24 Gravity outlet structures

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24.1 Introduction

When agricultural lands are located along rivers, lakes, estuaries, or coastal areas, dikes can protect them from being flooded. To enable the drainage of excess water from the protected area, the dikes are provided with outlet structures. These can be sluices with doors, gated culverts, siphons, and/or pumping stations. The water levels of the canals, rivers, lakes, or seas that receive this water may vary, because of tides, for instance. When the outer water levels are high, drainage might be temporarily restricted. This means that the drainage water accumulating inside the protected area has to be stored – in the soil, in ditches, in canals, and/or in ponding areas.

This chapter focuses on gravity outlet structures (i.e. drainage sluices and gated culverts) and their design. Section 24.2 concerns the boundary conditions for the design of these structures, in particular the water levels of the receiving water ('outer water') and the water level of the area to be drained ('inner water'). As salt intrusion might be of importance for the location of the gated structure and for the elevation of its crest, Section 24.2.3 deals briefly with this topic.

Hydraulic aspects relevant to the design of a gravity outlet structure are presented in Section 24.3, which also elaborates on other design-related aspects.

24.2 Boundary Conditions

A gravity outlet forms the boundary between two bodies of water: the inner water, which is inside the drained area, and the receiving or outer water.

We can distinguish three types of drainage:

A. Tidal drainage: The areas to be drained are situated near seas, bays, estuaries, or along tidal rivers. Drainage can take place during periods of low water (ebb tide);
B. Drainage to non-tidal parts of rivers: Here, because of the occurrence of high river levels, especially during rainy seasons, drainage might be restricted for relatively long periods;
C. Drainage to lakes or inner seas: Drainage might be hampered when water levels have risen because of wind forces; this is known as 'wind set-up' and 'storm surge'.

A combination of A and C often occurs.

24.2.1 Problem Description

When the outer water levels are lower than the inner water levels, excess drainage water can be discharged through gravity outlet structures (Figure 24.1A). When the

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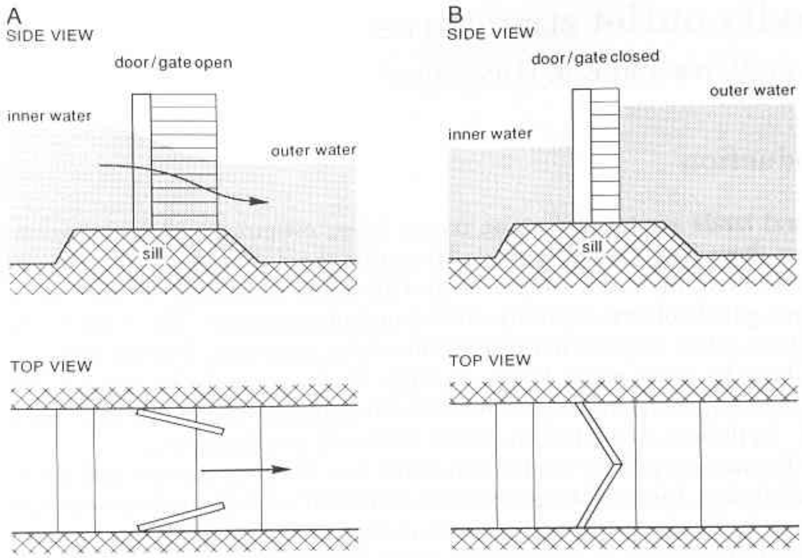

Figure 24.1 Functioning of a gravity outlet structure; A: Drainage when the outer water level is lower than the inner water level; B: No drainage when the outer water level is higher than the inner water level

outer water levels are higher, the doors or gates of the gravity outlet should be closed to prevent the intrusion of outer water and an unwanted rise in inner water levels (Figure 24.1B). During these periods of hampered drainage, the excess drainage water needs to be stored within the protected area. This storage can take place in the soil, in ditches, in canals, and/or in ponding areas. If the storage capacity in the protected area is not sufficient, drainage by pumps (in combination with gravity outlet structures) should be considered.

Figure 24.2 shows the change in the inner water level when drainage is taking place through a gravity outlet. The outer water level is under the influence of the tide. The periods when drainage takes place are called the drainage periods. During these periods, the inner water level falls. When the outlet is closed, the inner water level will rise again, because the discharge from the agricultural land continues. During these periods, the water will have to be stored in the area; these are the storage periods.

The success of a gravity outlet structure depends on the volume of storage available in the area. The storage volume should be sufficiently large to store the accumulating excess drainage water when the outlet structure is closed. When storage in soils is neglected, the available storage volume is the product of the wet surface area at a certain water level (in ditches, canals, and ponding areas) and the permissible rise of the inner water level. Of primary importance is the maximum allowable storage level.

The water levels in Figure 24.2 will be discussed in Section 24.2.4.

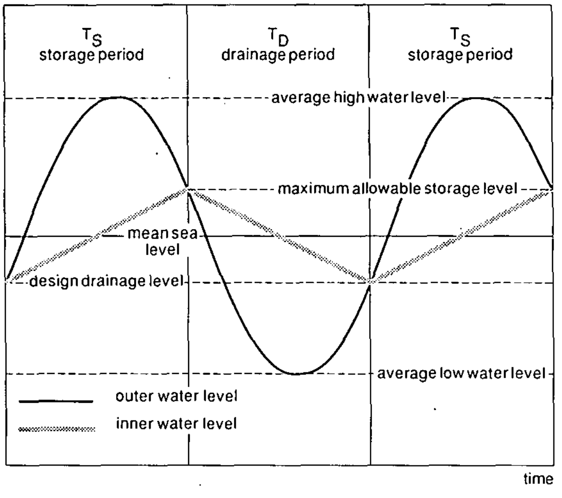

Figure 24.2 Water levels on both sides of the outlet structure

24.2.2 Outer Water Levels

Outer water levels may be under the influence of tides, river floods, density currents, waves, wind set-up, and storm surges. Possible combinations of these phenomena occur in the downstream reaches of rivers.

Three different situations of inner and outer water levels can occur:
1) The outer water level is always higher than the inner water level. Here, the water always has to be pumped from the drained area (Chapter 23);
2) The outer water level is always lower than the inner water level. This allows continuous drainage by gravity;
3) The outer water level fluctuates between being higher and lower than the inner water. These water level fluctuations can be caused by tides, surges, and/or river floods. Here, 'gated structures' are required.

