must have been influenced during the succession of transgressions and regressions by such processes as density currents, diffusion, groundwater flow and dispersion. Diffusion, in itself a slow process, may have played an important role during the long periods of the geological history. There is direct evidence to prove that diffusion was prevailing in changing the salinity of the groundwater during the natural 'transgression' of the Zuiderzee in The Netherlands (ingress of the sea after 1200 AD) and the man made 'regression' after 1932 (transformation into a fresh-water reservoir).

Salt-water intrusion

One of the main problems of water management in deltas is the occurrence of salt-water intrusion which can be defined as the occurrence of a high salinity of surface- and groundwater rendering the water unfit for various purposes.

Salt-water intrusion is a natural feature of deltas, but it has often been aggravated by the interference of man, especially in industrialized areas. In this section the natural processes are discussed whereas a next chapter is dealing with the situation in developed deltas and also with salinity control.

There are several 'sources' of salt in a delta, but the one which is common to all deltas and which is usually the most important one is the intrusion of sea water in open estuaries. By virtue of the fact that sea water has a density which is about 2½% higher than that of fresh water, the sea water penetrates over the bottom in upstream direction into the lower river reach with the fresh river water flowing on top into the opposite direction (Fig. 7).

Sea-water intrusion into open estuaries takes place whether there are tides or not. If there are no tides and if the estuary channel presents regular cross-sections a situation develops as suggested in figure 7 with a rather sharp interface between the fresh and the saline water. The sea water on the bottom is stagnant ('arrested salt-water wedge') and the turbulent flow of fresh water over the wedge causes some mixing at the interface. An example of this situation is found in the Rhône river debouching into the Mediterranean Sea with its weak tides.

If the tidal range is significant the mixing becomes more pronounced. This is still furthered by irregular channel profiles, tidal harbour basins and rapid changes in the upland discharge. The stratification disappears and although the concentration is always higher near the bottom than near the surface, an average concentration over a cross-section can be defined.

For a given river discharge this concentration decreases in upstream direction, in first approximation exponentially. The concentration also varies with the tidal phase: with rising tide the saline effect penetrates further and retreats with falling tide.

The analysis of the sea-water intrusion belongs to the field of tidal hydraulics and is quite intricate. Several approaches, formulae and models, often controversial, have been developed in countries like the U.S.A., U.K., France, Japan, U.S.S.R. and The Netherlands. At present an effort is made in the framework of the International Hydrological Programme of Unesco to make an intercomparison of the available tools. It is significant to note that it is not yet possible to make a prediction of the sea-water intrusion in a channel of known geometry without a considerable amount of data on recorded salinity in a number of stations under different conditions of upland discharge and tidal range.

The distance from the coastline over which the saline effect is felt depends amoung others on the upland discharge and the channel depth. This holds for both stratified and mixed estuaries. The lower the discharge, the longer the brackish reach. An extreme case is provided by the Gambia river in West Africa where during minimum river flow the concentration at 235 km from the mouth is still 1.5 g total salt per litre. Experience with the Rotterdam Waterway in The Netherlands has shown that deepening of channels, for instance by dredging in the interest of navigation, has a considerable effect on the saline penetration. Whereas in the beginning of this century with a channel depth of around 9 m the intrusion at low flow extended not more than some 10 km from the coastline, the saline effect penetrated progressively further as the channel was gradually deepened to 17 m to reach a point 35 km from the coastline.

The saline water in the river branches penetrates into the tidal creeks and other water courses of the land areas of the delta. Since these channels are not supplied with water from the river basin and only act as outfalls of local drainage, the saline water penetrates far inland during periods without rain on the delta.

A second source of salt is formed by the saline or brackish groundwater under a delta as mentioned above. Oozing of this water brings salt into the surface water and the soils.

In developed deltas navigation locks between the sea and fresh-water canals form imported sources of salt. Locks are no barriers against sea-water intrusion. It is again the small difference in density between the sea water and the fresh water that causes the intrusion. When –after equalizing the levels of the lock chamber and the sea– the outer gates are opened, all the originally fresh water in the lock chamber, down to the bottom, is replaced by the heavier sea water and the fresh water is driven out. A similar process is taking place when after that the inner gates are opened. In this way a considerable volume of sea water spreads into the fresh-water canal.

