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Publication n° 39 de l'Association Internationale d'Hydrologie
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Summary

This paper gives a brief description of some aspects of the vertical movements of the water level in rivers due to ice.

1. Normal rise of water level due to an ice sheet

It is a wellknown fact that, when drift ice in a river is frozen up to an ice sheet, this process is accompanied by a sudden rise of the water level of the river (1). The pith of the matter is presented in fig. 1.

This occurs every two to five winters in the Netherlands on the rivers Rhine and Meuse. *Fig. 2 gives some examples.*

During frost the discharge of the rivers is small as a rule. So there is no danger in these elevations. From the magnitude of 2½ à 3 m it can be deduced that the ice cover in cases as shown in fig. 2 is about twice as rough as the bottom of a river.

Now there are three typical complications which deserve our further attention:

1) ice dams

2) sudden rise at the end of an ice period

3) disturbance of the normal discharge distribution among the three Rhine branches.

2. Ice dams

There is a great difference between an ice sheet and an ice dam. An ice sheet is of nearly uniform thickness of about 20 to 40 cm, whereas an ice dam can have a thickness of several meters.

Fig. 3 shows in B an ice sheet of some 35 km of length. Up the river there is a back water curve of 60 km length. The rise of the water above the original level is 3.10 m, i.e. 70% of the depth. From this a reduction of C to 2/3 of the original value can be computed. So the ice sheet must have been rather rough.

Fig. 3 shows in C an ice dam. If we take the same roughness of 2/3 and a length of the dam of 2.5 km, it can be computed that

$$\left(\frac{h_{\text{dam}}}{h_1}\right)^{1^2/_3} \text{ must be } 2^2/_3 \cdot 3/2 \sqrt{\frac{2.5 \text{ km}}{3.60} \cdot \frac{0.40}{2.5 \text{ km}}} = 0.8$$

so $h_{\text{dam}} = 0.9\, h_1$

In this location $h_1 = 5.40$ m and so h_d must be 4.80 m. That is: the cross-section is reduced to 90% of that when the river is open. It is important to remark here that even in a case like this, a closing of the river is altogether out of the question. The original cross-section is almost fully maintained.

The average thickness of the ice cover is meanwhile in this case

$$9.00 - 4.80 = 4.20 \text{ m}$$

so 10 to 20 times the thickness of an ice sheet.

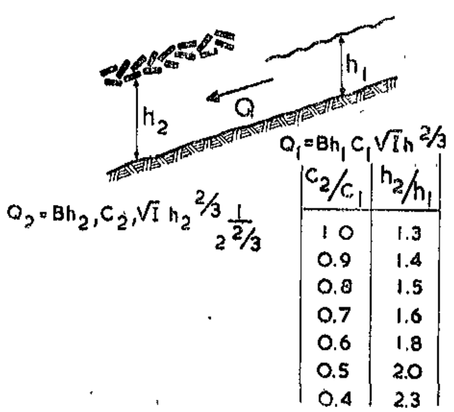


Fig. 1
Principle of the rise of the water level when the ice packs.

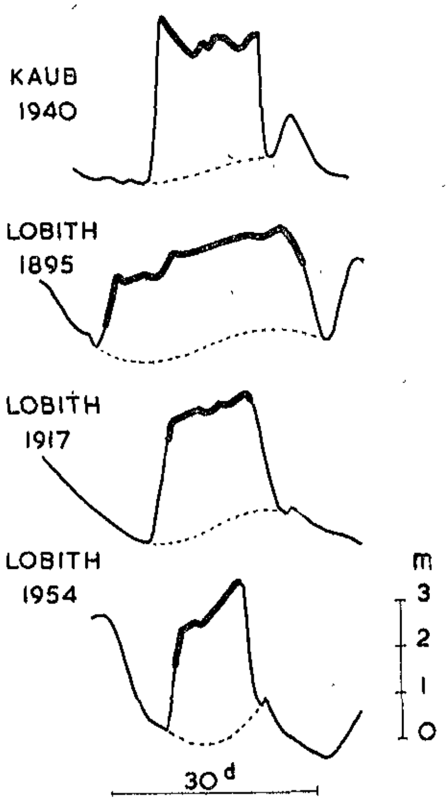


Fig. 2
The elevation of the water level of the river Rhine at Kaub (Lorelei) and Lobith during some periods of ice cover.

Reach of a river, frozen over.