Tides

Tides are the daily or twice-daily rise and fall of the water level in oceans, seas, and lakes. Tides are related to the attraction forces between large celestial bodies, especially the Earth, the moon, and the sun. Figure 24.3 shows the solar system.

The movements within the solar system are:
- The Earth moves around the sun in 365.256 days;
- The moon moves around the Earth in 27.32 days;
- The Earth rotates on its axis in 24 hours.

As a result of the rotation of the Earth and the movement of the moon and the sun, long waves develop and travel around the Earth. (Long waves have a very small amplitude compared to their length.) They are altered by submarine and coastal

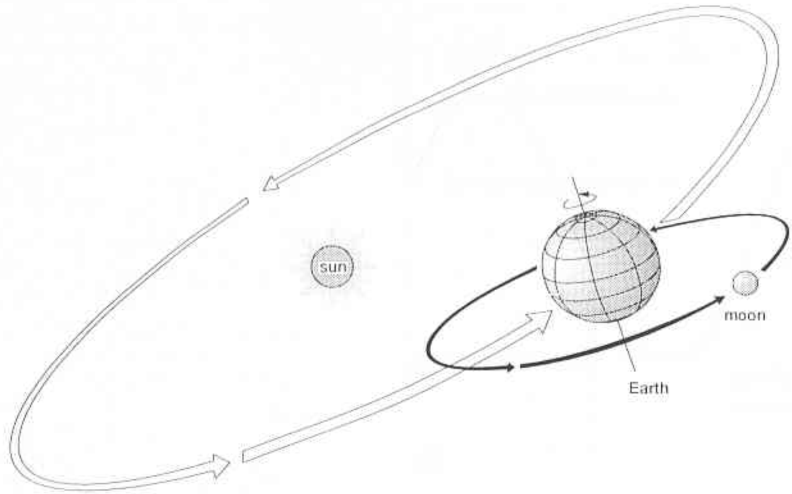

Figure 24.3 The solar system

topography, resonance in bays and estuaries, Coriolis forces, and other factors.

Tidal waves can be observed by measuring the water levels along coasts and near the mouths of rivers at regular time intervals (hours). Figure 24.4 gives an example of a tidal observation over a period of one lunar month.

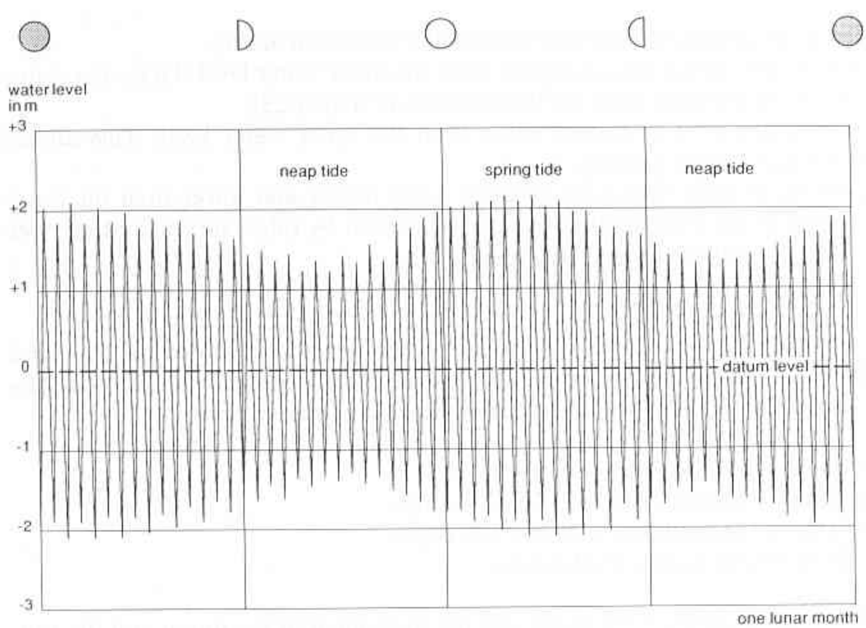

Figure 24.4 An example of the tidal fluctuations observed from new moon to new moon at Flushing, The Netherlands

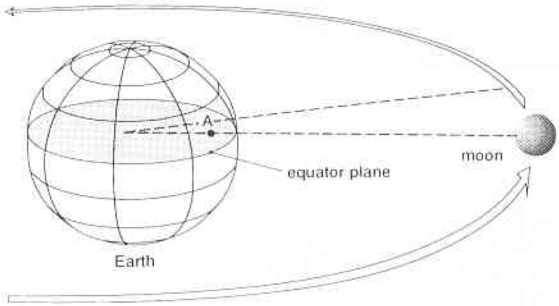

Figure 24.5 Simplified presentation of the Earth-moon system with the system's centre of gravity located at Point A

The System Earth-Moon: Lunar Tide

For an explanation of tidal phenomena, let us first consider the Earth-moon system. We simplify the system by assuming that the entire Earth is covered with a layer of water, that the moon is moving in the equator plane of the Earth, and that there is no Earth rotation.

The Earth-moon system has its centre of gravity at Point A (Figure 24.5), which means that the Earth-moon system rotates around that point. One system rotation lasts approximately 27.32 days. While rotating, the two bodies exert attraction, or gravitational forces, on each other. For the sake of equilibrium, these forces must be counterbalanced by centrifugal forces. Because of these two forces, the thickness of the water layer on Earth will increase on the side facing the moon and on the side opposite to that. In this way, some tidal deformation can already be observed (Figure 24.6).

In reality, however, the Earth rotates on its axis in 24 hours. This axis makes an angle with the Earth-moon plane, which varies between 18° and 29°: this is the moon's declination α (Figure 24.7).