Finally, the river water may contain an appreciable amount of salt. This is a natural feature in arid zones. The concentration may be excessive if the river water is contaminated by saline effluent from saline soils or from industries like the potassium mining and coal mining in the basin of the Rhine river.

Hydrology and climate

In general the hydrology of a river basin reflects the climatological conditions of that basin. Where rainfall is small and erratic, the streamflow is ephemeral. With abundant and frequent rainfall the flow is well-sustained and floods often occur.

In deltas, especially of large rivers where the delta is remote from the main intake area, a different situation may be encountered. A typical example in this respect is the delta of the Nile river which is situated in a climatic zone with hardly any rainfall whereas the river is supplied with water in a humid tropical zone. Without this circumstance the delta would not even exist. The term ‘zonal deltas’ has been proposed to characterize this situation. Practically all deltas in the arid zone belong to this group.

But also in the temperate zones the river flow in a delta does not always reflect the local climatological conditions. Thus in the delta of the Rhine river, where in summer local water courses often run dry, the flow of the river is well sustained during that season. The origin of this supply is found in the melting of ‘high snow’ in Switzerland, some 1000 km away from the delta, It is precisely this circumstance which has greatly contributed to the economic development of the delta.

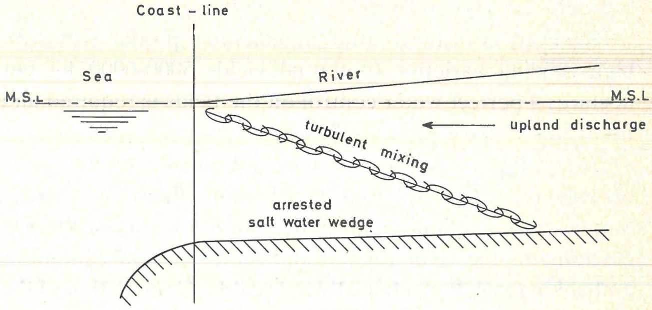

Fig. 7
Sea-water intrusion into an open estuary.

Thus the hydrologic conditions of the land areas of a delta depend not only on the local climate, but also on the river regime and on the water-level variations of the body of water in which the delta is extending. The result is a great diversity in hydrologic conditions and hence in potentialities for economic development.

HUMAN INTERFERENCE AND HYDROLOGIC EFFECTS

Flood protection in the river reach

Early human settlements in deltas took place on the natural levees in the river reach, that is the reach beyond the effect of possible storm surges and saline intrusion. On these levees with generally good soils and adequate drainage, various crops can be raised outside the flood season. The back-swamps or depressions are often waterlogged and may be more or less saline.

Land utilization on a larger scale and still in the absence of flood protection is also possible in the deltas of the humid tropical zone where rice can be grown which is aquatic plant. Rice can even grow in an increasing depth of water provided that the rate of rise does not exceed 5-10 cm per day. A special variety is the so-called floating rice which can grow in water depths up to 3 or 4 metres attaining stem lengths of 4-5 m. However, the yield (1000-1500 kg of paddy per hectare) is low compared with the more downstream areas where the depth of flooding is smaller and other varieties are grown with shorter stems (yield of local varieties up to 2500 kg per hectare).

Such a cultivation of the back-swamps during the flood season is not possible when the floods are flashy drowning the plants. This is one of the reasons why in the delta of the Red river in the northern part of Vietnam where the floods are flashy a flood protection system was built perhaps 2000 years ago whereas in the equally densely populated and productive delta of the Mekong river with gentle floods the entire delta is exposed to the river floods.

However, in order to attain a maximum productivity with high-yielding varieties (potential yields 5000-6000 kg per hectare) a perfect water control on the fields is required and flood waters have to be excluded.