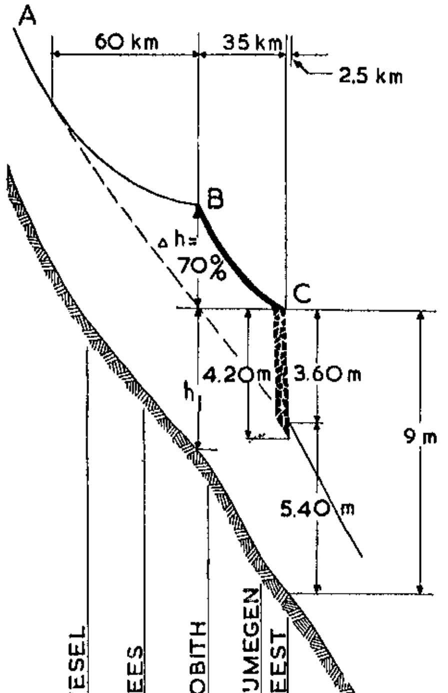


Fig. 3
Ice dam on the Rhine near Deest, 1940.
A = open river;
B = ice sheet;
C = ice dam.

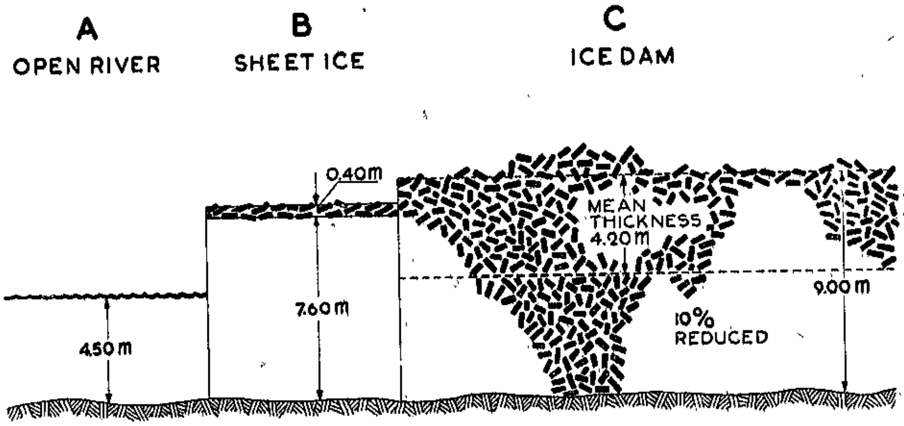


Fig. 4
Ice dam Rhine at Deest February 1947. Schematic cross-section of the 3 phases A, B, C of fig. 3.

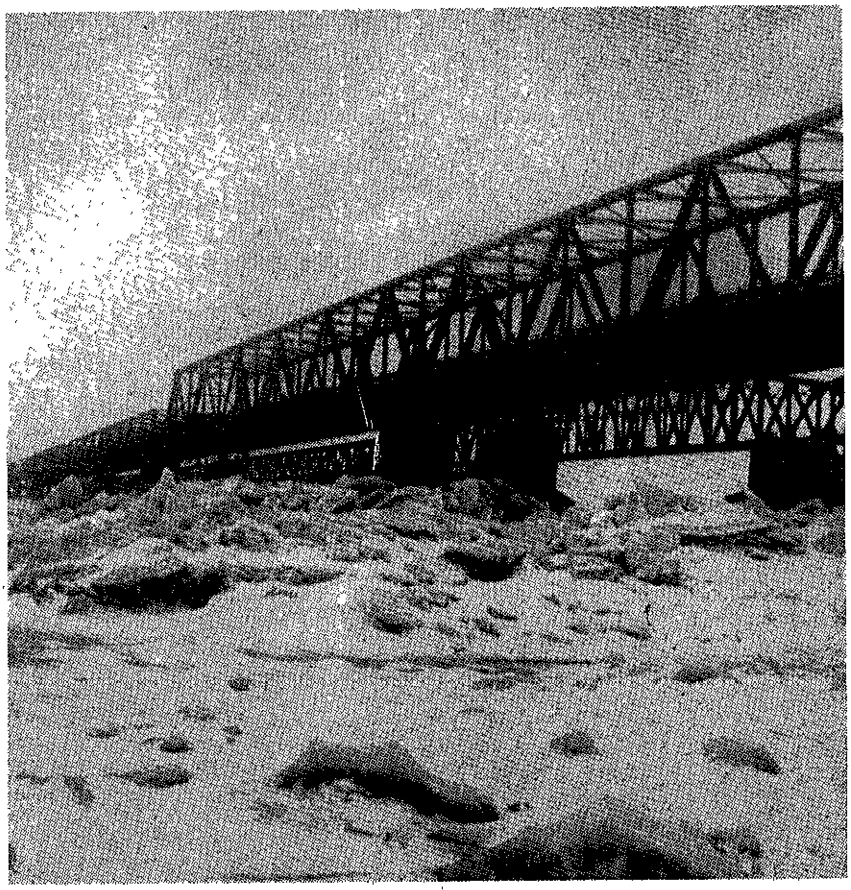


Fig. 5
Ice dam Zaltbommel 1942, downstream the bridges. The height of the ice above the water level is partially 4 m and more.