If we follow the path of rotation of a certain location on Earth, we can see that two high water levels occur within a full rotation (360°). On the plane of the Earth-

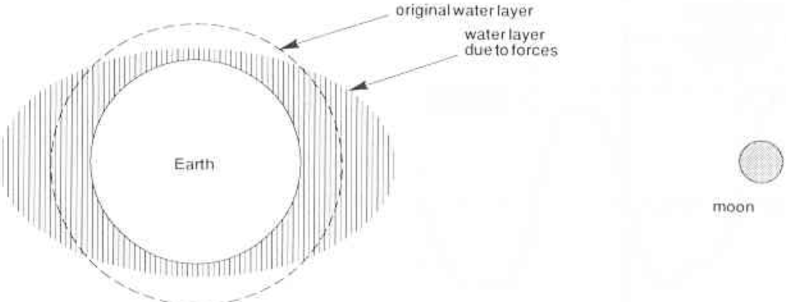

Figure 24.6 Cross-section of the Earth, indicating a deformation of the Earth's water layer by gravitational forces exerted by the moon, under the assumption that the entire Earth is covered with a layer of water

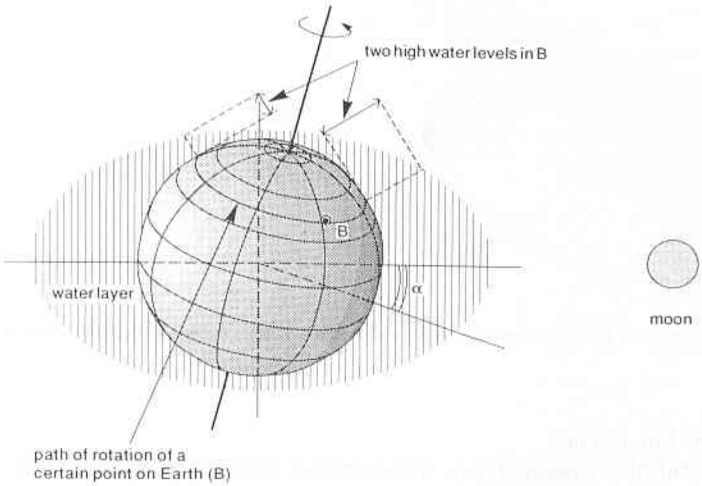

Figure 24.7 Side-view of the Earth-moon system, showing the rotation of the Earth on its axis at an angle α with the orbit of the moon (the moon's declination)

moon, the high water levels will be maximum, while, on the plane perpendicular to the Earth-moon, the high water levels will be minimum. As can be seen in Figure 24.7, the two high waters at Location B are not equal. This phenomenon is called the daily inequality (Figure 24.8), which is caused by the moon's declination. The daily inequality depends greatly on the degree of latitude.

The situation in which two high and two low waters occur in a period of about 24 hours is called a semi-diurnal tide. Considering the fact that both the Earth and the moon rotate explains the length of the period of the semi-diurnal tide. In 24 hours, the Earth makes one revolution on its axis. During that time, the moon will have

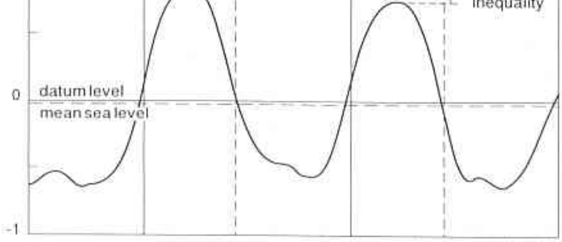

Figure 24.8 Daily inequality of tides

moved some 13° as well (being 360°/27.3 days). This implies that it takes another (13°/360°) × 24 hours, or about 50 minutes, to arrive at the same situation as the day before. Thus a semi-diurnal tide period, being half of this time, is 12 hours and 25 minutes (= 12.42 hours).

The first assumption (i.e. that the entire earth is covered with water) still needs to be corrected. Actually, there is only a narrow strip of water all around the world, and this is located near the South Pole (63° to 64° Southern Latitude). In this channel, tidal waves are generated and from there they progress to the oceans up north. The oceanic water masses of the Earth respond in a complex manner to the tide-generating forces. The reasons for this response include:

- The effect of submarine and coastal topography, because the speed of tidal waves in oceans is a function of the depth;
- Resonance effects in bays and estuaries;
- Forces resulting from the rotation of the earth (e.g. Coriolis forces).

Because of these phenomena, the tidal form and tidal range (average difference between all high and low water levels) may differ quite substantially from one location to another. The largest tidal ranges are observed in bays, gulfs, and estuaries, where resonance occurs: e.g. 13 m in the Severn Estuary (U.K.) and 16 m in the Bay of Funda, Nova Scotia (Canada).

Influence of the Sun: Spring and Neap Tides

The sun is the other tide-generating force, although its force is only 46% of that of the moon. The period of this force is exactly 24 hours, being the rotation time of the Earth on its axis. It is because of the dominant lunar influence that tides occur fifty minutes later than on the previous day. Where the solar influence is dominant, however, (e.g. at Tahiti) tides occur at the same time each day.

During full and new moon, the forces acting on the Earth by the sun and the moon reinforce each other. Then, the attraction forces act in the same direction, which results in the largest tidal variation: spring tide. When the moon is in its first or third quarter, the gravitational forces of both celestial bodies act perpendicular to each other, resulting in the smallest variation: neap tide. Both phenomena are presented in Figure 24.9.

So, during a period of about 28 days, there will be two spring tides and two neap tides. The actual occurrence of spring and neap tide in the example of Figure 24.9 is some two days later than the occurrence of the face of the moon, because of the travel time from the South Pole areas to the place under consideration, and because of the effects of damping, reflection, and other local influences. This time difference is called the age of the tide.