The traditional and often cheapest way of flood protection on location is the erection of embankments or river dikes. Simple as the method seems to be, it may have serious repercussions on the river regime and under certain conditions embanking may be technically unfeasible. Constriction of the river flow and elimination of the overbank-storage embankments bring about a rise of the flood stages especially when the floods are of a flashy nature (Fig. 8). This is the case of the Pampanga river in Luzon (Philippines) where a rise was predicted of 2 to 3 metres. Another side effect of embanking may be an accelerated rise of the river bed causing an additional rise of the flood stages. A rising river bed is a natural feature in a delta which is expanding into the sea but in addition embanking may produce a sudden and considerable increase. This has caused almost unsolvable problems like in the deltas of the Rhine river, the Red river in Vietnam and the Yellow river in China. In the former one the problem was solved after 1850 by a *deus ex machina* in the form of the bucket dredger borrowing sand for construction purposes; in the other two areas a very vulnerable situation still exists and can only be improved by the construction of upstream flood-detention reservoirs.

Flood protection in the coastal zone

Flood protection in the coastal zone is most spectacular in deltas exposed to storm surges. It is also the most dramatic situation because of the direct threat to human lives. The history of hydraulic engineering in The Netherlands is a history of disasters, of lost battles against the sea followed by technical counter-offensives. The early settlers on the tidal flats in the coastal zone of The Netherlands (500 BC-1000 AD) did not build sea dikes but had recourse to artifically erected dwelling mounds. Later these mounds were connected by embankments encircling large land areas.

Only a brief while ago, on February 1st, 1953, nearly two thousand people lost their lives when the sea launched a major attack on the defence system. These losses appear insignificant compared to a number of about 300,000 people who perished November 12th, 1970 in the coastal zone of Bangladesh. In September 1959 with the occurrence of the Ise Bay typhoon near Nagoya (Japan) considerable damage in a highly industrialized zone was inflicted and nearly 5000 casualties were deplored.

It seems that in the course of ages there always appears a storm surge exceeding all previous ones and against which one is not armed. In statistical hydrology no upper limit is assumed and the frequencies of exceedance of given storm-surge levels are determined on the basis of actual records. Then the question of the design frequency is examined taking into account economic considerations. In this way the new defence system is designed for a storm surge with a probability of exceedance of 1% per century (or average return period 10,000 years). At Hook of Holland this is a level of 5 m above mean sea level. This seems to lead to an almost absolute safety but by supposing that all factors determining a storm surge of the maximum magnitude as they have actually been recorded over rather short periods in the past do coincide, it can be shown that a storm surge higher by more than $2\frac{1}{2}$ metres than the design level is physically possible.

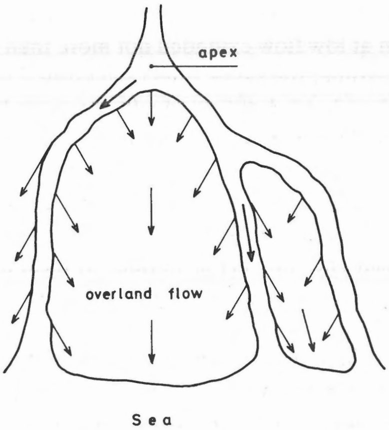

Fig. 8
Overland flow and overbank storage in a non-embanked delta.

The cyclone level in the coastline of Bangladesh on November 12th, 1970 was around 6.3 m above mean sea level. By lack of data the frequency of occurrence cannot be established, but it is likely that levels up to 9 m above mean sea level have really occurred during the last two centuries or so. Under these conditions it is practically impossible to build embankments offering any acceptable degree of safety. It is noteworthy that after the disaster of 1970 – like 2000 years ago in The Netherlands – dwelling mounds or kilas were built as well as high concrete shelter-structures, but for various reasons these attempts were not very successful.

The response in The Netherlands and in Japan after the diasasters of 1953 and 1959 respectively, consisted of the closure of the estuaries by dams preventing the storm surges to enter. In this way the primary defence line is considerably shortened and if the existing sea dikes are maintained, they can function as a second line, should the first one fail.

Drainage and irrigation

It is obvious that, next to flood protection, drainage, defined as removal of excess water from rainfall, is the primary element of water control in deltas. Specific aspects of drainage in deltas are related to the low permeability of the soils by virtue of their heavy texture, the small available gradients to convey the drainage water to the outfalls and the high levels of the rivers and the sea which should receive the excess water.

The low permeability of the soils to be drained leads to small spacings of the field drains which may open trenches or tile drains of earthenware and plastic. In case of 'dry crops' the phreatic table would be kept well under the surface to prevent suffocation of the plants by lack of oxygen and disruption of soil structure.