Fig. 4 illustrates the difference between sheet and dam. A is the free river (phase A) of fig. 3. B represents the sheet ice (phase B) and C represents a cross-section of the ice dam. The mean thickness is 4.20 m. But as easily can be seen in the fields, an ice dam consists of thin and thick parties. It has happened that there were left little ponds of open water amidst a big ice dam soon afterwards frozen over with black ice. So at some areas the thickness is 1 or 2 dm. Consequently at other spots the thickness must be twice as great as the mean, or more than 8 m.

Since at this station the depth of the retained water was 9 m, it is probable that the ice dam reached to the bottom at several places. So the cross-section of an ice dam may have the structure as sketched in fig. 4. From this appears that the highly increased resistance of the river is caused by the very rough and irregular ice mass which rests on the water and partly on the bottom.

In accordance with this topographic structure beneath the surface we find a similar irregularity on the upper side.

As a result of a dam similar to that shown in fig. 5, in 1942 the dammed water piled up to a level 60 cm higher than the highest level ever measured before. It will be clear that this situation is not without danger, for in our country the rivers Rhine and Meuse flow to sea with levels higher than the surrounding regions.

It is impossible to define a limit above which the level of the river cannot be dammed up. Higher levels than have been observed seem to be possible.

This is shown in fig. 6 representing the ice dam near Wesel in 1947, some 50 km upstream the Netherlands-German frontier. The discharge without ice would have given 5 m depth. The total elevation is 5 m.

The length of the ice dam is supposed to be 2 km. The normal fall on this stretch is 0,22 m, but the ice dam caused a fall of 3 m. From this results, with $C_2/C_1 = 1/3$

$$\left(\frac{h_3}{h_1}\right)^{1\,2/3} = 2^{2/3}\frac{C_1}{C_3}\sqrt{\frac{I_1}{I_3}} = 2^{2/3}\,3\sqrt{\frac{0,22}{3,00}} = 1.3$$

$h_3 = 1.2\,h_1 = 6$ m

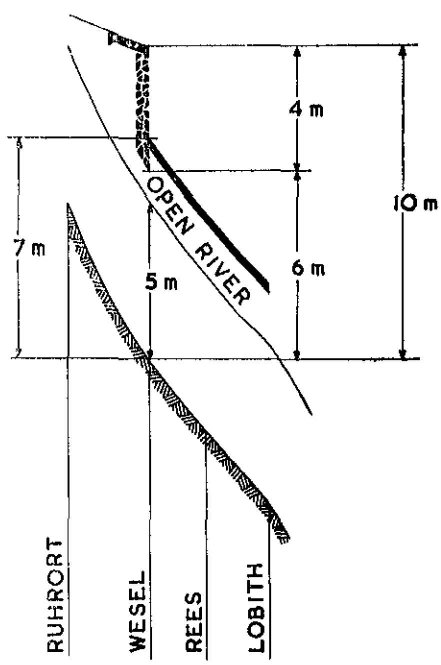


Fig. 6
Ice dam near Wesel, 1947. Mean thickness 4 m.

So the mean thickness of the ice must have been $10 - 6 = 4$ m, that is in the same order of magnitude as the dam of fig. 3. In this case moreover the ice is floating on the river and the original cross-section is not reduced but on the contrary enlarged by 20%.

3. Sudden rise of short duration

Most interesting is the development shown in fig. 7. The period of sheet ice ends in a sudden rise, immediately followed up by sinking back to the level of a free river.

As shown by the curves of Lobith 1917, 1921 and 1933, in all these cases there was no increased discharge at all. This process can be explained in the following way.