Influence of Other Tidal Components

So far, we have assumed that the orbits of the moon around the Earth and of the Earth around the sun are circular. In reality, these orbits are elliptical, which implies that the distances moon-Earth and Earth-sun are not constant, but vary somewhat. For that reason, the magnitude of the tide-generating forces varies as well. Furthermore, the angle between the moon-Earth plane and the sun-Earth plane is

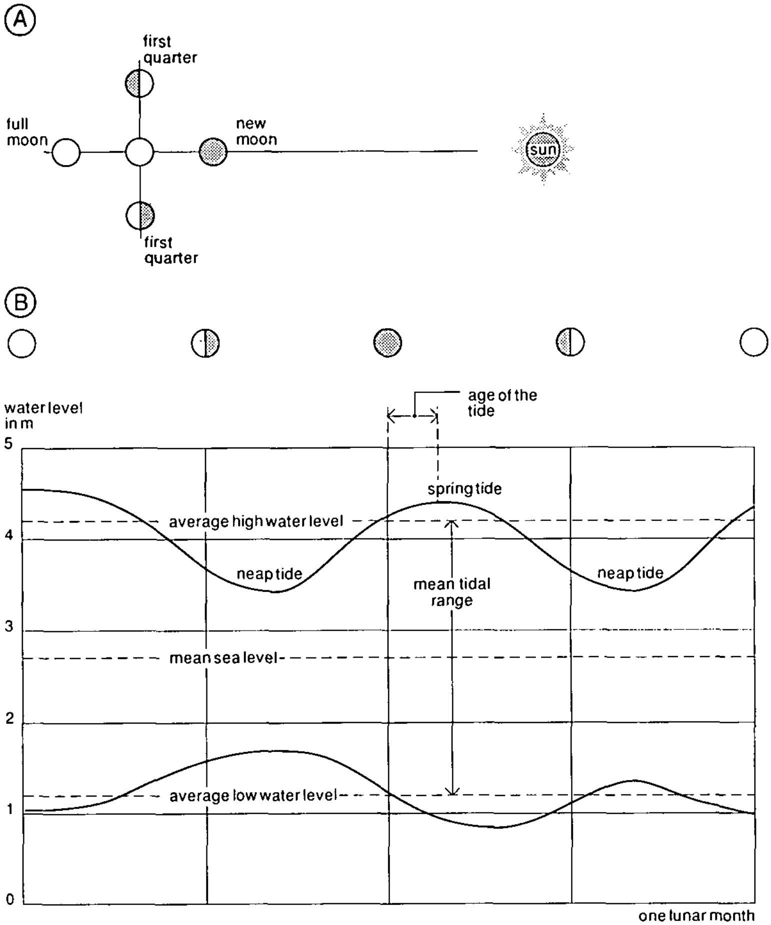

Figure 24.9 A: The lunar cycle; B: Envelopes of high and low water show the fluctuation of the tide during one lunar cycle (after Smedema and Rycroft 1983). Daily fluctuations are shown in Figure 24.4

not constant, which also has an effect on the generating forces. The above phenomena result in a complex of tidal components, of which elliptical tides are just one kind.

To explain the combined effect of all tidal phenomena satisfactorily, we shall use the Harmonic Analysis method.

Harmonic Analysis

The Harmonic Analysis is one of the methods of arriving at a mathematical description of the tide. It can be used to derive accurate tidal predictions (see also Pugh 1987, Kalkwijk 1984 and Schureman 1958). The vertical movement of the water is described as the linear superposition of tidal components, called constituents. In total, there are more than two hundred constituents with varying degrees of importance.

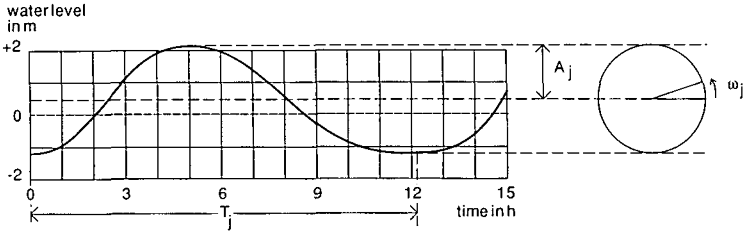

Figure 24.10 Sinusoidal curve describing the water level fluctuation due to a single constituent

Each constituent (with subscript $_j$) can be characterized by three factors (Figure 24.10):

- Amplitude A_j: Vertical difference in height between the highest (or lowest) level and the average level in metres;
- Angular speed ω_j: Angular speed, expressed in degrees/hour: $\omega_j = 360°/T_j$ (T: time in hours for a constituent to re-occur);
- Phase lag α_j: Phase lag, expressed in degrees, indicating the time difference between the passage of a celestial body through the meridian of the considered place and the real time of occurrence ('age of the tide').

The effect of an individual constituent, j, on the average sea water level follows a sinusoidal curve, which can be expressed by

$$h_j(t) = A_j \cos(\omega_j t - \alpha_j) \tag{24.1}$$

where

$h_j(t)$ = water level resulting from constituent j related to mean sea level/MSL (m)
A_j = amplitude (m)
ω_j = angular speed (degrees/h)
t = time considered (h)
α_j = phase lag (degrees)

The tidal level h(t) (related to MSL), which is the combined effect of all constituents, is the result of the superposition of all these individual sinusoidal curves:

$$h(t) = h_{MSL} + \sum_{j=1}^{n} [A_j \cos(\omega_j t - \alpha_j)] \tag{24.2}$$

where

$h(t)$ = water level related to MSL at time t (m)
h_{MSL} = average water level (= mean sea level) (m)

For a first approximation of a tide, most of the tidal phenomena can be described quite effectively by a relatively small number of constituents.

Table 24.1 presents the characteristics of the four most important tidal constituents.

Table 24.1 Most important tidal components

Symbol	Description	ω_j (degrees/h)	T_j (h) (= $360°/\omega_j$)
M_2	Main lunar tide	28.98410	12.42
S_2	Main solar tide	30.00000	12.00
K_1	Sun/moon declination tide	15.04107	23.93
O_1	Moon declination tide	13.94303	25.82

Types of Tides

Depending on the geographical location, the following types of tides can be distinguished (Figure 24.11):

– Diurnal tides: These tides have one high water and one low water each lunar day (24 hours, 50 minutes);