Deltas are virtually level areas. Gross slopes (elevation of the apex above sea level divided by the distance to the sea) range from 1×10^{-5} to 5×10^{-4} (1 cm per km to 50 cm per km). Especially the large deltas of the humid tropical zone are in the lower range. These slopes only exist in the longitudinal direction. Under these conditions the drainage canals have to be designed with small velocities ranging from 0.2 to 0.4 m/s. Since drainage water is usually clear, favourable conditions exist for the growth of reeds and other aquatic vegetation clogging the canals. The problem exists not only in tropical areas (water hyacinth) but also in temperate zones (duckweed). Mechanical or chemical abatement still poses many problems.

Perhaps the biggest problem is that of the mode of ultimate disposal of the large volumes of drainage water. In periods that drainage is needed the river levels are high and pump lift would be necessary, which obviously is an expensive affair. If the tides are not weak, the tidal movement can be used for a removal by gravity. Sluices are built at the outfalls of the drainage canals and the gates are opened when during ebb-tide the outside water level falls below the water level in the canal. Figure 1 explains why this is only possible in the coastal strip. If gravity disposal is also to be applied for upstream portions of the delta, long drainage canals have to be excavated to convey excess water to that coastal strip.

Not only drainage, but also irrigation in deltas differs in some respects from irrigation in other settings. The small gradients in deltas entail problems when the irrigation water contains silt settling in the canals. To prevent silting up the velocities, and hence the hydraulic gradients, must be increased which makes it necessary to install booster pumping stations. Since irrigation is mostly needed during periods with lower river levels the river water destined for irrigation has to be lifted. This can be realized by building a weir or headwork near the apex of the delta, piling up the water; from there high-level irrigation canals branch off (deltas in S.E. India and Thailand).The other way is to pump the water from the river or a canal on location. The use of small pumps by the individual farmers has become very popular in the deltas of the Irrawaddy and Mekong rivers where no headworks and major irrigation canals exist.

A special type of water supply is the so-called tidal irrigation by which water from the river is gravitated into irrigation canals during periods of high tide in the river. This can only be done in those tidal reaches where the water is still fresh even with a low river flow. The ultimate delivery to the fields is either by subirrigation (infiltration into the soil from the ditches) or by pump-lift.

Salinity control

As set forth earlier salt-water intrusion is a natural feature of deltaic areas. The intrusion increases by many of the measures required for the utilization and reclamation of deltas like dredging of navigation channels, opening up of tidal harbour basins, construction of navigation locks, abstraction of river water, drainage of low-lying areas and recovery of fresh groundwater. This encroachment into the natural conditions has led to a number of technical measures profoundly affecting the environment.

Preventive measures aim a halting or reducing of the saline intrusion. The most radical way of preventing sea water to intrude into estuaries of tidal embayments is to close the entrance by a dam equipped with sluices to drain off excess water during periods of high river flow. If the enclosed water area is considerable, a reservoir can be obtained with fresh water. Large-scale projects of this type have been implemented in Japan (Kojima Bay and Hachiro Gata) and in The Netherlands (Zuiderzee works and Delta works). Such schemes are often multiple-purpose schemes as providing greater safety against storm surges, improved drainage conditions and shorter road communications. A negative aspect of such schemes lies in the high costs involved.

If damming off is not feasible the almost only practicable way of reducing the sea-water intrusion is to increase the upland discharge. This can be effectuated by diversion of water in the delta (Rhine delta) or by releases of water from storage reservoirs upstream (Nile delta, Chao Phya delta in Thailand and contemplated for the Mekong delta). The discharge required for this purpose is generally high compared to other uses of water. If an increase of upland discharge is not possible or not economical, the only way-out that remains is to locate the intakes of the irrigation well upstream from the intrusion limit in the river during low-flow periods and to convey the water from these intakes to the downstream areas.

Reducing the depth of the channel would be very effective but is only practicable under rather special conditions (Rotterdam Waterway).

Repressive measures aim at removing saline water, especially in drainage-cum-irrigation canals which are exposed to a supply of brackish water. It consists of rinsing or flushing with fresh water from the river or from coastal reservoirs. It will be described in the next chapter. Here, too, large volumes of water are required.

