7 Hydraulic structures for channels

7.1 Introduction

Hydraulic structures in channels have three main functions:

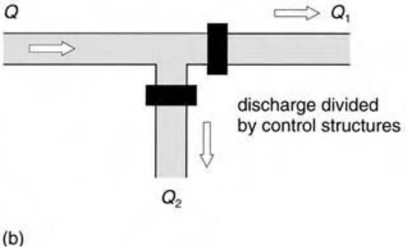
- measuring and controlling discharge
- controlling water levels
- dissipating unwanted energy.

The measurement and control of discharge in channels are perhaps one of the more obvious uses of hydraulic structures (Figure 7.1). Large irrigation networks, for example, require structures at each canal junction to measure and control discharge so that there is a fair and equitable distribution of water. It is not enough just to construct a canal junction and hope that the flow will divide itself properly between the two. Natural rivers too need regular flow measurement so that engineers can make sure there is an adequate supply to meet the growing demands for domestic and industrial uses as well as maintaining base flows for environmental purposes. It is important to ensure that minimum base flows are maintained in dry summer periods to protect fish stocks and environmentally sensitive wetlands. Flood flows are also measured so that adequate precautions can be taken to avoid or control flooding particularly in urban areas where damage can be very costly.

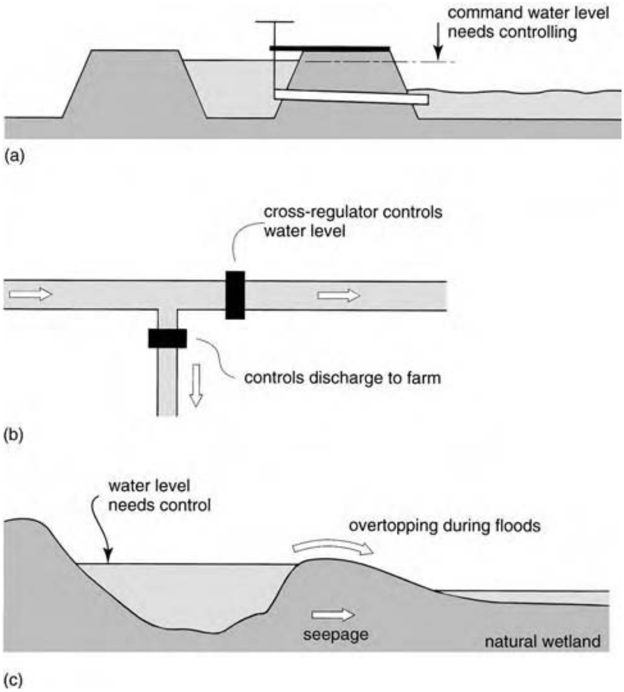
The need to control water levels in channels may not be so obvious. On irrigation schemes water level control is just as important as discharge control. The canals are built up higher than the surrounding ground level so there is enough energy for water to flow by gravity through pipes from the channels into the farms (Figure 7.2a). The water level (known as the command) must be carefully controlled if each farm is to receive the right discharge. But all too often the water level drops because of low flows or seepage losses. This reduces the discharge through the pipes making it difficult for farmers to irrigate properly. To avoid this problem, hydraulic structures are built across the canals to raise the water levels back to their command levels. Such structures are called *cross regulators* (Figure 7.2).

Another example of the need for water level control might be on a river close to a natural wetland site which is valued for its bird population or its special plants (Figure 7.2b). Water might enter the site either by the flooding from the river as it overtops its banks or through seepage from its bed and sides. Either way the wetland is very dependent on the water level in the river as well as its flow to avoid it drying out and causing irreparable damage

(a) Discharge regulator in a canal system in France



7.1 Measuring and controlling discharge.



7.2 Controlling water levels.

to flora and fauna. Fluctuations in water level can be avoided by building a structure across the river to hold the water at the desired level throughout the year even though the discharge may vary significantly.

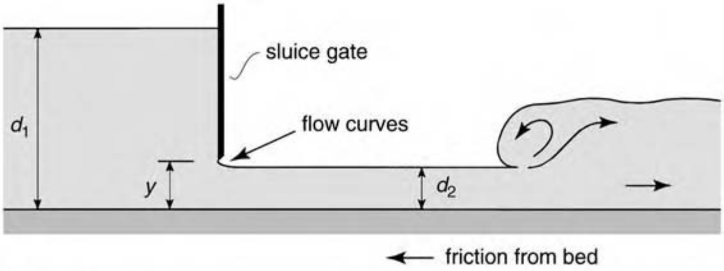
Hydraulic structures are also very useful for getting rid of unwanted energy. When water flows down dam spillways it can reach speeds of 60 km/h and more and is capable of doing a lot of damage. Hydraulic structures are used to stop such high speed flows and dissipate the kinetic energy by creating hydraulic jumps.

Some hydraulic structures only carry out one of the functions described above whilst others perform all three functions at the same time. So a hydraulic structure may be used for discharge measurement, and at the same time may be performing a water level control function and dissipating unwanted energy.

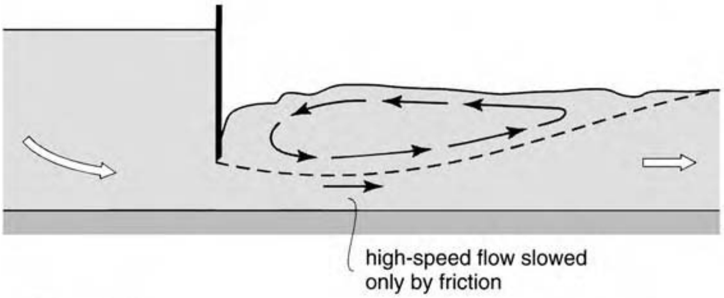
From the point of view of measuring discharge and controlling water levels, there are only two types of structure. Some structures allow water to flow through them and these are called *orifice structures*. Others allow water to flow over them and these are called *weirs or flumes*. Hydraulically, they behave in quite different ways and so each has certain applications for which they are best suited. The energy dissipating function can be attached to both of these structure types.

7.2 Orifice structures

The principles of orifice flow were described earlier in Chapter 3. In practice, orifice structures have fixed or movable gates rather than just a simple opening. The sluice gate described in Section 5.4.3 is a good example of this type of structure. The flow under the gate is very similar to orifice flow but not quite (Figure 7.3a). First, the flow contracts only on its upper surface as it goes under the gate and second there is additional friction from the bed of the



(a) Free flow



(b) Drowned flow

7.3 Orifice structures.

channel. So to find a formula for discharge for this structure the orifice formula is a good starting point, but it needs modifying.