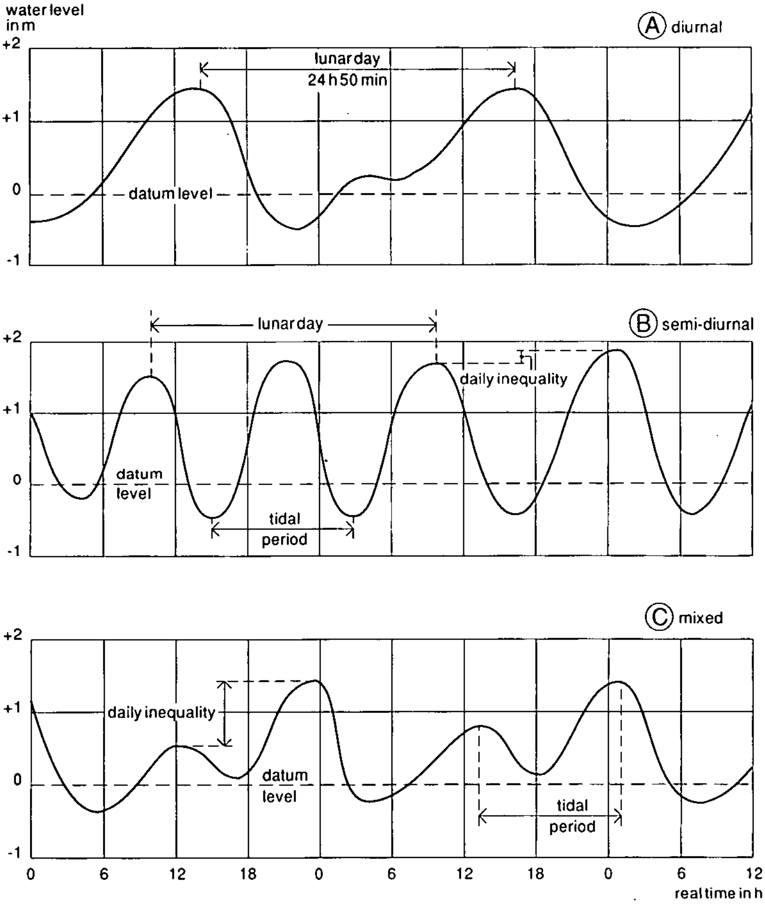

Figure 24.11 Types of tides; A: Diurnal tide; B: Semi-diurnal tide; C: Mixed tide

- Semi-diurnal tides: These are tides with two almost equal high waters and two almost equal low waters each lunar day. The differences between the two high waters and between the two low waters are so small that they can be represented by one value for the high waters and one value for the low waters per lunar day;
- Mixed tides: Mixed tides have different high waters, different low waters, or both, within one lunar day.

The type of tide (diurnal, semi-diurnal, or mixed) occurring in an area and the tidal range depend on a rather complex process of damping and amplifying.

Tidal Prediction

Tidal prediction is based on the principle of the Harmonic Analysis. The unknown characteristics of each constituent (phase and amplitude) at a given location can be obtained by analyzing measured tidal data. At the proposed site of a gravity outlet structure, the tidal data should be obtained with staff gauges or automatic gauges; an automatic gauge should always be complemented with a staff gauge to allow for periodic checking. The level of the gauge should be referenced to permanent and protected benchmarks. Wind effects can be eliminated from the observations through readings at more or less windless moments and/or by taking observations over longer periods.

To check the reliability of the measured data, they should be correlated with records from the nearest permanent tidal observation station, which can be found in ports and harbours (Correlation methods were discussed in Chapter 6, Section 6.6). In this way, an insight can be obtained into the local effects that influence the shape of the tidal curve. When it is possible to determine a correlation between the two locations (under the condition that the records of the permanent observation station cover a sufficiently long period), a prediction of tidal levels can be made.

To predict a tide in accordance with the Admiralty Method (Schureman 1958), continuous observations at hourly intervals over a minimum period of 29 days are required, so that phenomena like spring and neap tide are included. Longer observations are required to eliminate other effects (like wind set-up, storm surges, and variations in water levels due to changes in barometric pressure). If the area to be drained is on a tidal river, the measuring period should cover a wet and a dry season as well.

A third method of tidal analysis is the Method of Least Squares (Kalkwijk, 1984). The tidal characteristics can be determined through minimizing the difference between a measured tidal signal and a basic sinusoidal function in which the unknown constituents are included. With the help of regression techniques, a best fit can be obtained. A great advantage of this method is that gaps in a registration (incomplete sets of data because, for instance, of the improper functioning of instruments, which occurs very often in practice) are not disastrous.

Influence of Tides on Downstream River Levels

In the downstream reaches of rivers that discharge into a sea or an ocean, water levels are influenced by the tides. These river reaches are called tidal rivers. In accordance with the propagation of the astronomical tides, a river can be subdivided into the

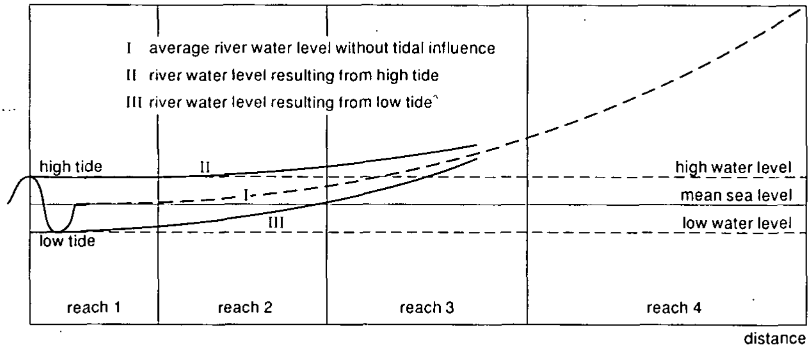

Figure 24.12 Subdivision of the deltaic reach of a river into four reaches according to the propagation of tides

following reaches (Figure 24.12):
- Reach 1: Where vertical tides occur with subsequent reversal of the current direction and where intrusion of saline water occurs;
- Reach 2: Where the river water is fresh, but otherwise the tidal phenomena are similar to those in Reach 1;
- Reach 3: Where the water levels are still affected by the tides, but where the current direction remains in downstream direction; the velocity, however, varies in accordance with the tide;
- Reach 4: Where the water levels and the flow depend upon the upstream discharges only.

In accordance with the propagation of high sea water levels, the river can be divided into three reaches (Figure 24.13):
- Reach a: Where the effect of sea levels predominates;
- Reach b: Where a combined effect of the sea and river floods occur (intermediate zone);
- Reach c: Where the effect of river floods predominates.