In arid regions the danger of soil salinization is very acute. The reason may not be so much the intrusion of water from the sea, but the high evaporation rates and the absence of rain periodically leaching the soils. Under these conditions concentration of the salts in the irrigation water takes place. Leaching of the soil with water and removal of the leachate by drainage are then necessary.

PRACTICAL PROBLEMS OF HYDROLOGY AND WATER MANAGEMENT

Water management in the delta of the Rhine river

The delta of the Rhine river in The Netherlands is an extreme case of a human intervention in a deltaic environment and of a complete modification of the hydrologic system. This results partly from the fact that this delta is a 'drowning' or 'moribund' delta which would not even exist today if man had not interfered in the process of delta deterioration. Lack of adequate sediment supply from upstream for further delta building-up and land subsidence with respect to sea level (15 to 20 cm per century) have created a vulnerable situation. Some 25% of the national territory is situated below mean sea level with minus 6.3 m as lowest altitude in reclaimed lakes. More than 50% has to be protected by embankments against the storm surges at sea and against the river floods[3].

The catchment area of the Rhine river at the place where the river enters the country is about 160,000 km² which is about 4.5 times the national acreage. Hence the country is blessed with a relative abundance of water (Table I) compared with, for instance, the British Isles or Belgium. On the other side of the picture are the high demographic density (400 capita per km²) and the high amounts of water required for salinity control equivalent to ²/₃ of the total demand. It is precisely this item on the demand balance which is characteristic for this type of delta.

These are average figures; during dry periods, especially during the month of June, the supplies fall below the demands. Water is then withdrawn from storage in the main coastal reservoirs such as the IJssel Lake and the Delta Lakes. From these reservoirs water can be distributed to the major part of the country through interconnected canals and lakes mainly by gravity. The most downstream weir on the Lower Rhine enables to control the supply of water from the Rhine through the IJssel river to the IJssel Lake. It is also planned to connect this main reservoir with the rivers in the west so that water can be abstracted from the reservoir and sustain the supply to the southwestern delta area. This is the general principle of the infrastructure for water management (Fig. 9).

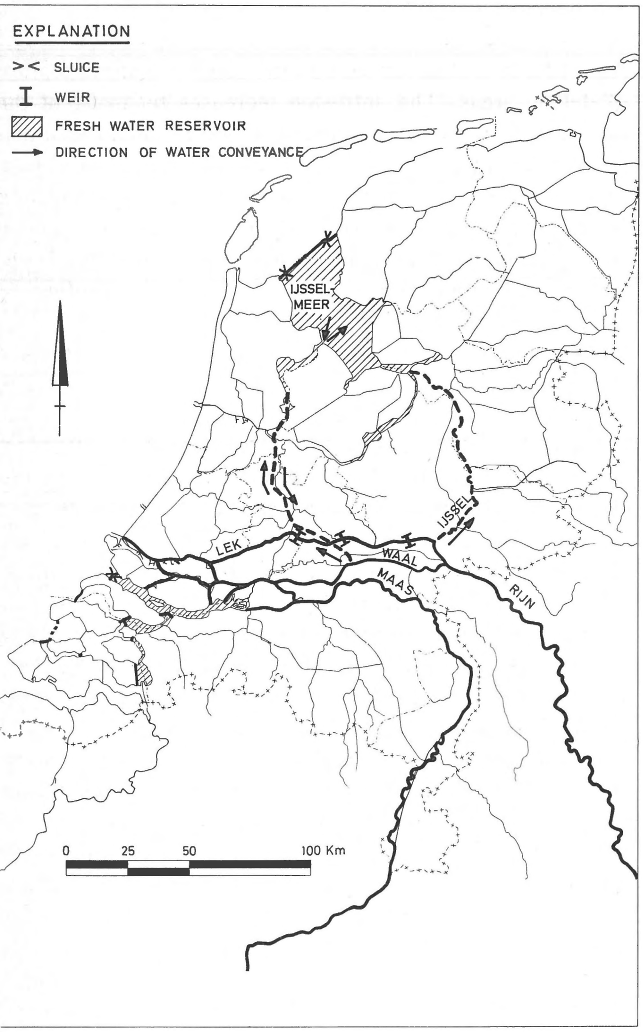

Fig. 9
Infrastructure of the water management of The Netherlands.