The formula for discharge from an orifice is:

$$Q = a\sqrt{2gh}$$

Modifying this for a sluice gate:

$$Q = C_d a\sqrt{2gd_1}$$

Where Q is discharge (m/s^3); a is area of gate opening (m^2); C_d is a coefficient of discharge; d_1 is the water depth upstream of the orifice (m).

This looks to be a simple formula. It is an attempt to relate the discharge to the area of the gate opening a and the up-stream water depth d_1 because both are easy to measure. However, the relationship is not so simple; as a result, C_d is not a simple coefficient of discharge as defined earlier in Chapter 3. It takes account of the contraction of the flow under the gate, but, in addition, it allows for energy losses and the effects of the size of gate opening and the head on the gate. So C_d is not a simple constant number like the coefficient of contraction C_c. Usually the manufacturer of hydraulic gates will supply suitable values of C_d so that 'simple' discharge formulae can be used.

7.2.1 Free and drowned flow

The sluice gate example shows the flow freely passing under the gate with a hydraulic jump downstream. The downstream depth d_2 has no effect on the upstream depth d_1. This is referred to as *free flow* and the formula quoted above for calculating discharge is based on this condition.

In some circumstances the jump can move upstream and drown out the gate and is referred to as *drowned flow* (Figure 7.3b). The flow downstream may look very turbulent and have the appearance of a jump but inside the flow the action is quite different. There is very little turbulent mixing taking place and the super-critical flow is shooting underneath the sub-critical flow. This high speed jet is not stopped quickly as it would in a jump but slows down gradually over a long distance through the forces of friction on the channel bed. This flow can do a lot of damage to an unprotected channel even though the water surface may appear to be quite tranquil on the surface. Under drowned conditions the formula for discharge must be modified to take account of the downstream water level which now has a direct influence on the upstream water level.

7.3 Weirs and flumes

Weirs and flumes are both overflow structures with very different characteristics to orifices. Many different types of weirs have been developed to suit a wide range of operating conditions, some comprise just a thin sheet of metal across a channel (*sharp-crested weirs*), whereas others are much more substantial (*solid weirs*). Both are based on the principle of changing the energy in a channel and using the energy and continuity equations to develop a formula for discharge based on depth (pressure) measurements upstream. But solid weirs rely on an energy change which is sufficient to make the flow go through the critical point. Because of this they are sometimes called *critical-depth structures*. Sharp-crested weirs do not have this constraint – but they do have others.

Flumes are also critical-depth structures but rely on changing the energy by narrowing the channel width rather than raising the bed. Sometimes engineers combine weirs and flumes by both raising the bed and narrowing the width to achieve the desired energy change. It does not really matter which way critical flow is achieved so long as it occurs.

7.4 Sharp-crested weirs

Sharp-crested weirs are used to measure relatively small discharges (Figure 7.4a). They comprise a thin sheet of metal such as brass or steel (sometimes wood can be used for temporary weirs) into which a specially shaped opening is cut. This must be accurately cut leaving a sharp edge with a bevel on the downstream side. When located in a channel, the thin sheet is sealed into the bed and sides so that all the water flows through the opening. By measuring the depth of water above the opening, known as the head on the weir, the discharge can be calculated using a formula derived from the energy equation. There is a unique relationship between the head on the weir and the discharge and one simple depth measurement determines the discharge.

7.4.1 Rectangular weirs

This weir has a rectangular opening (Figure 7.4b). Water flows through this and plunges downstream. The overflowing water is often called the *nappe*. The discharge is calculated using the formula:

$$Q = \frac{2}{3} C_d L \sqrt{2g} H^{1.5}$$

where C_d is a coefficient of discharge; L is length of weir (m); H is the head on the weir measured above the crest (m).

C_d allows for all the discrepancies between theory and practice.

7.4.2 Vee-notch weirs

This weir has a triangular shaped notch and is ideally suited for measuring small discharges (Figure 7.4c). If a rectangular weir was used for low flows, the head would be very small and difficult to measure accurately. Using a vee weir, the small flow is concentrated in the bottom of the vee providing a reasonable head for measurement.

The discharge is calculated using the formula:

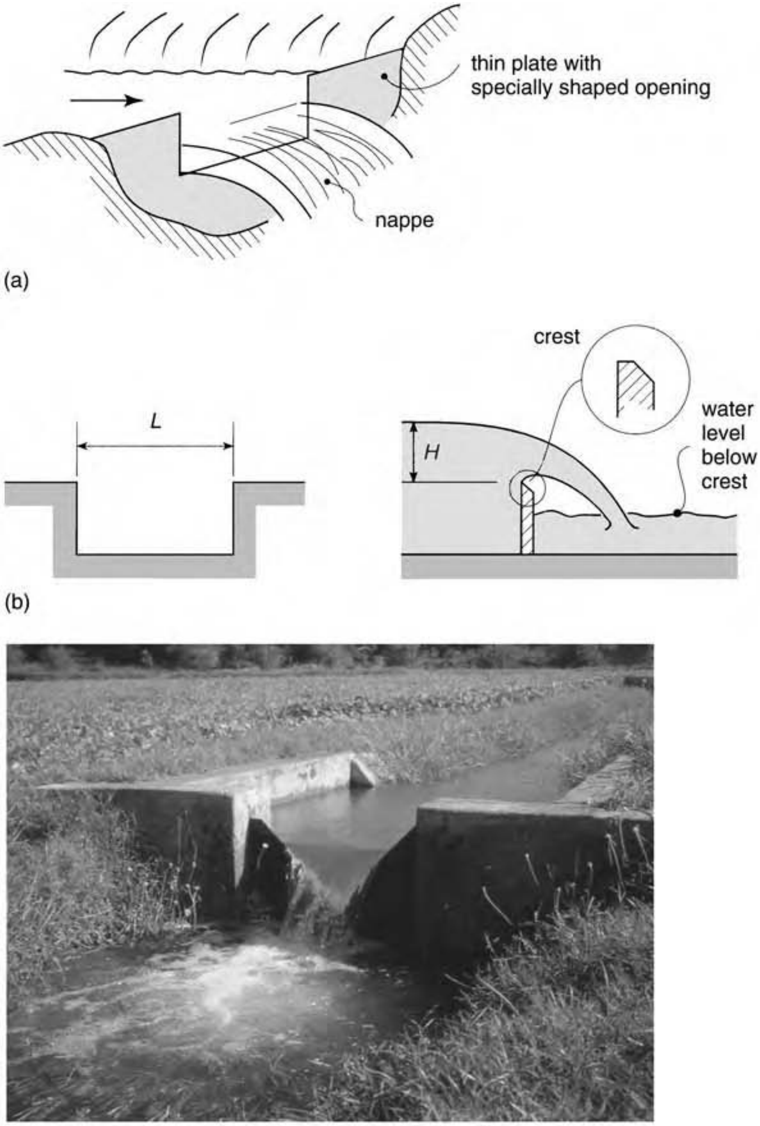
$$Q = \frac{8}{15} C_d \sqrt{2g} \tan\left(\frac{\theta}{2}\right) H^{2.5}$$

where θ is the angle of the notch.