At the onset of thaw when warmer water reaches the ice sheet, the latter breasd down and comes into motion. At this very moment the depth of the river is increàsek from h_1 to h_2. Hence the discharge increases for a short time from Q to

$$Q^1 = Bh_2\, C_2\sqrt{I}_h 2/3 = Bh_1 C_1 2/3\sqrt{Ih_1}\ .\ 2^2/_3\,\frac{C_1}{C_2} = 2Q.$$

So the discharge is doubled. This increased discharge begins to run and meets at the same moment the ice sheet downstream still fixed. In order to convey this doubled quantity of water the cross-section under the ice sheet demands enlarging at the rate:

$$\frac{h_3}{h_2}\,1^2/_3 = 2 \ \text{so}\ \ h_3 = 1.5\,h_2$$

Hence the second rise is of the same magnitude as the first one. Immediately after this elevation the ice sheet in the downstream section comes into motion and becomes drift ice too, and so on. After this the surface sinks back to the level of a free river.

This phenomenon can only occur under the following circumstances:

1. the absence of ice dams
2. a constant discharge
3. thaw coming from the east
4. an increasing water temperature.

Only in a few cases these conditions are fulfilled. Not in every ice winter these interesting events can be observed.

4. Disturbed distribution of the discharge among the three Rhine branches

The Rhine, having a catchment area of 160,000 km², can discharge more than 13000 m³/sec. The largest discharge never coincides with ice on the river. Yet once there has been 8000 m³/sec while at the same moment there was still ice on two of the Rhine branches (1941).

Let us take however a discharge of 4000 m³/sec, that is about twice the yearly average. In a period of 50 years it has occured 3 times that 4000 m³/sec coincided with an ice sheet on the 3 Rhine branches in the Netherlands. So this is not a rare phenomenon.

Under normal conditions this quantity is carried off by the three branches of the Rhine in the Netherlands as shown in fig. 8.

This distribution is very important, for every branch can only carry off his own part without risk. Now it is not excluded that the ice sheet has location as shown in fig. 9.

Fig. 9 shows that by consequence of an ice sheet on the Waal coinciding with a free stretch on the right hand branch, the discharge of the Waal will be reduced from 2800 m³/sec by 600 to 2200 m³/sec, that is a reduction to 80%. The second branch takes $1200 + 600 = 1800$ m³/sec, that is an increase of 50%.

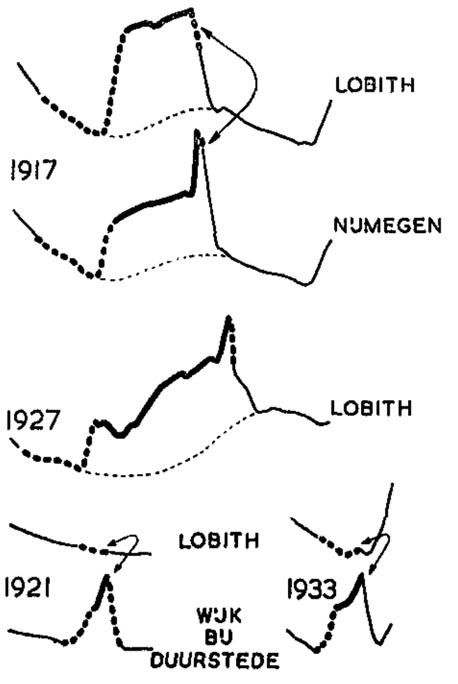


Fig. 7
Sudden rise of the sheet ice at the end of a frost period.

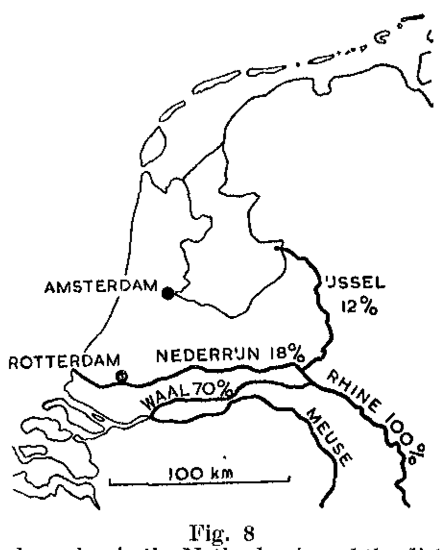


Fig. 8
Situation of the 3 Rhine branches in the Netherlands and the distribution of a discharge of 4000 m³/sec.

When the IJssel is covered with sheet ice, this branch will only take its original part of 480 m³/sec. So the Neder-Rijn will have to carry off the 600 m³/sec and the discharge of this branch is increased by 80% to 1320 m³/sec. This quantity is not yet a large one compared to the maximum discharge of this branch, viz 2600 m³/sec.