Table I
Water supply and estimated future water demand in The Nether-ands.

Mean annual supply	mm depth	10^9 m^3	Estimated demand year 2000	mm depth	10^9 m^3
Rain	750	30	Domestic + industrial	165	6.6
Rhine	1725	69	Agricultural	82	3.3
Meuse	200	8	Rinsing canal system	305	12.2
Rivulets	75	3	Minimum outflow Rhine	233	9.3
	2750	110		785	31.4

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[3] The remainder of the national territory consists chiefly of high Pleistocene areas.

[4] Mean annual rainfall is 25 mm in Cairo and 190 mm in Alexandria.

Salinity control and drainage in the delta of the Nile river

Another extreme development of a deltaic area with conditions that are almost the opposite of those in the Rhine delta, has taken place in the delta of the Nile river, the most classical delta in human history. Except for a coastal strip near Alexandria, rainfall is too small to be significant for agriculture[4]. With irrigation crops can be grown the whole year round and it is in this fact that lies the main justification of the Assuan High Dam. In the delta (total area 23,000 km^2, cultivated nearly 18,000 km^2), a system of perennial irrigation was completed about 85 years ago, permitting the introduction of cotton and sugar cane.

About 50% of the cultivated area suffers from deterioration. This is due to the expansion in perennial irrigation in the absence of an adequate drainage system with drainage at the farm level as well as a major system. As a result agricultural production has been growing at a rather slow rate in spite of improved farm-management practices and the introduction of high-yielding varieties. The operation of the Assuan High Dam started in 1964 and made it possible to reclaim new areas and to make water available whenever it was required by the farmer.

Excessive water use and poor water management caused a rise of the water table. This tendency existed already before 1964, but it was accelerated after that date. Since the groundwater is brackish, especially in the northern part of the delta, saline water rises by capillary ascend into the root zone from where the water evaporates leaving the salt behind. Moreover, the irrigation water, also from a general point of view, contains a non-negligeable amount of salt (250 mg total salt per liter) which also remains in the soil.

Like in other irrigation areas of the arid zones the only way to avoid soil salinization is to remove the accumulated salts from the soil by leaching with fresh water which is supplied in addition to the water consumed by the crops. For this a field drainage system is required (Fig. 10) consisting of tile drains with the double function of keeping the phreatic table well below the surface (1.2 to 1.5 m) and removing the leachate from the soil. Ultimately the leaching water has to be disposed to the sea or the Nile branches. This requires a system of drainage canals and pumping stations. Altogether some 13,000 km^2 in the delta need adequate drainage. Present rate of implementation is about 800 km^2 per year which will rise to 1000 km^2 per year in 1982. The amount of water drained off is considerable (17×10^9 m^3 per year); a part consists of non-used water from irrigation canals. As far as quality permits, this water will be returned to the irrigation system for re-use.

The large deltas in South-East Asia

In South-East Asia, along the Bay of Bengal, the Gulf of Martaban, the Gulf of Siam and the Gulf of Tongking, a chain is found of large deltas of a number of large rivers such as the Krishna, Godavari, Ganges, Irrawaddy, Chao Phya, Mekong and Red river. Most of these deltas are situated in a tropical savannah climate or a monsoon climate with a pronounced wet season from around June till November and a pronounced dry season during the other months. All these deltas are densely populated with densities up to 500 capita per km^2 like in Bangladesh. Rice is the prevailing crop and since the productivity is relatively high, these areas are considered as the rice bowls of the region.

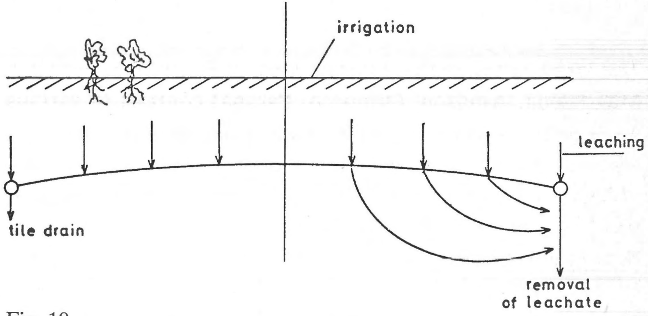

Fig. 10
Leaching of the soil for salinity control.