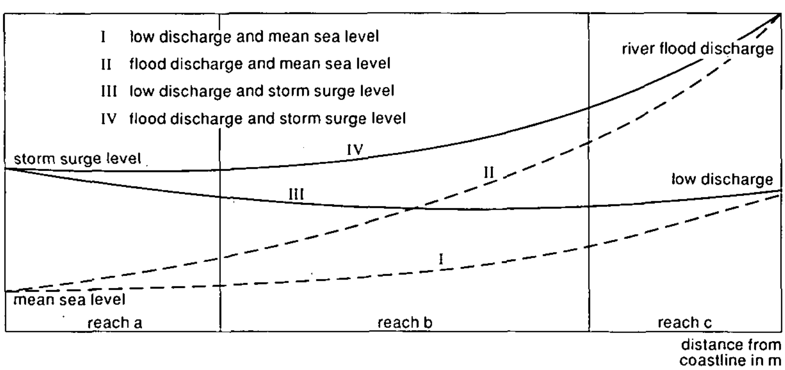

Figure 24.13 Subdivision of the deltaic reach of a river into three reaches according to the type of predominant floods

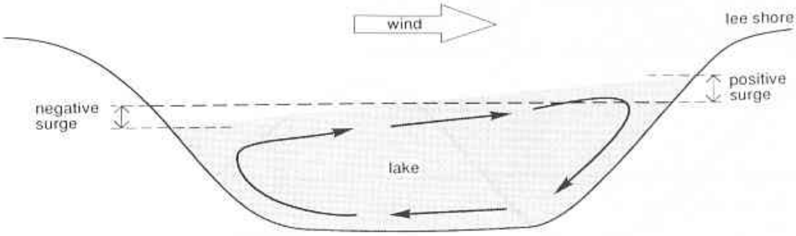

Figure 24.14 Effect of surges on the water level of an enclosed lake. The wind causes a current to the lee shore of the lake, which is compensated for by a return current on the bottom

The propagation of abnormally high sea levels, in combination with the effect of river floods, is an important factor in the design of outlet structures. To be able to determine the most unfavourable outer water level for the design of an outlet structure, one has to determine in which river reach the outlet will be located.

Tidal Currents
The vertical tidal movements, called vertical tides, are caused by the astronomical forces. In their turn, the vertical tides create tidal currents, which are called horizontal tides. These horizontal tides appear, for instance, at the entrance of a bay that is under tidal influence. They are a function of the tidal volume (i.e. the quantity of water passing between high and low water), because in each tidal cycle the tidal volume has to enter and leave through the entrance to the bay. The direction of the tidal current is into the bay when the water level is rising. At high water or slightly later, the current will be zero (= high water slack). With falling water, the current is directed out of the bay, reaching a maximum at mean sea level and decreasing to zero just after low water (= low water slack).

Storm Surges
Abnormal meteorological conditions can cause large deviations from the computed tidal levels. In this respect, the wind is the most important factor. Any variations that cause a rise (or a fall) of the water level above (or below) the computed level through the action of wind is called a storm surge. Gales may cause the outer water level to rise or fall by several metres in large waterbodies.

Figure 24.14 shows a wind surge in an enclosed lake. The current near the water surface, which is induced by the wind and results in a positive storm surge on the lee shore of the lake, is compensated for by a return current along the bottom. After some time, an equilibrium situation will develop.

Variations in barometric pressure may also cause deviations from the computed tide. This effect, however, is much smaller than that of the wind, being of the order of one centimetre per millibar.

The effect of a surge on expected tidal levels can be seen in Figure 24.15. It can be observed that the resulting water level is a linear superposition of expected levels and surge levels.

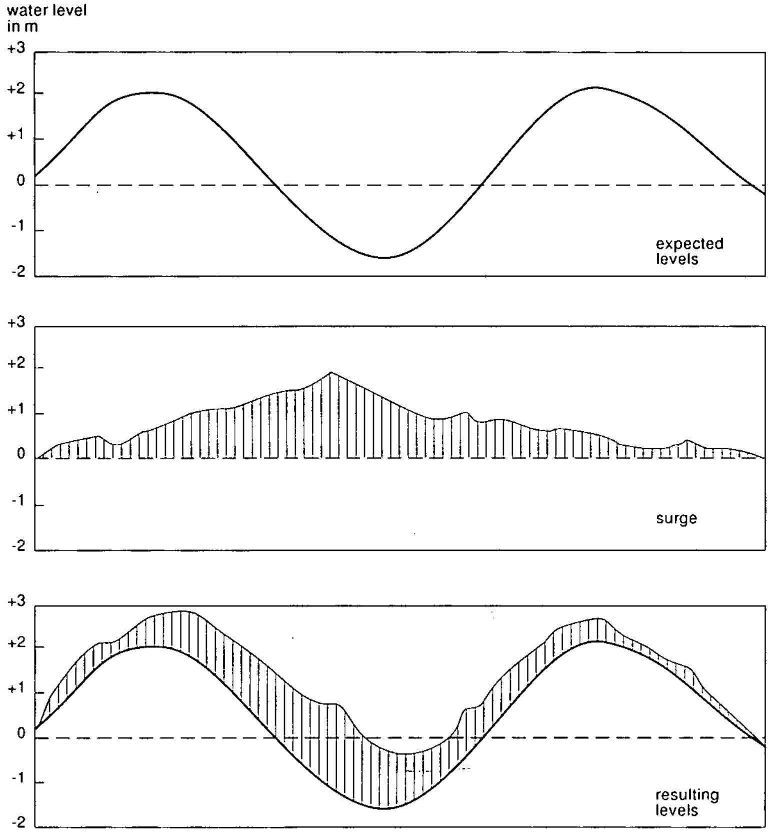

Figure 24.15 Effect of a surge on expected tidal levels

River Floods

River floods are caused by the discharge of extreme runoffs (originating from upstream catchment areas) or by local rainfall. The characteristics of the river basin and the catchment area determine the characteristics of the flood: i.e. its duration, peak, and shape.

Gentle floods occur in rivers with relatively large catchment areas and long travel times to the river mouths (e.g. the Chao-Phrya in Thailand with a catchment area of 160 000 km^2).

Flash floods occur in steep areas with relatively short rivers (e.g. the Cho-Shui in China with a catchment area of 3150 km^2; Figure 24.16).

For design purposes, representative floods are needed. These can be obtained by establishing the relationship between river water levels at the site of the proposed gravity outlet structure and their frequency of occurrence. Such a relationship should be based on records covering a sufficiently long period. On the basis of a selected return period (e.g. 5 or 25 years), the design flood can be found (see also Chapter 6 Frequency Analysis.)