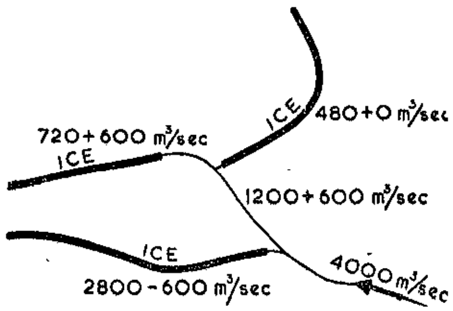
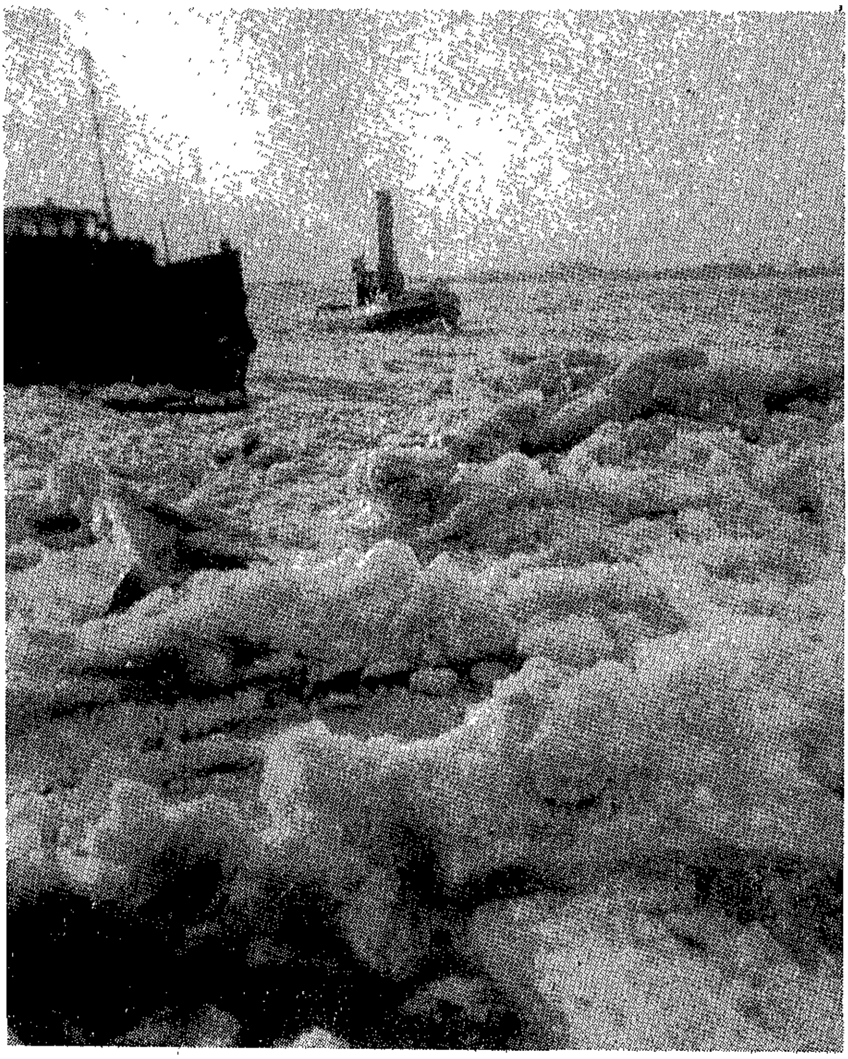


Fig. 9
Disturbance of the distribution of the discharge of 4000 m³/sec.



Ice breakers working on the Waal, 1954.

When however there happens to be ice on this branch, the levels are usually some 2 or 3 m higher. Hence they would surpass the levels of the highest known discharge of the Rhine (1926).

A coincidance as this one, physically speaking, is possible in every ice winter in which the Waal is covered with an ice sheet. That is in 15 winters in a century. The probability of the coincidance however is estimated as being not higher than 5 or 10%. So we may expect this situation in the order of once in a century.

As will be clear it is of great importance to establish a free path before the onset of the thaw. To that purpose the government orders every ice winter to break the ice at least on the river Waal. In 1940 over a length of 90 km, in 1942 over 150 km, in 1947 over 110 km, in 1954 over 120 km.

(1) S. Kolupaila, «Die Berechnung der Winterabflussmengen»; *Tallinn* 1928.

Ir. P. J. Wemelsfelder, « De invloed van het ijs op de waterstanden der grote rivieren », *De Ingenieur* 1940 No. 7.

W. Lasloffy, « Régime des glaces des rivières », *La Houille Blanche*, 1948.