Characteristics of the water flow inside the Danube Delta

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SUMMARY: The hydrologic regime of the Danube Delta presents some characteristics which have required an original method of investigation.

Because of their close inter-relation, the morphological aspects have to be considered as parts of the same organic whole. It follows, that the morphohydrographic elements can be divided into two distinct categories: 1) positive elements (soils of predeltaic origin, river and maritime ridges) and 2) negative elements (the hydrographical network and the depressions inside the delta).

The depressions inside the delta play an important part as an accumulation basin in the water circulation system between the arms and the interior of the delta.

Dependent on the volume of water brought by the Danube, the interior of the delta between the arms is divided into subdepressions during the low water period and depressions during the medium water period.

The water flow regime in the delta is determined by the variations of the Danube discharges at Ceatal Izmail together with the influence of the Black Sea levels and water accumulation inside the delta.

The principal water courses are presented in the paper, namely:

1. The main arms;
2. The connecting channels between the arms and the inside of the delta;
3. The connecting channels between the arms and the outside of the delta;
4. The connecting channels between the inside zones and the sea.

Further, the peculiar aspects of the water flow are presented from the quantitative point of view. Both the variation connected with the Danube discharges and the variation of the distribution coefficients of the discharges flowing through the main arms have been determined.

These discharges on their way to the sea are modified by water storage inside the delta, by the rate of increase of the water levels and by the duration of high waters. This result has been plotted as a diagram showing the differences between the discharges at the branching point and at the mouth of the arms, on the one hand, and the discharges at the apex of the delta, on the other hand.

The water flow between the arms and the exterior of the delta has been determined taking into account both the discharge variation at the starting point of the channels and the variation of the levels at their mouths. The channel flow between the Danube arms and the interior of the delta is determined considering the discharges and the levels at both ends of the channels.

Variations of the volumes accumulated yearly inside the delta are also determined.

The second part of the paper deals with the problem of flooding. The problem is tackled by determining the complex relationships between the levels of the arms and those of the delta inside. These relationships also take into account a coefficient which expresses the increasing and decreasing gradients of the levels.

Finally, using a map of flood extent, the variation curve of the delta flooded surface, conditioned by the discharges flowing through the arms, was determined.

The paper ends with some conclusions on the methodology to be applied for the next stage of the delta hydrology investigation, insisting on the necessity for hydrometric activity under a special programme different from the classical one, both in the laboratories and in the field so as to agree with the particular aspects of the water flow shown in the present paper.

RÉSUMÉ : Les particularités du régime hydrologique du delta du Danube ont imposé une méthode originale de recherches. L'interpénétration des aspects morphologiques est si forte qu'on doit les considérer comme des facettes d'un même ensemble.

Les éléments morphohydrographiques peuvent être repartis en deux catégories distinctes : 1) positifs (les restes des terrains prédeltaïques, bancs de sable le long des berges et des côtes) et 2) négatifs (réseau hydrographique et dépressions à l'intérieur du delta).

Les dépressions de l'intérieur du delta jouent le rôle important de réservoir d'accumulation dans la circulation de l'eau entre les bras et l'intérieur.
En fonction de l’apport de l’eau du Danube, l’intérieur du delta entre les bras se divise à mesure de la décroissance de cet apport, formant des sous-dépressions au cours de la période des basses eaux, et des dépressions au cours des débits moyens du Danube.

Le régime de l’écoulement des eaux dans le delta est conditionné par la variation des débits du Danube à Cetatea Izmail et est influencé aussi par les variations des niveaux de la mer Noire ainsi que par les accumulations d’eau à l’intérieur du delta.

Dans la communication sont décrites les principales voies d’écoulement des eaux :
1. Les bras principaux ;
2. Les canaux de liaison entre les bras et l’intérieur du delta ;
3. Les canaux de liaison entre les bras et l’extérieur du delta ;
4. Les canaux de liaison entre les zones intérieures et la mer.

Ensuite on présente les solutions quantitatives des problèmes particuliers de l’écoulement des eaux par le delta. On a déterminé la variation, avec le débit du Danube et dans le temps, des coefficients de répartition des débits écoulés par les bras principaux.

Les débits des bras varient le long du parcours jusqu’à la mer, sous l’influence de l’état des accumulations de l’intérieur du delta, les gradients de hausse des niveaux de l’eau, la durée des basses eaux. Ce fait est illustré par une corrélation graphique de la différence entre les débits à l’origine et à l’embouchure d’un bras et les débits au sommet du delta.