7.4.3 Some practical points

There are several conditions that must be met for these weirs to work properly. These are set out in detail in British Standard BS3680 (see references for details). The following are some of the key points:

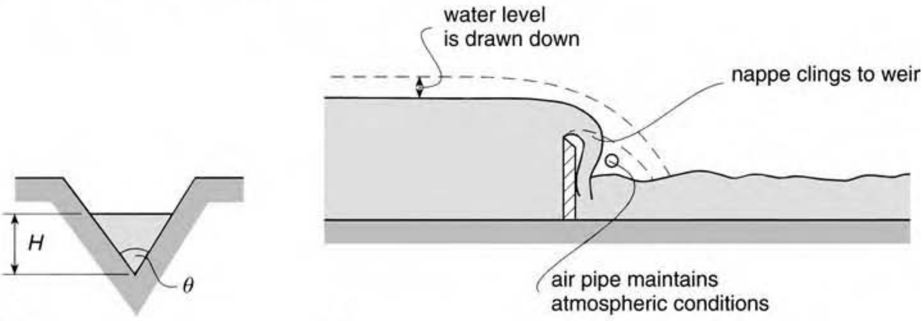
- The water must fall clear of the weir plate into the downstream channel. Notice the bevelled edge on the crest facing downstream which creates the sharp edge and helps the water to spring clear. If this did not happen the flow clings to the downstream plate and draws down the flow reducing the head on the weir (Figure 7.4d). Using the above formula with the reduced value of head would clearly not give the right discharge.



(a)

(b)

(c) Photograph of a V-shaped weir



(d) (e)

7.4 Sharp-crested weirs.

- Flow over the weir must be open to the atmospheres so that the pressure around it is always atmospheric. Sometimes the falling water draws air from underneath the weir and unless this air is replaced a vacuum may form which causes the flow to cling to the downstream face (Figure 7.4d). This draws down the upstream water level reducing the head on the weir and giving a false value of discharge when it is put into the formula. To prevent this, air must be allowed to flow freely under the nappe.
- The weir crest must always be set above the downstream water level. This is the *free flow* condition for sharp-crested weirs. If the downstream level rises beyond the crest, it starts to raise the upstream level and so the weir becomes *drowned*. Another word that is used to describe this condition is *submerged flow*. The formula no longer works when the flow is drowned and so this situation must be avoided by careful setting of the weir crest level.
- The head H must be measured a few metres upstream of the weir to avoid the draw-down effect close to the weir.
- When deciding what size of weir to use it is important to make sure there is a reasonable head so that it can be measured accurately. This implies that you need to have some idea of the discharge to be measured before you can select the right weir size to measure it. If the head is only say, 4 mm then 1 mm error in measuring it is a 25% error and will result in a significant error in the discharge. However, if the head is 100 mm then a 1 mm error in measuring the head is only a 1% error and so is not so significant.

Sharp-crested weirs can be very accurate discharge measuring devices provided they are constructed carefully and properly installed. However, they can be easily damaged, in particular the sharp crest. If this becomes rounded or dented through impact with floating debris, the flow pattern over the weir changes and this reduces its accuracy. For this reason they tend to be unsuited for long-term use in natural channels but well suited for temporary measurements in small channels, in places where they can be regularly maintained and for accurate flow measurement in laboratories.

7.5 Solid weirs

These are much more robust than sharp-crested weirs and are used extensively for flow measurement and water level regulation in rivers and canals (Figure 7.5a).

All solid weirs work on the principle *that the flow over the weir must go through the critical depth*. The idea of critical depth was discussed in Chapter 6 where it was shown that it was the height of a weir which determined whether or not the flow goes critical. Once this happens a formula for discharge can be developed using the concept of specific energy and the special conditions that occur at the critical point.

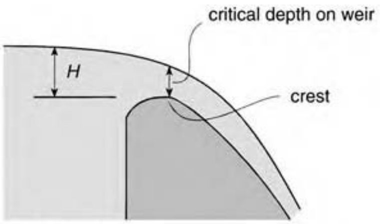
The formula links the channel discharge (Q) with the upstream water depth *measured above the weir crest* (H).

$$Q = CLH^{1.5}$$

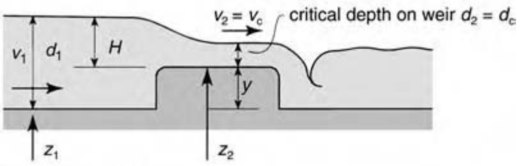
where C is weir coefficient; L is length of the weir crest (m); H is head on the weir measured from the crest (m).

To see how this formula is developed see the box.

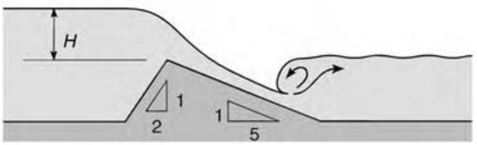
As there is some draw down close to the weir, the head is usually measured a few metres upstream where the water level is unaffected by the weir.



(a) Solid weir



(b) broad-crested weir



(c) Crump weir

7.5 Solid weirs.

DERIVATION: FORMULA FOR DISCHARGE OVER A CRITICAL FLOW STRUCTURE

Derive a formula for discharge for a critical flow structure in an open channel. Use a broad-crested weir as an example of a critical flow structure, although the analysis would be the same for any similar structure (Figure 7.5b).

First write down the total energy equation for the flow in the channel (point 1) and the flow on the weir (point 2):

total energy at point 1 = total energy at point 2

$$d_1 + \frac{v_1^2}{2g} + z_1 = d_2 + \frac{v_2^2}{2g} + z_2$$

Now:

$$z_2 - z_1 = y$$

That is, the height of the weir is equal to the difference in the potential energy and so:

$$d_1 + \frac{v_1^2}{2g} = d_2 + \frac{v_2^2}{2g} + y$$

But at the critical depth:

$$d_2 = d_c$$

And:

$$v_2 = v_c$$

Substitute these into the energy equation:

$$d_1 + \frac{v_1^2}{2g} = d_c + \frac{v_c^2}{2g} + y$$

But at the critical depth:

$$\frac{v_c^2}{2g} = \frac{d_c}{2}$$

(See derivation of the formula for critical depth in Section 5.7.4.) Put this into the equation:

$$d_1 + \frac{v_1^2}{2g} = d_c + \frac{d_c}{2} + y$$

Rearrange this:

$$d_1 + \frac{v_1^2}{2g} - y = \frac{3}{2}d_c$$

But critical depth can be calculated from the formula:

$$d_c = \sqrt[3]{\frac{q^2}{g}}$$

(See derivation of the formula for critical depth in Section 5.7.4.) Also put:

$$d_1 + \frac{v_1^2}{2g} - y = H$$

This means that *H* is measured from the weir crest and so:

$$H = \frac{3}{2}\sqrt[3]{\frac{q^2}{g}}$$

Rearrange this for *q*:

$$q = \left(\frac{2}{3}\right)^{3/2} g^{1/2}H^{3/2}$$

$$q = 1.71H^{3/2}$$

This is the theoretical flow and an allowance now needs to be made for minor energy losses. This is usually combined with the 1.17 and introduced as a coefficient *C*. So:

$$q = CH^{1.5}$$

Here q is the discharge per unit width and so the full discharge Q is calculated by multiplying this by the length of the weir L:

$$Q = CLH^{1.5}$$

Note that strictly speaking H is the measurement from the weir crest to the energy line as it includes the kinetic energy term. In practice H is measured from the weir crest to the water surface. The error involved in this is relatively small and can be taken into account in the value of the weir coefficient C.

As the formula is based on critical depth it is not dependent on the shape of the weir. So the same formula can be used for any critical-depth weir, not just for broad-crested weirs. Only the value of C changes to take account of the different weir shapes.

7.5.1 Determining the height of a weir

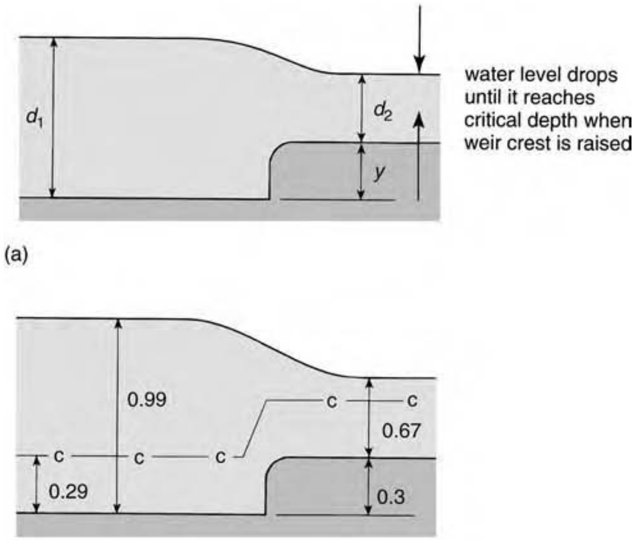
Just how high a weir must be for the flow to go critical is determined from the specific energy diagram. The effect of constructing a weir in a channel is the same as building a step up on the bed as described in Section 5.7.3. This was concerned only with looking at what happens to the depth when water flows over a step. In the case of a step up, the depth on the step decreased and the velocity increased (Figure 7.6a). At that time no thought was given to making the flow go critical. A worked example showed that for a 0.3 m high step up, the depth of water was reduced from 0.99 m upstream to 0.67 m on the step (this is summarised in Figure 7.6b). This is still well above the critical depth of 0.29 m (see calculation in Section 5.7.4).

Now assume that the step up on the bed is a weir and the intention is to make the flow go critical on the weir crest. This can be achieved by raising the crest level. Raising it from 0.3 m to 0.56 m further reduces the depth on the weir from 0.67 m to 0.29 m which is the critical depth (Figure 7.6c) (this can be worked out using the specific energy diagram in Section 5.7.3). This is the minimum weir height required for critical flow. Note that although the weir height has increased by 0.26 m, the upstream depth remains unchanged at 0.99 m. If the weir height is increased beyond 0.56 m the flow will still go critical on the crest and remain at the critical depth of 0.29 m. It will not and cannot fall below this value. The difference will be in the upstream water level upstream which will now rise. Remember there is a unique relationship between the head on a weir and the discharge. So if the weir is raised by a further 0.1 m to 0.66 m the upstream water level will also be raised by 0.1 m to maintain the correct head on the weir (Figure 7.6d).

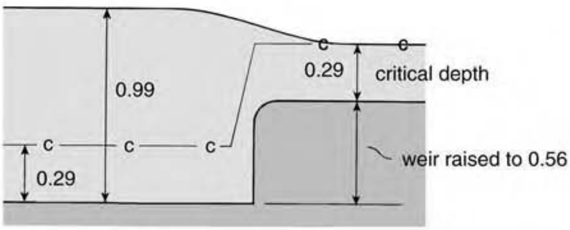
The operation of weirs is often misunderstood and it is believed that they cause the flow to back up and so raise water levels upstream. This only happens once critical conditions are achieved on the weir. When a weir is too low for critical flow it is the water level on the weir which drops. The upstream level is unaffected. But once critical flow is achieved, raising the weir more than is necessary will have a direct effect on the upstream water level.

7.5.1.1 Being sure of critical flow

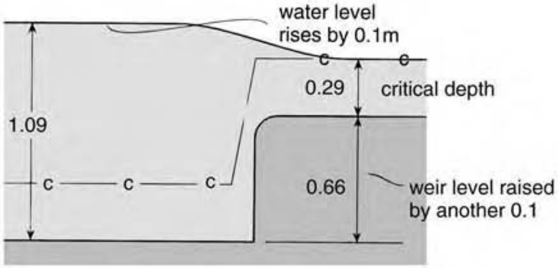
Critical flow must occur for the discharge formula to work. But in practice it is not always possible to see critical flow and so some detective work is needed. Figure 7.7 shows the changing flow conditions as water flows over a weir. Upstream the flow is sub-critical, it then



(b) Sub-critical flow on weir



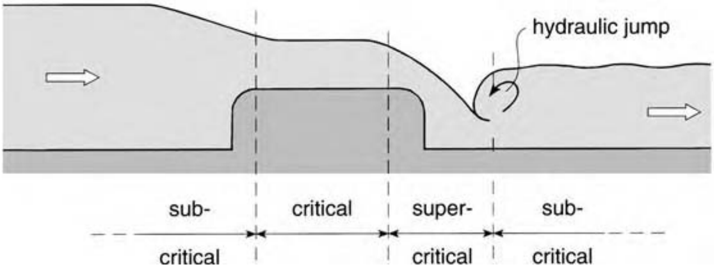
(c) Flow goes critical on weir



(d) Raising weir crest level affects upstream water level

7.6 Determining the height of a weir.

goes critical over the weir and then super-critical downstream. It changes back to sub-critical through a hydraulic jump. When this sequence of changes occurs it can be reasoned that critical flow must have occurred and so the weir is working properly. The changes are best verified in reverse from the downstream side. Remember a hydraulic jump can only form when the flow is super-critical and so if there is a hydraulic jump in the downstream channel, the flow over the



7.7 Being sure of critical flow.

weir must be super-critical. If the upstream flow is sub-critical, which can be verified by the water surface dropping as water flows over the weir, then somewhere in between the flow must have gone critical. So a hydraulic jump downstream is good evidence that critical flow has occurred.