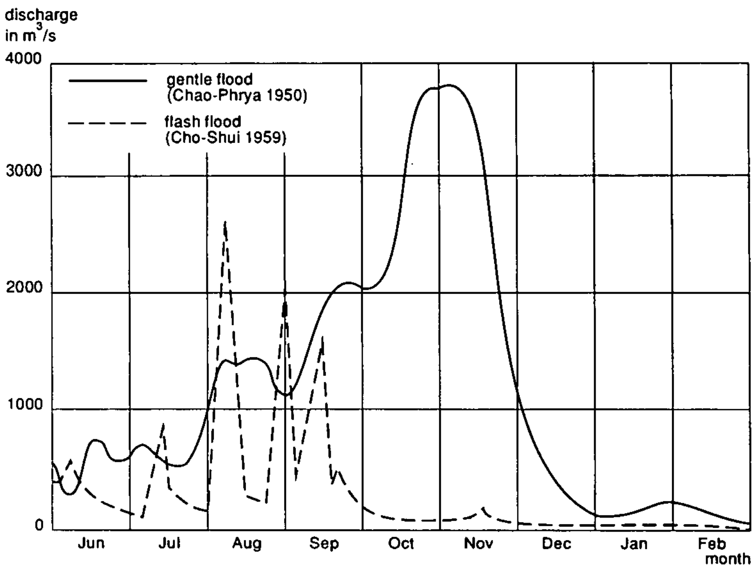

Figure 24.16 Typical hydrographs of gentle floods and flash floods

24.2.3 Salt Intrusion

Along coasts, estuaries, and tidal rivers, salt and brackish water pose a constant threat to agriculture. Salt water intrudes into estuaries in the upstream direction, because the density of the salt sea water is higher than that of the fresh river water (ρ_s = 1028 kg/m^3, ρ_f = 1000 kg/m^3). The rate of intrusion and the kind of mixing in the estuary depend on the river discharge, the tidal period, and the flood volume (i.e. the volume of water that enters the estuary in the period between low and high tide). It can be classified by the mixing parameter α.

$$\alpha = \frac{Q\,T}{A_o\,E} \tag{24.3}$$

where

- α = mixing parameter: the ratio between the river discharge and the flood volume (–)
- Q = river discharge (m^3/s)
- T = tidal period (s)
- A_o = cross-section at the estuary mouth (m^2)
- E = tidal excursion: the distance which a water particle travels along the estuary between low water slack and high water slack (m)

As can be seen in Figure 24.17, extreme intrusions occur in periods when the river discharge is low (i.e. the dry season).

To investigate whether the envisaged location of a gravity outlet structure is subject to salt intrusion or not, water samples should be taken along a stretch of some 10

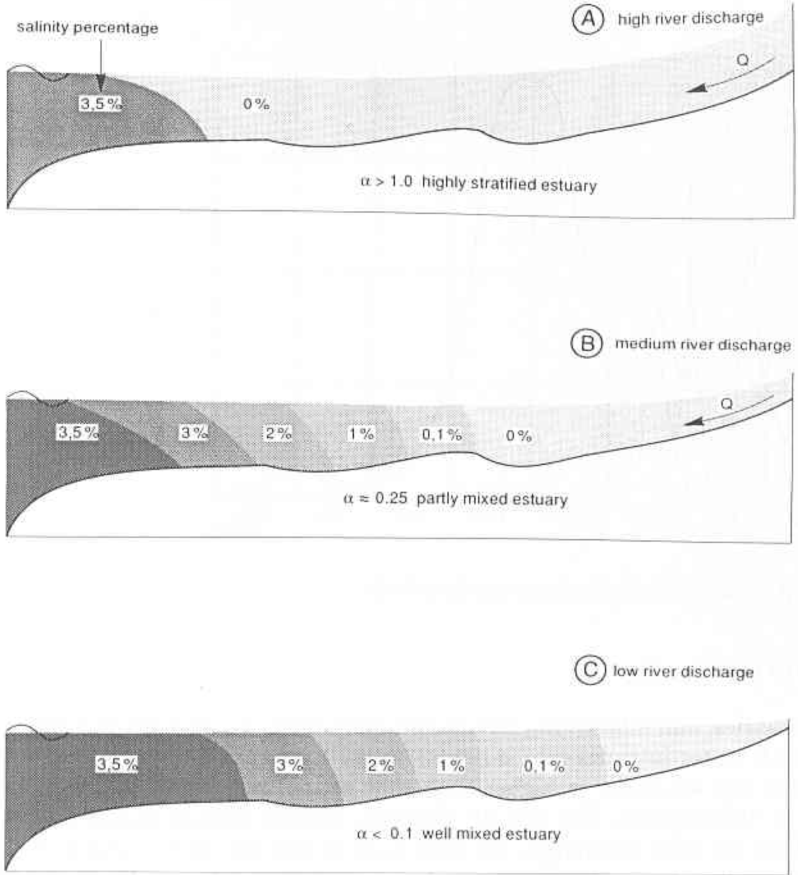

Figure 24.17 Various types of mixing in an estuary; A: Stratified estuary; B: Partially mixed estuary; C: Mixed estuary (Savenije 1992)

km upstream and some 10 km downstream of the location, at intervals of, say, 1 km. This sampling should be done at high water spring tide during the dry season (when the river discharge is low). In this way, one can obtain a longitudinal profile that shows the change in salt concentration as a function of the location of the envisaged gravity outlet.

To facilitate the choice of the sampling locations, two calculation methods will be presented.

The calculation method of Van Os and Abraham (1990) determines the minimum salt intrusion length, measured from the mouth of the estuary. For this determination, the 'estuary densimetric Froude number' Fr_o needs to be determined.

$$Fr_o = \frac{u^2}{\frac{\rho_s - \rho_f}{\rho} g h_o} \tag{24.4}$$

where

Fr_o = estuary densimetric Froude number (–)
u = maximum mean ebb flow velocity (profile averaged; m/s)
ρ_s = density of sea water (kg/m^3)
ρ_f = density of fresh river water (kg/m^3)
ρ = density of either sea water or river water (kg/m^3)
g = acceleration due to gravity (m/s^2)
h_o = water depth at the mouth of the estuary (m)

The minimum salt intrusion length can then be determined by

$$L_{min} = 0.55 \frac{C^2 h_o}{Fr_o\, g\, \alpha} \tag{24.5}$$

where, in addition to the symbols already defined,
L_{min} = minimum salt intrusion length (m)
C = Chézy coefficient: for estuaries approximately 60-70 (m$^{\frac{1}{2}}$/s)

To find the maximum intrusion length, the tidal excursion length E should be added to L_{min}. The order of magnitude of E is about 10 km for a semi-diurnal tide and about 20 km for a diurnal tide.