L’écoulement des eaux par les canaux entre les bras et l’extérieur du delta a été déterminé en tenant compte de la variation des débits à l’origine des canaux ainsi que de la variation des niveaux de l’élément aquatique à l’embouchure des canaux.

L’écoulement des eaux par les canaux entre les bras du Danube et l’intérieur du delta est déterminé en utilisant la corrélation entre les débits et les niveaux aux deux extrémités des canaux.

On détermine ensuite la variation des volumes d’eau accumulés chaque année à l’intérieur du delta.

Dans la seconde partie de la communication on traite le problème des inondations du delta. Le problème est abordé en partant de la détermination des liaisons complexes entre les niveaux des eaux dans les bras et ceux de l’intérieur du delta. On utilise un coefficient exprimant les gradients de hausse et de baisse des niveaux sur les bras principaux.

Enfin, à l’aide d’une carte des inondations on a déterminé la courbe de variation de la surface inondée dans le delta en fonction des débits écoulés par les bras.

Dans la dernière partie de la communication on exprime la méthode d’étude hydrologique du delta pour l’étape suivante et on insiste sur le fait que l’activité hydrométrique aux stations et par expéditions doit avoir un programme différent du classique, conformément aux aspects particuliers de l’écoulement des eaux, aspects examinés au cours de la communication.

The hydrologic regime of the Danube delta shows certain characteristics that require an original method of research. Firstly the morphohydrographical factors which affect the characteristics of the flow will be pointed out. Secondly the more complex problem of the water flow over the entire area of the Danube delta is considered as well as flooding caused by water flow variations in space and time.

Some conclusions are drawn in the last part of the paper concerning the methodology of the hydrological study of the Danube delta for the future.

I. MORPHOHYDROGRAPHICAL FACTORS WHICH AFFECT WATER FLOW

(a) GEOGRAPHICAL POSITION AND THE BOUNDARIES OF THE DANUBE DELTA

The Danube River after collecting the waters from a watershed of some 800,000 km² flows into the Black Sea through three main arms; these arms and the space within them form the Danube delta. The Danube delta lies between the parallels 46°42' and 44°21' latitude north and the meridians 28°14' and 29°46' longitude east.
The steep bank of the northern boundary of the Danube delta separates the great zone of the lakes of Ialpug, Catelpug and Chitai from the plateau of Buceag. The southern boundary separates the southern area belonging to the Sf. Gheorghe arm and the lake-complex Razelm-Sinoe from the plateau of North Dobrogea. The East boundary is the sea coast from Primorskoe to the Gura Bubaz and the West one crosses the branching point of the Danube river called Ceatal Izmail.

Between the above-mentioned boundaries the Danube delta (including the peripheral lacustrine zone) extends to 5,640 km\(^2\), coming thus second in Europe in size (next to the Volga delta which extends to 10,000 km\(^2\) and followed by the Po delta (1,500 km\(^2\)).

(b) THE MORPHOHYDROGRAPHICAL ELEMENTS

The morphological elements are so closely interrelated with the hydrographical ones that a strict delimitation between them is impracticable. Hence morphology and hydrography must be studied as components of the same unit. The Danube delta is a real inlay of morphohydrographical elements which can be divided into positive and negative elements.

1. The positive morphohydrographical elements are:

- The predeltaic ground remnants or the traces of past, among which the most important are the Chilia ridge (separated from the Buceag plateau) and the Stipoe ridge which has been covered mostly by river sediments in more recent times;
- River ridges, placed longitudinally on both sides of the main arms of the channels, canals and ox-bows, which are the result of a long history of accumulation caused by high water levels.
- Maritime ridges which are in fact, old raised beaches, as for example the ridges Letea, Caraorman, Sărăturile, etc.

2. Negative morphohydrographical elements are:

- The hydrographical network;
- The depressions inside the delta.

The hydrographical network consists of the main arms and, inside the delta, of the connecting canals and channels between arms, lakes and ox-bows. The estuaries and the lagoons may also be considered as elements of the hydrographical network.

The depressions are the most characteristic morphohydrographical element of the Danube delta. They arise from the river and marine-river ridges acting like dams partitioning the entire surface of the delta within the arms. Their different altitude divides the delta in sunken areas, the more numerous and less extended, the lower the general water level. The water penetrating through canals and channels submerges the lowest zones thus disclosing many sub-regions. As the water level rises in the Danube arms the water invades larger and larger areas, which remain nevertheless separated by the higher inside ridges.

When water completely overflows the ridges, the surface of the delta lies almost entirely under water except the heights of the Chilia ridge and, partially, the Letea and Caraorman. During the decrease of the water level, the process described above is reversed.