Note that it is not important to know exactly where critical flow occurs. It is enough just to know that it has occurred for the formula to work.

7.5.2 Broad-crested weirs

These are very common structures used for flow measurement. They have a broad rectangular shape with a level crest rounded at the edge (Figure 7.5b). The value of *C* for a broad-crested weir is 1.6 and so the formula becomes:

$$Q = 1.6\,L\,H^{1.5}$$

One disadvantage of this weir is the region of dead water just upstream. Silt and debris can accumulate here and this can seriously reduce the accuracy of the weir formula. Another is the head loss between the upstream and downstream levels. Whenever a weir (or a flume) is installed in a channel there is always a loss of energy particularly if there is a hydraulic jump downstream. This is the hydraulic price to be paid for measuring the flow.

EXAMPLE: CALCULATING DISCHARGE USING A BROAD-CRESTED WEIR

A broad-crested weir is used to measure discharge in a channel. If the weir is 2 m long and the head on the crest is 0.35 m, calculate the discharge.
The discharge over a broad-crested weir can be calculated using the formula:

$$Q = 1.6\,L\,H^{1.5}$$

Put in values for length L and head H:

$$Q = 1.6 \times 2 \times 0.35^{1.5}$$

$$Q = 0.66\ \text{m}^3/\text{s}$$

7.5.3 Crump weirs

These weirs are commonly used in the UK for discharge measurement in rivers. Like the broad-crested weir it relies on critical conditions occurring for the discharge formula to work. It has a triangular-shaped section (Figure 7.5c). The upstream slope is 1 in 2 and the downstream is 1 in 5. The sloping upstream face helps to reduce the dead water region which occurs with broad-crested weirs. It can also tolerate a high level of submergence. Its crest can also be constructed in a vee shape so that it can be used accurately for both small and large discharges.

7.5.4 Round-crested weirs

Weirs of this kind are commonly used on dam spillways (Figure 7.5a). The weir profile is carefully shaped so that it is very similar to the underside of the falling nappe of a sharp-crested weir (compare the two shapes in Figure 7.5a and Figure 7.4b). Many standard designs are available which have been calibrated in the laboratory using hydraulic models to obtain the C values. An example is the standard weir designs produced by the US Bureau of Reclamation (see references for details). By constructing a weir to the dimensions given in their publications, the discharge can be measured accurately using their C values (usually between 3.0 and 4.0).

7.5.5 Drowned flow

Weirs which rely on critical depth are much less sensitive to being *drowned* (or *submerged*) than the sharp-crested type. This means that the downstream water level can rise above the weir crest without it affecting the performance of the structure *provided* the flow still goes critical somewhere on the weir. There are ways of using weirs even when they are completely submerged but they are far less accurate and both upstream and downstream water depths must be measured. It is better to avoid this situation if at all possible.

7.6 Flumes

Flumes also rely on critical flow for measuring discharges. They are sometimes called *throated flumes* because critical conditions are achieved by narrowing the width of the channel (Figure 7.8). Downstream of the throat there is a short length of super-critical flow followed by a hydraulic jump. This returns the flow to sub-critical. The formula for discharge can be determined in the same way as for solid weirs. The result is as follows:

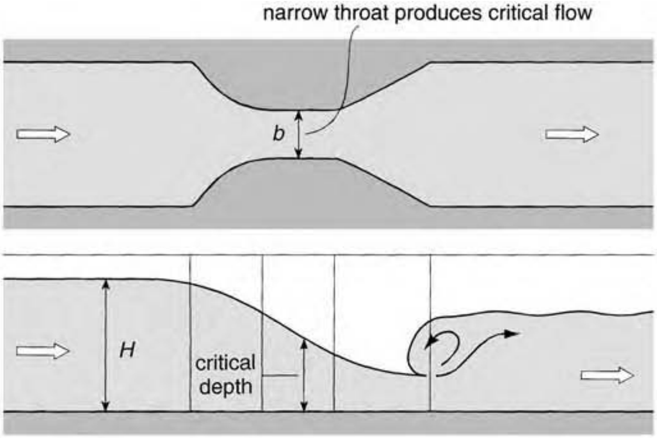
$$Q = 1.65\, b\, H^{1.5}$$

where b is width of the flume throat (m); H is upstream depth of water (m).

The head loss through flumes is much lower than for weirs and so they are ideally suited for use in channels in very flat areas where head losses need to be kept as low as possible.

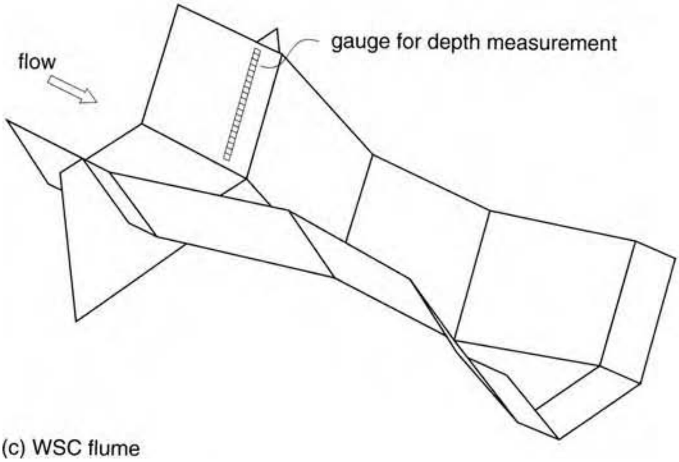
7.6.1 Parshall flumes

Parshall flumes are used extensively in the USA and were developed by R.L. Parshall in 1926 (Figure 7.8b). They gained popularity in many other countries because the construction details, dimensions and calibration curves relating upstream depth to discharge have been widely published. There are several different sizes available to measure flows up to 90 m^3/s. They are



(a) Venturi flume

(b) Parshall flume



(c) WSC flume

7.8 Flumes.

relatively simple to construct from a range of materials such as wood, concrete and metal because they have no curved surfaces.

If they are made and installed as recommended they provide accurate discharge measurement.

7.6.2 WSC flumes

This is a range of standard flumes for measuring small discharges from less than 1.0 l/s up to 50 l/s developed by Washington State University in USA (Figure 7.8c). They are vee-shaped so that they can be used to measure low flows accurately and, like Parshall flumes, they can be easily made up in a workshop from metal or glass fibre. They are particularly useful as portable flumes for spot measurements in small channels and irrigation furrows.