A second method of determining salt intrusion in estuaries is the Savenije method (Savenije 1992). With this method, the maximum salt intrusion length can be determined directly

$$L_{max} = L_b \ln \left(\frac{220\, u\, E\, h_o\, A_o}{K\, Q\, L_b^2} \sqrt{\frac{\alpha}{Fr_o} \frac{\rho}{\rho_s - \rho_f}} + 1 \right) \tag{24.6}$$

where

L_{max} = maximum salt intrusion length (m)
L_b = convergence length, which follows from the relation
$A_x = A_o e^{-x/L_b}$ and can be determined by a regression of A_x on x (m)
A_x = cross-section at distance x (m^2)
x = distance from the estuary mouth (m)
A_o = cross-section at the river mouth (m^2)
K = Van de Burgh coefficient: $K = 0.075 \times h_o$ (–)

Both methods give a good indication of the order of magnitude of the salt intrusion length in tidal rivers and estuaries.

Example 24.1: Rotterdam Waterway
The following data are given:
Q = 1550 m^3/s
T = 12 hours 25 minutes = 44 700 s
A_o = 6478 m^2
E = 14.5 × 10^3 m
u = 1.1 m/s

$\rho \quad = 1000 \text{ kg/m}^3$
$\rho_s \quad = 1025 \text{ kg/m}^3$
$g \quad = 9.8 \text{ m/s}^2$
$h_o \quad = 15.8 \text{ m}$
$C \quad = 60 \text{ m}^{\frac{1}{2}}\text{/s}$
$L_b \quad = 1.0 \times 10^5 \text{ m}$
$H \quad = 1.7 \text{ m}$

A Van Os and Abraham

To determine the minimum salt intrusion length, first the mixing parameter α and the densimetric Froude number are determined

$$\text{Equation 24.3: } \alpha = \frac{1550 \times 44700}{6478 \times 14.5 \times 10^3} = 0.74$$

$$\text{Equation 24.4: } Fr_o = \frac{1.1^2}{\frac{1025-1000}{1025} \times 9.8 \times 15.8} = 0.32$$

Now the minimum salt intrusion length can be determined

$$\text{Equation 24.5: } L_{min} = 0.55 \frac{.60^2 \times 15.8}{0.32 \times 9.8 \times 0.74} = 13.5 \text{ km}$$

This length is almost the same as the observed one (16 km).
The maximum intrusion length becomes

$$L_{max} = L_{min} + E = 28 \text{ km}$$

Within the accuracy of the input data, the conclusion is that L_{max} will be in the range of 21 to 35 km.

B Savenije

This method also uses the mixing parameter α (= 0.74). Furthermore, the Van de Burgh coefficient needs to be determined

$$K = 0.075 \times h_o = 0.075 \times 15.8 = 1.19$$

Now the maximum salt intrusion length can be calculated

Equation 24.6: $L_{max} =$

$$10^5 \times \ln \left(\frac{220 \times 1.1 \times 14.5 \times 10^3 \times 15.8 \times 6478}{1.19 \times 1550 \times 10^{10}} \sqrt{\frac{0.75}{0.32} \times \frac{1025}{1025 - 1000}} + 1 \right) = 17 \text{ km}$$

Given the accuracy of the input data, L_{max} will be in the range 12 to 22 km. Combining the outcome of the two methods leads to the conclusion that L_{max} will most probably be in the range of 16 to 29 km.

Example 24.2: Chao Phrya

The following data are given:

$Q \quad = 150 \text{ m}^3\text{/s}$
$T \quad = 44\,700 \text{ s}$

$A_o = 4250\ m^2$
$E = 22 \times 10^3\ m$
$u = 1.5\ m/s$
$\rho = 1000\ kg/m^3$
$\rho_s = 1025\ kg/m^3$
$g = 9.8\ m/s^2$
$h_o = 8\ m$
$C = 60\ m^{\frac{1}{2}}/s$
$L_b = 1.09 \times 10^5\ m$
$H = 2.3\ m$

A Van Os and Abraham

$$\text{Mixing parameter: } \alpha = \frac{150 \times 44700}{4250 \times 22 \times 10^3} = 0.07$$

$$\text{Densimetric Froude number: } Fr_o = \frac{1.5^2}{\frac{1025\text{–}1000}{1025} \times 9.8 \times 8} = 1.18$$

$$\text{Minimum salt intrusion length: } L_{min} = 0.55 \frac{60^2 \times 8}{1.18 \times 9.8 \times 0.07} = 20\ km$$

In this case, a minimum salt intrusion length of 17 km was observed.

$$\text{Maximum salt intrusion length: } L_{max} = L_{min} + E = 42\ km$$

B Savenije
Van de Burgh coefficient: $K = 0.075 \times 8 = 0.60$

Maximum salt intrusion length:

$$L_{max} = 1.09 \times 10^5 \times \ln\left(\frac{220 \times 1.5 \times 22 \times 10^3 \times 8 \times 4250}{0.60 \times 150 \times (1.09 \times 10^5)^2}\right.$$

$$\left.\sqrt{\frac{0.07}{1.18} \times \frac{1025}{1025 - 1000}} + 1\right) = 33\ km$$

For this case, the actual L_{max} will most probably be in the range of 29 to 46 km.

24.2.4 Inner Water Levels

The drainage system will have to store the excess drainage water and convey it from the drained area in such a way that, on the basis of the desired groundwater levels in the field, the inner water levels remain in between the following two boundaries (see also Figure 24.2):

– Design Drainage Level/DDL: The DDL is the lower boundary. If the water drops below this level, damage may occur, e.g. crops may suffer from water stress due