The morphohydrographical elements mentioned are grouped in subzones with distinct, specific characteristics, each of these subzones being divided into smaller units. This has led to the idea of a physiographic zoning of the delta by taking into account the significant features of each zone and subzone.

The physiographic conditions of the Danube delta are highly differentiated from the surrounding regions and require an original method for investigating the hydrological
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regime. This regime depends on variations on discharge at the branching-point, Cetatal Izmail, the so-called delta apex.

Two other important factors which influence the hydrologic regime are:
— The variation of the Black Sea hydrological elements in time and space;
— The territory lying between the Danube main arms, which acts like a huge reservoir.

II. THE COMPLEX PHENOMENON OF THE WATER FLOW OVER THE ENTIRE AREA OF THE DANUBE DELTA

1. General

The determining factor for water flow in the delta is obviously the amount of water of the Danube at the delta apex.

The waters once in the delta flow towards the sea through the main channels: the Chilia and Tulcea arms, the latter branching after several miles into Sulina and Sf. Gheorghe arms. Between these principal arms and the inside of the delta, the water flows through many connecting ways which form the natural accumulation basin of the Danube delta and of some external areas (the lacustral complexes North and South the delta). Studying the complex through the delta it is possible to distinguish three main types of water connecting ways.

— Connecting ways between the arms and the inside of the delta, through which water penetrates as the level rises and retreats as the level falls. Therefore, water is circulating in these channels in both directions depending on the level differences at their extremities.
— Connecting ways between the arms and the external area, which generally are unidirectional flows, from the delta to the outside, because the basic level where they discharge is almost always lower than that of the delta.
— Connecting ways between the inside and outside zones and the sea, through which the waters generally flow into the sea.

This short description shows that the water flow regime through the delta depends on the discharge regime at the delta apex and on the regulating effect of the Danube delta interior, acting like an accumulating basin.

Further, some of these more particular problems together with the way of solving them will be presented.

2. DISTRIBUTION OF THE DANUBE DISCHARGE AMONG THE MAIN ARMS OF THE DANUBE DELTA AND ITS VARIATION IN TIME

As a method of plotting the distribution of discharges through the main arms a comparative analysis was made of discharges gauged at a frequency very close to the time lag, thus achieving a relative simultaneity.

The following relations have been determined on the basis of the correlations between discharges measured relatively simultaneously:

\[ \alpha = \frac{Q_{\text{Chilia}}}{Q_{\text{Danube}}} \quad \alpha' = \frac{Q_{\text{Tulcea}}}{Q_{\text{Danube}}} \quad \beta = \frac{Q_{\text{Sulina}}}{Q_{\text{Danube}}} \quad \gamma = \frac{Q_{\text{Sf. Gheorghe}}}{Q_{\text{Danube}}} \]

and also of the ratios.
2) \[ m = \frac{Q_{\text{Sulina}}}{Q_{\text{Tulcea}}} \quad \text{and} \quad m' = \frac{Q_{\text{Sf. Gheorghe}}}{Q_{\text{Danube}}} \]

Between these ratio coefficients there are the relationships:
\[ \alpha + \alpha' = \alpha + \beta + \gamma = 1 \quad \text{and} \quad m + m' = 1. \]

These ratios have no constant values but they depend on the Danube river discharges. Figure 1 shows the variation diagrams of the relations \( \alpha, \alpha', m, m' \) for the period 1928-1929 as a function of the Danube discharge.

\[\text{FIGURE 1. The variation with the Danube discharges at the delta apex of the percentages } \alpha, \alpha', (a), m \text{ and } m' (b) \text{ during the period 1928-1929.}\]
The variation of the relations as functions of the Danube discharges is a clue to the flow conditions of the arms. Thus, when for a certain arm the percentage of the total discharge increases in low-water periods, this indicates that the flow conditions, as a whole, are good and flow is not prevented by sand banks or bars, etc. When the percentage from the total discharge diminishes in low-water periods the flow conditions are generally unfavourable.

For the years 1928-1929 good flow conditions were reported for the arms Chilia and Sulina and unfavourable for the Sf. Gheorghe and Tulcea ones.

Variations in time of the Danube discharge distribution among the main delta arms are explained by the variation of the flow conditions as a whole, influenced by their natural developments and by man.

Measurements effected since 1856 have enabled the plotting of the chronological variation of these relations, considered for the mean discharge of the Danube river, as illustrated in figure 2.