7.6.3 Combination weir-flumes

Sometimes both weir and flume effects are combined to achieve critical flow. The advantages of the vee for low flows can also be added. In such cases a laboratory model test is needed to determine the *C* value in the discharge equation.

7.7 Discharge measurement

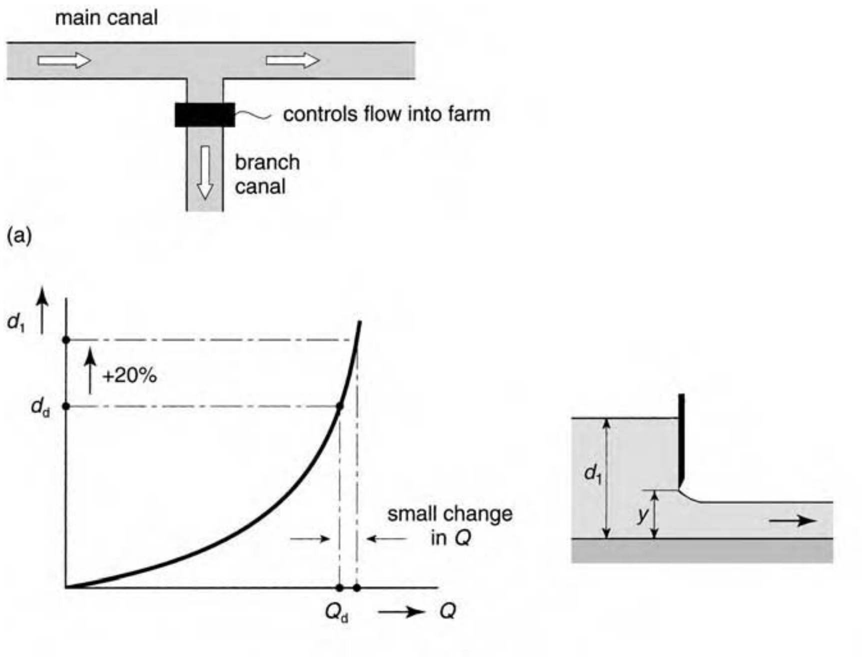
Weirs, flumes and orifices can all be used for discharge measurement. But weirs and flumes are better suited to measuring discharges in rivers when there can be large variations in flow. Weirs and flumes not only require a simple head reading to measure discharge but they can also pass large flows without causing the upstream level to rise significantly and cause flooding. Orifice structures too can be used for flow measurement but both upstream and downstream water levels are usually required to determine discharge. Large variations in flow also mean that the gates will need constant attention for opening and closing.

7.8 Discharge control

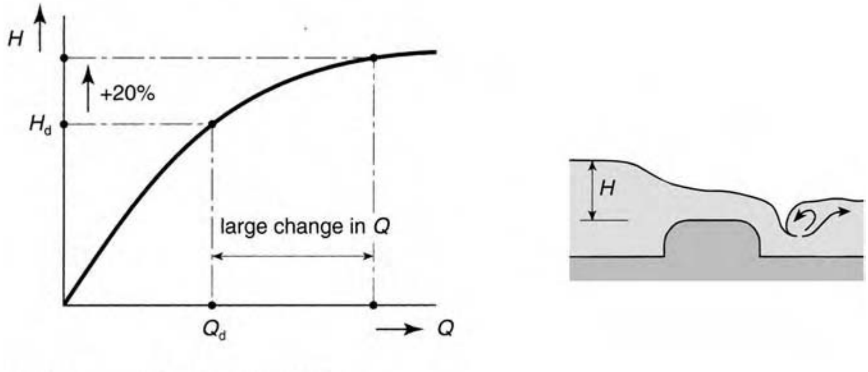
Although orifices are rather cumbersome for discharge measurement they are very useful for discharge control. This is because the discharge through an orifice is not very sensitive to changes in upstream water level. Consider as an example, an irrigation canal system where a branch canal takes water from a main canal (Figure 7.9a). The structure at the head of the branch controls the discharge to farmers downstream. The ideal structure for this would be an orifice and the reason lies in its hydraulic characteristic curve (Figure 7.9b). This is a graph of the orifice discharge equation:

$$Q = C\sqrt{2gd_1}$$

In this simple example, the orifice opening is assumed to be fixed and so discharge *Q* changes only when the upstream depth d_1 changes. The point Q_d and d_d on the graph represents the normal operating condition. Now suppose the main canal operating depth rises by say, 20%, because of changes in the water demand elsewhere in the system. The effect that this would have on the discharge into the branch (through the orifice) is to change it by only 5%. So even though there is a significant change in the main canal this is hardly noticed in the branch. This can be very useful for ensuring a reliable, constant flow to a farmer even though the main canal may be varying considerably due to changing demands.



(b) Using an orifice for discharge control



(c) Using a weir for discharge control

7.9 Discharge control.

In contrast, if a weir (or flume) is installed at the head of the branch canal, it would be very easy to use for discharge measurement but it would not be so good for controlling the flow. Again look at the hydraulic characteristic curve for a weir (Figure 7.9). This is a graph of the weir discharge equation:

$$Q = CLH^{1.5}$$

Q_d and H_d represent the normal operating condition. Now if the water level in the main canal rises by 20% this almost doubles the discharge in the branch canal. So this type of structure is very sensitive to water level changes and would not make a very good discharge control structure.

These examples show the sensitivity of the two types of control structure. This is how they react to small changes in water level. But they refer to fixed structures. Most structures have gates (both weirs and orifices) which can be used to adjust the discharge but this adds to the burden of managing the channels. Better to use a structure which is hydraulically suited to the job to be done and which reduces the need for continual monitoring and adjustment.

7.9 Water level control

Orifices, weirs and flumes can all be used for water level control. But the very reason that makes an orifice a good discharge regulator make it unsuitable for good water level control. Conversely, a weir (or flume) is well suited to water level control but not for discharge control.

Imagine the water level in a river needs to be controlled to stabilise water levels in a nearby wetland site and it needs to be more or less the same both winter and summer even though the river flows change from a small flow to a flood. The structure best suited for this would be a weir as it can pass a wide range of flows with only small changes in head (water level). An orifice structure would not be suitable because large changes in water level would occur as the flow changed and the structure would require a great deal of attention and adjustment.