In spite of the general similarity of the physical and socioeconomic conditions of the various deltas, different technical developments have taken place modifying the original hydrological conditions to different degrees. With the exception of the delta of the Red river in the northern part of Vietnam where, because of the flashy floods, the areas exposed to flooding could not be utilized in the absence of embankments, the deltaic areas in the early stages of human occupancy were used for agricultural purposes without much flood protection. Human habitat and rice varieties were adapted to the prevailing hydrologic conditions.

The main crop is grown during the wet season. However, in the Chao Phya delta and also elsewhere, rainfall during that season is not sufficient, on the average, to meet the crop demands. There is a need for supplementary irrigation and, originally, this water was supplied by the river floods.

In the Irrawaddy delta, however, a general excess of water exists and there is interest to protect the areas from being flooded by river water. For this reason the construction of flood-protection embankments started already a century ago. In view of the repercussions of embanking a unique system of open or horseshoe-shaped embankments was built. In the delta of the Chao Phya the development followed another course: in 1956 a headwork or diversion was completed near the apex of the delta for a control of the distribution of the flood waters over the river branches and canals. More recently two multiple-purpose reservoirs were built in the upper reaches of the river enabling to control the floods and to increase the dry-season flow. The system of uncontrolled irrigation by flooding has been gradually turned into a system for controlled irrigation and also dry-season irrigation can be expanded.

Deltas of South America

The large deltas on the Atlantic coast of South America (Rio Magdalena, Amazon, Orinocco, Paraná) contrast in various ways with the large deltas of South-East Asia. The latter – although technically underdeveloped - are almost entirely utilized and densely populated. The former are still in a first stage of human occupancy. This is partly due to the general demographic density which is much smaller in South America than in Asia, but it can also be related to the fact that wet paddy is the staple crop in South-East Asia whereas, traditionally, mais (corn) prevails in South America. For this crop, deltas which are virtually exposed to frequent flooding, do not offer ideal conditions.

The Amazon is the largest river in the world as far as the discharge is concerned. The average annual flow to the sea is around 226,000 m^3/s, representing 18% of the total flow of all rivers in the world. It also carries an enormous amount of silt as suspended load which is estimated at around 1,000 million ton per year. Yet the delta of the Amazon is not advancing into the sea. The explanation is found in the existence of the Equatorial Current which deflects the silt-laden flow to the northwest along the Atlantic coast; deposition takes place in the coastal zone of Amapá and up to the Guianas. As a result the area of recent alluvial deposits ('várzea') is relatively small: some 25,000 km^2 including the Amapá deposits. The total delta area (downstream from the Xingú river) may be some 100,000 km^2, but most of this area consists of 'terra firme' formed in a fresh-water environment in the early Pleistocene. Unlike the alluvial areas the 'terra firme' is not exposed to flooding.

The Rio Magdalena provides an example of another large river with a considerable sediment load, but without a delta which is still being built out further into the sea. Here the explanation is found in the existence of a large zone (20,000 km^2) of tectonic subsidence just before the river reaches the sea. In this zone, which forms a sort of inland delta, sedimentation takes place keeping approximately pace with the subsidence. The area also acts as a natural flood-detention reservoir so that the flood peaks downstream from the area are lower than upstream. There are typical delta formations in the area with numerous creeks between natural levees encircling small lakes and waterlogged lands ('cienagas'). Complete embanking of this area would cause a complete upset of the hydrology and morphology of the downstream river reach.

Table II
Water supply and demand in some East-Asian deltas.

	Mean		
	annual rain	monsoon rain	crop requirement
Chao Phya delta	1500	1000	1400
Irrawaddy delta	2200	1600	1400
Mekong delta	2000	1500	1400

The deltas of the Atlantic coast of South America are – in general – not exposed to significant storm surges. There is, however, an important local set-up of the sea level in the shallow gulf of the Rio de la Plata during southeastern winds so that the delta of the Paraná, inside the gulf, is occasionally exposed to storm-surge levels of 2-3 m above high tide.

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