This figure shows that over the 100 years of records essential changes occurred in the variation of the Danube discharge distribution among the delta arms at about the year 1900, and certainly between 1890 and 1910. Now important works were carried out to

![Figure 2](image-url)

**Figure 2.** Variation from 1850 to 1960 for low levels of the Danube of the percentages $\alpha$, $\alpha'$, $\beta$, $\gamma$, ($a$) and $m$ and $m'$ ($b$).
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improve navigation on the Sulina canal between 1880-1902, these consisted of corrections and trainings of the arm course along 31 km, thus shortening its original length by 25%. This improvement of the flow conditions on the Sulina arm, since 1880, have played a decision part in the variation in time of the Danube discharge distribution among the delta arms.

From 1850 to the present, the Chilia arm had the largest discharge (approximately 70%) round the year 1900 and in the same period the Tulcea arm had obviously the lowest (approximately 30%).

The discharge through the Sulina arm was fairly constant (approximately 7%) until about 1900 when its discharge has continuously increased (approx. 12% in 1921, to 17% in 1960).

The discharge through the Sf. Gheorghe arm diminished continuously between 1850 and 1900 (from approx. 30% to approx. 20%) to become almost constant from 1900 up to the present (approx. 20%). Studying the distribution of the Tulcea arm discharge between Sulina and Sf. Gheorghe arms from 1850 to the present it can be stated that up to 1890 the Sulina arm received a relatively constant percentage of the Tulcea arm discharge (some 20%) which permanently increased until it reached the present value (approx. 45%).

The data show a diminishing of the Chilia arm discharge as a result of the increased discharge of the Sulina arm which influenced both the Tulcea and Sf. Gheorghe arms, the latter obviously having natural tendency to reduce its activity.

3. WATER FLOW ALONG THE ARMS BETWEEN THE APEX OF THE DANUBE DELTA AND THE BLACK SEA

The water flow from the delta apex to the sea has been studied taking into account the water changes between the arms and the inside of the delta.

During periods of rising water each arm comes part of the total discharge of the Danube. However each discharge is modified along the arms and diminishes because of water losses occurring in the connecting ways between the arms and inside the delta as well as on the ridge lines when they are flooded. The volume of lost is a complex function dependent, for a given morphohydrographical situation, on several factors.

These are: the situation inside the delta, previous to the beginning of high waters, the gradients of use in water level, the maximum level recorded, the duration of high levels, etc. A balanced state occurs at a certain moment, when the river waters begin to fall and the flow process between the river arms and the inside of the delta reverses, flowing from the inside towards the arms. This moment does not usually occur when the waters reach the peak flood but when the levels between the Danube and the inside of the delta are balanced. From that moment the Danube discharges from each arm increase gradually along the mouth. Variation of the discharge along the river arm is shown by the connecting diagram between the Sulina arm discharge at the branching point and mouth ($\Delta Q$) and the Danube discharges ($Q_D$) at the delta apex (fig. 3).

This diagram demonstrates that for floods with notably high gradients of the rising and falling levels, the magnitude of the water discharge variation depends on the Danube discharge (for the studied case, the year 1958). Under different actual hydrological conditions in the delta it has been found that for the same peak discharges the variations differ greatly.


Among the secondary ways of water flow to the sea, the Sf. Gheorghe arm and the lake complex Razelm-Sinoe play a specially important part. Through these canals with
considerable discharges, the lakes receive a permanent supply of fresh water which accounts for their piscicultural importance.

The canals, which in present are branching from the Sf. Gheorghe arm towards the Razelm, from up to downstream, are: Girla Lipovenilor, Dunavăt, Dranov, Crasnicol and Palade.

![Diagram showing the correlation between differences of the discharges of the Sulina canal on the reach Ceatal-Sf. Gheorghe and the mouth (ΔQ) and the Danube discharges (Q_D) at the delta apex.](image)

**Figure 3.** Relation between differences of the discharges of the Sulina canal on the reach Ceatal-Sf. Gheorghe and the mouth (ΔQ) and the Danube discharges (Q_D) at the delta apex.

The Dunavăt and Dranov canals which are the most important for the amount of water they can carry, have a direct connection with the Razelm lake, and the canals Crasnicol, Girla Lipovenilor and Palade are connected with the Razelm through the southern peripheral zone.

It is to be pointed out that by these five canals only a part of the total discharge received from the Sf. Gheorghe arm reaches the Razelm lake. Another part supplies, by way of secondary canals, the inside of the Dranov depression. A third part returns into the Sf. Gheorghe arm from the inside of the depression when the water level on this arm falls very low. An important part in supplying the arm with water from the inside is played by the canals Crasnicol and Palade, the flow from the inside towards the arm on the Dunavăt, Dranov and Girla Lipovenilor being very infrequent.