Another water level control problem occurs in reservoirs. When a dam is built across a river to store water, a spillway is also constructed to pass severe flood flows safely into the downstream channel to avoid over-topping the dam. The ideal structure for this is a weir because large discharges can flow over it for relatively small increases in water level. The rise in water level can be calculated using the weir discharge formula and this helps to determine the height of the dam. A freeboard is also added to the anticipated maximum water level as an added safety measure. The spillway can be the most expensive part of constructing a new dam. Many small dams are built on small seasonal streams in developing countries to conserve water for domestic and agricultural use. But even a small dam will need a spillway and although the stream may look small and dry up occasionally, they can suffer from very severe floods which are difficult to determine in advance, particularly when rainfall and discharge data for the stream are not available. Building a spillway for such conditions can be prohibitively expensive and far exceed the cost of the dam and so it may be cheaper in sparsely populated areas to let the dam be washed away and then re-build it on the rare occasions that this happens. There are of course many other factors to take into account besides dam reconstruction costs, such as the effects downstream of a dam break. It is a sobering thought that even the biggest and most important dams can fail because of severe flooding. They have large spillways to protect them from very severe floods which are carefully assessed at the design stage. But it is impossible to say that they will safely carry every flood. Nature seems to have a way of testing us by sending unexpected rainstorms but fortunately these events are few and far between.

One way of avoiding the expensive spillway problem is to construct a reservoir at the side of a river rather than use the river channel itself. This is called *off-stream storage*. Water is taken from the river by gravity or by pumping into a reservoir and only a modest spillway is then needed which would have the same capacity as the inlet discharge. When a flood comes down the river there is no obstruction in its path and so it flows safely pass the reservoir.

7.10 Energy dissipators

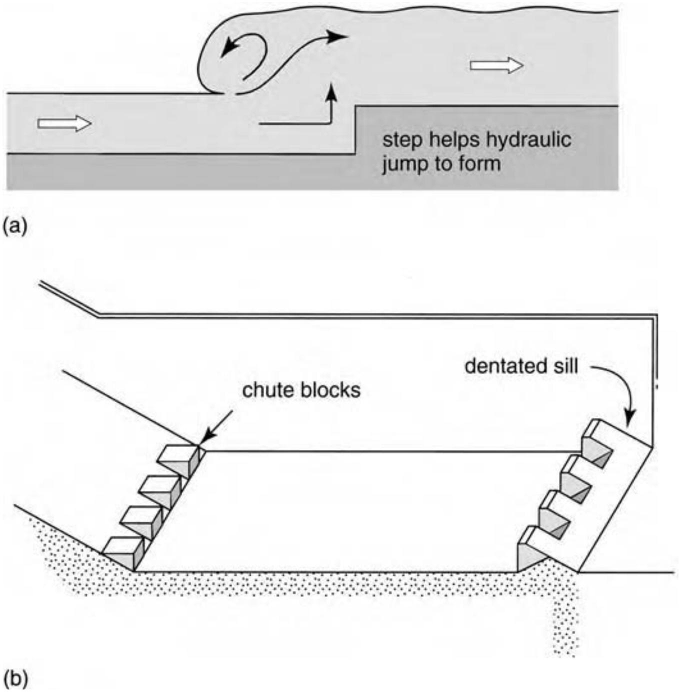
7.10.1 Stilling basins

When water flows over a weir or through a flume and becomes super-critical it can do a lot of damage to the downstream channel if it is left unprotected. This is particularly true when water rushes down an overflow spillway on a dam. The water can reach very high velocities by the time it gets to the bottom. Scour can be prevented by lining the channel but this can be an expensive option.

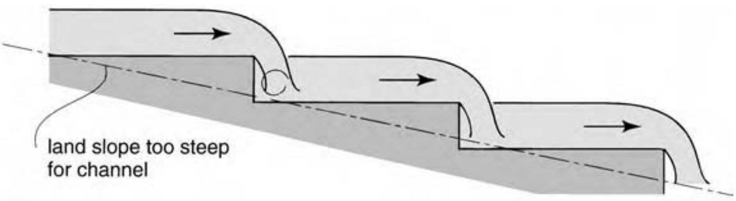
The alternative is to convert the flow to sub-critical using a hydraulic jump. The requirements for a jump are super-critical flow upstream and sub-critical flow in the downstream channel. The main problem is to create the right flow conditions in the downstream channel for a jump to occur even though the discharge may range from a small overspill flow to a large flood. Consider what happens when flow reaches the bottom of a spillway. If the tail-water is too shallow for a jump to form the super-critical flow will shoot off downstream and no jump will form. If the water is too deep the jump will be drowned and the super-critical flow will rush underneath and still cause erosion for some distance downstream. These problems can be resolved by building *stilling basins* which create and confine hydraulic jumps even though the tail-water may not be at the ideal depth for a jump to occur naturally. There are many different designs available but perhaps the simplest is a small vertical wall placed across the channel (Figure 7.10a). Other more sophisticated designs have been developed in laboratories using models as it is not possible to design them using formulae. The choice of stilling basin is linked to the Froude Number of the upstream super-critical flow (Figure 7.10b).

7.10.2 Drop structures

Drop structures are used to take flow down steep slopes step by step to dissipate energy and so avoid erosion (Figure 7.11). Channels on steep sloping land are prone to erosion because of the high velocities. One option to avoid this is to line channels with concrete or brick but another is to construct natural channels on a gentle gradient and to build in steps like a



7.10 Stilling basins.



(a)

(b) Drop structure on an irrigation canal in Iraq

7.11 Drop structures.

staircase. The water flows gently and safely along the shallow reaches of channel and then drops to the next reach through a drop structure. Often a drop is made into a weir so that it can also be used for discharge measurement. It can also be fitted with gates so that it can be used for water level and discharge control. Drop structures are usually combined with stilling basins so that unwanted energy is got rid of effectively.

7.11 Siphons

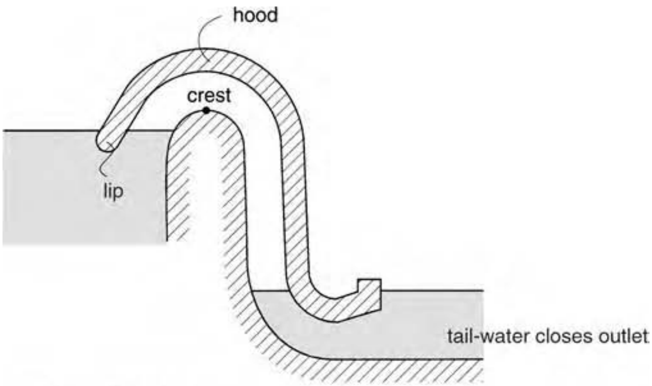
Siphons are hydraulic structures which have always fascinated engineers. Used long ago by ancient Greeks and Egyptians, they began to be used seriously in civil engineering in the mid-19th century as spillways on storage reservoirs. More recently, their special characteristics have been put to use in providing protection against sudden surges in hydropower intakes and in controlling water levels in rivers and canals subjected to flooding.

Although siphons have been successfully installed in many parts of the world, there is still a general lack of guidelines for designers. This is borne out by the wide variety of siphon shapes and sizes that have been used. Invariably design is based on intuition and experience of previous siphon structures, and few engineers would attempt to install such a structure without first carrying out a model study.