To determine the discharge on the main canals, relatively simultaneous discharge measurements have been used which helped to establish the correlation, the diagram of which is shown in figure 4.

The correlation indicates the relative equality of Dranov and Dunavăt canals at their branching from Sf. Gheorghe arm. Correlations \( b \) and \( a \) show that when the Dunavăt is taking from Sf. Gheorghe a discharge of over 10 m\(^3\)/s and the Dranov more than 6 m\(^3\)/s,
the discharges at the start of the canals are larger than at their outfall into the Razelm lake. When discharges are below these values, the Dranov depression supplies the canals with water, the discharges of which are larger at their outfall into the lake than at their branching point from the arm. In order to determine the discharges of the Gîrla Lipovenilor and Crasnical canals correlations have been established between the discharges of the Dunavăt and Dranov canals. These correlations show that the discharges of the Gîrla Lipovenilor are from 0.27 to 0.23 of the Dunavăt discharges and those of the Crasinicol range from 0.30 to 0.40 of the Dranov discharges when the latter is over 20 m³/s.

![Figure 4](image-url)

**Figure 4. Correlations of water discharges measured relatively simultaneously on the Dunavăt and Dranov canals**

a. Dunavăt at the origin — Dranov at the origin;
b. Dunavăt at the origin — Dunavăt at the mouth;
c. Dranov at the origin — Dranov at the mouth;
d. Dunavăt at the mouth — Dranov at the mouth.

The rating curve having been determined for the branching point of the Dunavăt canal, the discharges of all the canals have been computed using the above mentioned correlations. The results given as mean yearly discharges are shown in the table below.
TABLE 1. Variation of the water discharge along the Dunavăț and Dranov in m³/s (1959-1961)

<table>
<thead>
<tr>
<th>Danube discharge at the delta apex</th>
<th>3,000</th>
<th>6,300</th>
<th>10,600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of the canal discharges at the branching point</td>
<td>11.6</td>
<td>46</td>
<td>100</td>
</tr>
<tr>
<td>Sum of the canal discharges at the mouths</td>
<td>13.0</td>
<td>32.5</td>
<td>-13.5</td>
</tr>
<tr>
<td>Differences</td>
<td>+1.4</td>
<td>-13.5</td>
<td>-36</td>
</tr>
</tbody>
</table>

5. WATER FLOW THROUGH THE CANALS LYING BETWEEN THE DANUBE RIVER ARMS AND THE INSIDE OF THE DELTA

Begun in 1959 the measurements of discharges of the main canals which connect the Danube arms with the inside of the delta have aimed at elucidation of two problems: firstly to show that water flow inside the delta depends both on the Danube regime phase at the delta apex and on the given hydrological state and secondly to determine quantitatively the water volumes entering the delta depressions and their return into the Danube arms.

The assumptions previously mentioned have been confirmed by the results obtained by the hydrological expeditions begun in 1959.

The problem of determining the discharges through the canals lying between the arms and the delta inside has been solved taking into account the characteristics of the water flow on these canals. Water flow in both directions is a function of the water levels at the extremities of the canals (at the arms and the inside of the delta) the rating curves being in this case different from the usual ones. Figure 5 illustrates one of these correlations for the Periteașca canal.

![Relation Q/MAH = f (H) for the Periteașca channel: 1. The flow from the arm towards the inside of the delta. 2. The flow from the inside towards the arm.](image)

Another method to determine the discharges of the canals which connect the Danube arms with the inside of the delta is to establish a relation between discharges and levels recorded at the canals' extremities \((H_1, H_2)\). Such a family of curves \(Q = f(H_1, H_2)\) is shown in figure 6.

Between 1967 and 1968 daily measurements of the discharges have been effected on the majority of the canals connecting Danube arms and the inside of the delta, by means of floats which permitted (under good stability of the bed conditions of the canals) calculation of the daily values of the discharges in both directions.

Figure 7 shows a complex diagram which includes the flow direction as well as the daily variation of the discharges.
Figure 6. Relation $Q = f(H_1, H_2)$ for the Eracle canal: $Q_1$ the flow from the inside towards the arm; $Q_2$ the flow from the arm towards the inside of the delta.
Figure 7. Daily variation of discharges and flow direction in the Eracle canal during 1968: 1. The flow from the arm towards the inside of the delta; 2. The flow from the inside of the delta towards the arm; 3. Stagnant water.
6. **Water Flow Through the Inside of the Delta**

Water flow through the inside of the delta, between the different depressions as well as inside the same depression, occurs mainly on the inside canals, channels and ox-bows. For very high-waters, when the flow inside the delta is increased considerably not only between the several depressions and inside the same depression, but also through the swampy area; it may have the most varied directions, depending on the variations of the water surface slopes (closely connected with the stage of the Danube), on the way of water penetration from the arms into the inside of the delta and on the wind action, etc., under given morpho-hydrographical conditions.

In the study of the water flow in the canals, inside the delta, the same methods were applied as in the case of canals and channels between arms and the inside of the delta.

The problem has been solved since 1967, when the curves of the daily variation of discharges through these canals, as well as the water flow direction have been determined, based on daily stage measurements by floats.

The water flow through the delta swamp has been studied by special field measurements which have resulted in determining some of the roughness coefficients values of Pavlov-schi's formula, ranging between 0.19 and 0.26. The conclusion was that this coefficient varies with the density of the bog-reed (number of plants per unit surface), with the percentage of reed cover and with the stage of vegetation development. These studies, begun in 1960, are still in progress.

7. **Water Volumes Inside the Delta**

A through knowledge of the problems connected with the water volumes of the delta as a whole are of the greatest importance both for explaining the complex phenomenon of the Danube delta flow through the delta and for achieving a better, multi-purpose use of this sector of the Danube.

Considering the delta as a unit, its interior, namely the space between the Chilia, Tulcea, and Sf. Gheorghe arms and the sea, has a great volumetric capacity. For this region an approximate relationship has been established between the accumulated water volumes and the respective levels at the Tulcea gauging station. This relation permits approximate computation of the water volumes accumulated inside the delta from each autumn minimum until the next spring-summer maximum, considered as yearly maxima and minima.

Processing of these values despite their approximate character permits some conclusions.

The water volume accumulated yearly inside the delta has a mean value of some 2,230 millions m$^3$. During the last 40 years the greatest volumes were reached in 1939-1940 (approx. 4,330 millions m$^3$/an).

In 1941-1942 (some 3,830 millions m$^3$/an); in 1936-1937 (some 3,710 millions m$^3$/an) etc., and the lowest volumes in 1948-1949 (approx. 940 millions m$^3$/an), in 1930-1931 (approx. 1,080 millions m$^3$/an), in 1920-1921 (approx. 1,105 millions m$^3$/an), etc. The ratio between the largest and smallest volume accumulated in a year inside the delta for the last 40 years has the value of approximately 4.6.

### III. Flooding Process Problem

1. **General**

A first characteristic of the flooding process is that, for the same water level of the Danube, the flooding of the existing depressions differs because of their different hydrological regime. A second character is that under given hydrological conditions the delta flooding
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varies with each phase of the hydrological regime (increasing or decreasing) for the same level of the arms. These two characteristics hold good for a given hydrological situation.

The problem is more complex when solutions are requested for different floods, which reach different maximum levels and have also different rates of increase or decrease in level. The characteristics of each flood determine different supply routes to the delta interior, which lead to different patterns of flooding from one actual hydrological situation to another. Thus, because of the small relief energy and the characteristics of each flood flow regime the flooding process on the entire delta becomes exceptionally complex.

The first problem to be solved was the selection of the most appropriate flood for study. Studies effected have shown that from the hydrological point of view the year 1958 may be considered as a mean year and taking into account also that for this year hydrological data on the level inside the delta had been gathered, year 1958 has been selected as the year for calculating the mean flood.

A second problem is to determine the level variation inside the delta when the Danube levels variation at the delta apex are known. This problem may be solved by determining the regression relationship between levels in the arms and in the delta inside. They present some peculiarities due to the specific flow of the water between arms and canals, as mentioned above.

2. CHARACTERISTICS OF THE LEVEL CORRELATION BETWEEN THE MAIN ARMS AND THE DELTA INSIDE

The relationship between the levels examined simultaneously at the gauging stations on the main arms and inside the delta has shown that generally there is no unique correlation between the daily simultaneous levels inside the delta and those on the main arms, because of the compensating effect of flow between the arms.

This necessitated a search for correlations between the maximum and minimum values of stage corresponding to the moment of the beginning and the end of the regime stages. The points plotted on the graphs are not too scattered and display a certain consistency concerning their shape, as shown in figure 8 which illustrates the correlation between the level at a gauging station on one of the main arms (Uzlina-Danube) and at a gauging station inside the delta (Uzlina-lake).

It was noted that for a rise in level corresponding to the overflowing of the river ridges the shape of the correlation changes. This means that a rising of the level on the arms higher than the river ridges sometimes corresponds to a much higher rising of the level inside the delta than below this limit. The correlation approaches the line of 45° in levels, when the water levels on the arms balance those of inside the delta.

Correlations between the levels at different points inside the delta have been further established provided these points are situated inside the same depression.

The method permits only the characteristic values of the levels within the same depression to be obtained. Intermediate values may be obtained using the following method: hydrographs of the main arms levels and the corresponding hydrographs at a gauging station inside the delta are selected for the same periods. Correlations of the instantaneous levels are drawn.

\[ H_{\text{inside}} = f(H_{\text{arms}}) \]  

for a filling and emptying cycle of the delta inside. The correlation between the daily values of the levels at the Chilia Noua and Stipoc-Dam stations (fig. 9) shows that there is no single curve between the pairs of values but a loop with two distinct branches, one for the filling phase of the delta inside and the other for the emptying phase.

That means that in a given hydrological situation a single level on the Danube can correspond to two values of the levels of the inside. In another hydrological situation
Figure 8. Correlation of characteristic levels recorded at a gauging station on one of the main arms and at a gauging placed inside the delta.
for the same level on the Danube will correspond another pair of values of the inside as shown in figure 9 where three cycles of filling-emptying and their loops of correlation are shown. For each cycle, for a given level of one of the arms, two values of the level at a gauging station inside the delta correspond, \( H \) falling and \( H \) rising.

The difference between these levels, corresponding to a single level on the arms, is written:

\[
\Delta h = H_{\text{falling}} - H_{\text{rising}}
\]  \( \text{(5)} \)

This value \( \Delta h \) is correlated to the level on the Danube and it results in the diagram of figure 9.

**Figure 9.** Scheme of computation of daily levels inside the delta.
It was noticed that the variation of the value $dh$ depends greatly on a given development of the cycle, which is function of the rising and falling level gradients on the arms, for the studied periods.

In order to introduce this factor an empirical coefficient $\alpha$ was used. This coefficient characterizes the way the rising and falling velocities of the water levels (in cm/day) contribute to the phenomenon.

It is defined as the geometric mean of the velocities of rising and falling for each cycle.

$$\alpha = \sqrt{\frac{\text{rising arms}}{\text{falling arms}}}$$

(6)

It results in the value $dh$, as shown in figure 9, being a function of two variables, thus:

$$dh = f(H_{\text{arms}}, \alpha).$$

(7)

Based on relation (5) and (6) the levels inside the delta can be established when the levels on the arms are known. By way of example let us take the diagram 9 which illustrates the hydrograph of an arm on a long period of time $T$ and the corresponding hydrograph of a gauging station inside the delta for the period $T'$. It is clear that $T > T'$.

Point $A$ on the curve $H_{\text{Danube}}$ corresponds to a certain point $B$ on the curve $H_{\text{inside}}$ which is the second term of the relation (5) namely $H_{\text{inside}}^{rising}$.

Again, in a falling period on the Danube, level (point $A$) corresponds for the rising period to level $C$. From knowing the value of $\alpha$ corresponding to the period $T$ as well as the value of the Danube level corresponding to point $C$, the diagram shows:

$$H_{\text{inside}}^{rising} = H_{\text{inside}}^{falling} + dh.$$  

(8)

Thus, a series of intermediary values are obtained for the hydrograph of a gauging station inside the delta ranging from the maximum characteristic values to the minimum ones.

The method applied for data obtained at Chilia Nouă and Stipoe station gave satisfactory results.

![Figure 10. Relation between the flooded surface inside the delta and the levels at the Tulcea station.](image-url)
Once the above mentioned correlations were determined the second step was to draw up the delta flooding map, in the form of isolines of inundation, each one of them corresponding to a certain level recorded at the Tulcea station.

Planimetry applied to the flooded surfaces helped to determine the connecting curve between the flooded surface and the water level at Tulcea station (fig. 10).

Conclusions drawn after examining this map together with the graph in figure 10 are:

- Considerable flooding is manifest even at a 3 hydrograde level, especially for the downstream depressions of the Danube Delta.
- At 8 hydrograde only some 7.3% of the delta total surface remains unflooded, namely the highest ridges (Chilia, Letea, Caraorman and Sârâturile).
- Flooding over hydrograde 3 in the delta lasts from two to ten or eleven months (in 1921, 1926 and 1940, respectively). At the same time, flooding caused by high water levels in the Danube River floods occur sometimes for short periods near the outfall due to the rising of the sea level in heavy storm-weather.

The considerations expressed above lead to some conclusions as far as the methodology of the hydrological study of the Danube Delta for the further research period is concerned.

- Periodic aerial surveys at long intervals of the delta interior (10-20 years) and more frequently of the main arms, including also the branching points, the mouths and the main canals are necessary for a knowledge of the morphohydrographic evolution which occurs extremely fast in certain zones and accounts for the changes in the water flow spectrum through the delta.
- The permanent hydrometric network which is now relatively well developed on the main arms has also to be developed both on the main canals and in the inside of the delta.
- The gauging stations on the canals have to permit recording of level differences at both ends. The main task of the regular stations inside the delta is to assure the knowledge of the rhythm of filling and emptying of this accumulation basin which in fact the delta represents. Variations due both to the wind and to the sea level influence the delta as a whole so that automatic recorders should be set up at the hydrometric stations.
- The purpose of the permanent hydrographic network in the Danube delta is to permit computation of the volume of water in the delta and to learn its evolution, and its partition among the different units of the delta.
- The water discharge measurements intended to elucidate the complex problem of water circulation between the delta apex and the sea are to be effected in a specific manner. Thus, at the branching points of the main arms and canals, measurements are to be effected simultaneously, that being the best way for knowing the discharge distribution, the variation with the upstream discharge and with time. Measurements along arms and canals should be carried out from up stream towards downstream at regular intervals, corresponding to the time-lag. This procedure is required also by the necessity of comparison. There are also to be mentioned those situations in which it is necessary to undertake measurements of simultaneous or relatively simultaneous discharges in more points placed on the canals which connect the neighbouring zones.
- The study of the water flow from the delta apex towards the sea is supplied with most useful data by simultaneous surveys concerning the water flow direction, the so-called "maps of the flow spectrum". Such maps have been prepared by several teams of researchers working in the whole of the delta area.
- An improvement in this direction is to use more efficient methods (airphotography). It is also to be mentioned that for the study of the water circulation between the delta apex and the sea a systematic analysis of the physico-chemical properties has not been carried out so far. In this direction it is recommended that an efficient method as well as be adopted a convenient programme.

In conclusion, the necessity of assuring a continuity in the research activity of the complex hydrological problems of the Danube Delta should be pointed out.
DISCUSSION

I. Questions de M. Semenescu :

Je prie Monsieur Spătaru de bien vouloir éclaircir les questions suivantes :
1. Quelle sera l'augmentation de la profondeur à l'embouchure de Sulina en utilisant la solution proposée en tenant compte qu'à présent la profondeur garantie est de 7,32 m ?
2. Si l'orientation plus au nord de l'embouchure proposée ne sera pas mal influencée par les vents du nord et le débit solide apporté par les bras Chilia ?
3. L'actuelle solution utilisée depuis 50 ans pour assurer la navigation maritime à Sulina a permis de combiner le prolongement des jetées avec les dragages. La solution en fourchette proposée sera-t-elle aussi élastique que celle actuelle ?

Réponse de M. Spătaru :

Je dois préciser que les résultats que j'ai présentés dans la première publication ne sont pas les résultats définitifs dans l'étude entreprise qui concerne le problème complexe de la navigation dans le delta maritime du Danube et aussi plus précisément dans le secteur de l'embouchure de Sulina.

J'ai présenté quelques résultats obtenus sur modèle dans un état d'études qui paraît avoir quelque intérêt du point de vue de la meilleure connaissance du coin d'eau salée et de la structure des courants à l'embouchure du fleuve. Pour cela je ne suis pas en état de donner des réponses définitives pour les questions 1 et 3, concernant des problèmes hydrotechniques encore à étudier.

La direction du chenal navigable qui forme l'objet de la deuxième question est orientée vers l'est et non pas vers le nord.

Other comments :

Last two years a tremendous amount of researches have be done in the field of intrusion of salt water and on the general phenomenon of turbulence caused by the sea. We namely draw the attention on the first place on the problem of the deepening of shipping channels with researches mainly carried out in the Netherlands and on the researches carried out in the USA on distribution of salinity. There is an amount of theories and data available sufficient available sufficient to make a prevision.

Other comments :

I would like to make a comment on the speech of Mr. Spătaru that there is a world wide evidence (and I quite agree with one of the questions made earlier) that the salt wedge is generally very short, certainly on deep rivers and that furthermore the influence of the depth on the salt gradient is very large. Deepening of the shipping channel will have a tremendous effect on the salt penetration.