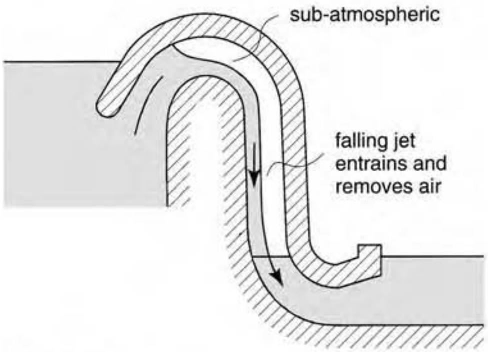
The principle of siphon operation is described in Section 4.7 in connection with pipe flow. In its very simplest form it is a pipe which rises above the hydraulic gradient over part of its length. The following siphon structures, although more sophisticated than a pipe, still follow this same principle.

7.11.1 Black-water siphons

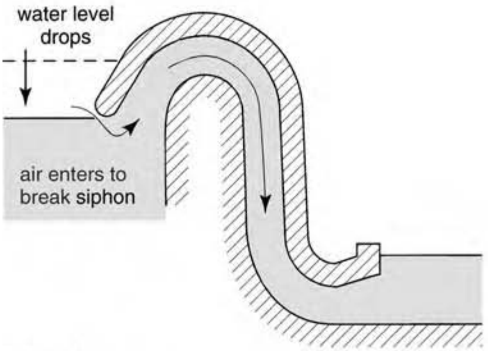
These are the most common types of siphon; Figure 7.12 shows how one can be used as a spillway from a reservoir. It consists of an enclosed barrel which is sealed from the atmosphere by the upstream and downstream water levels. The lower part is shaped like a weir and the upper part forms the hood.



(a) Typical siphon design



(b) Priming



(c) Depriming

7.12 Black-water siphon.

Water starts to flow through a siphon when the upstream water level rises above the crest. As the flow plunges into the downstream water it entrains and removes air from inside the barrel. As the barrel is sealed, air cannot enter from outside and so the pressure gradually falls and this increases the flow rate until the barrel is running full of water. At this stage the siphon is said to be *primed* and flow is described as *black-water flow*. This is in contrast to the flow just before priming when there is a lot of air entrained and it has a white appearance. This is termed *white-water flow*.

Priming takes place rapidly until the discharge reaches the siphon's full capacity. This is determined by the size of the barrel and the difference in energy available across the siphon. The siphon eventually starts to draw down the upstream water level and this continues even when the water level falls below the crest. Only when it is drawn down to the lip on the hood on the inlet can air enter the barrel and break the siphonic action. Flow then stops rapidly and will only begin again when the siphon is reprimed.

Black-water siphons have several advantages over conventional spillways. There are no moving parts such as gates and so they do not need constant attention from operators. They respond automatically, and rapidly, to changes in flow and water levels and so floods which come unexpectedly in the night do not cause problems. Their compactness also means that they are very useful when crest lengths for conventional weir spillways are limited. But they are not without problems. The abruptness of priming produces a sudden rush of water which can cause problems downstream. They are also prone to *hunting* when the flow towards a siphon is less than the siphon capacity. They are continually priming and de-priming and this can cause surges downstream and vibration which is not good for the structure.

7.11.2 Air-regulated siphons

This type of siphon is a more recent development and offers many advantages over the more common black-water siphon. It automatically adjusts its discharge to match the approach flow and at the same time maintains a constant water level on the upstream side. This is achieved by the siphon passing a mixture of air and water.

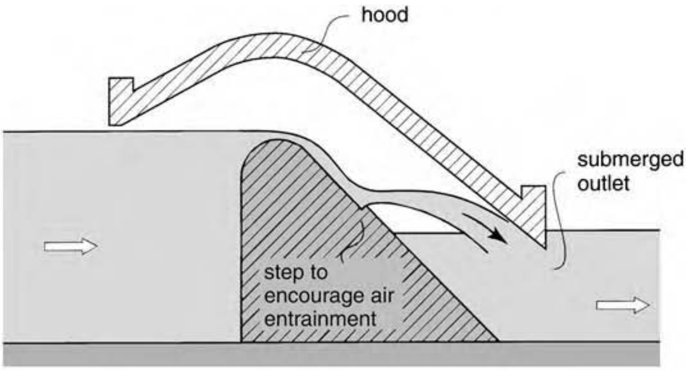
Air-regulated siphons are typically used for water level control in reservoirs and in rivers and canals. They will maintain a constant water level in a channel even though the discharge is changing. This would be an ideal structure for the wetland example discussed earlier.

Figure 7.13a shows a typical air-regulated siphon for a river. There needs to be sufficient energy available to entrain air in the barrel and take it out to prime the siphon. This one is designed to operate at very low heads of 1–2 m (difference between the upstream and downstream water levels). The siphon is shaped in many ways like a black-water siphon and relies on the barrel being enclosed and sealed by the upstream and downstream water levels. But the main difference is the inlet to the hood or upstream lip. This is set above the crest level whereas in a black-water siphon it is set below. A step is also included in the down-leg to encourage turbulence and air entrainment.

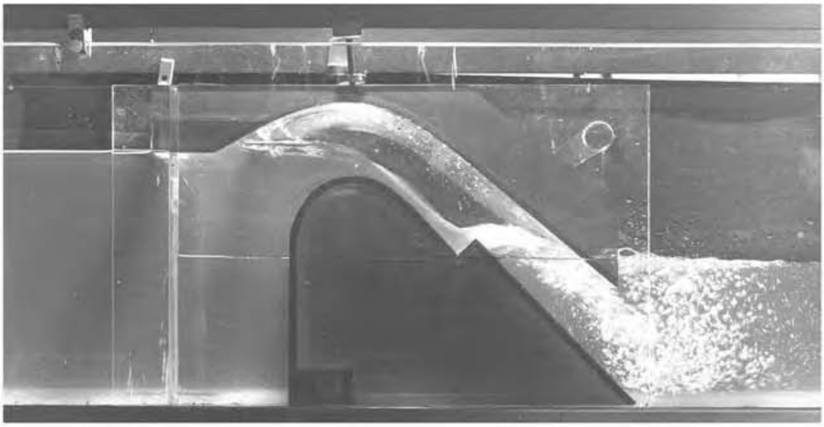
The operation of the siphon has several distinct phases (Figure 7.13 a–e):

Phase I – Free weir flow (Figure 7.13a) As the upstream water level starts to rise due to increased flow, water flows over the crest and plunges into the downstream pool. The structure behaves as a conventional free flowing weir. As the water level has not yet reached the upstream lip, air which is evacuated by the flow is immediately replaced and the pressure in the barrel remains atmospheric.

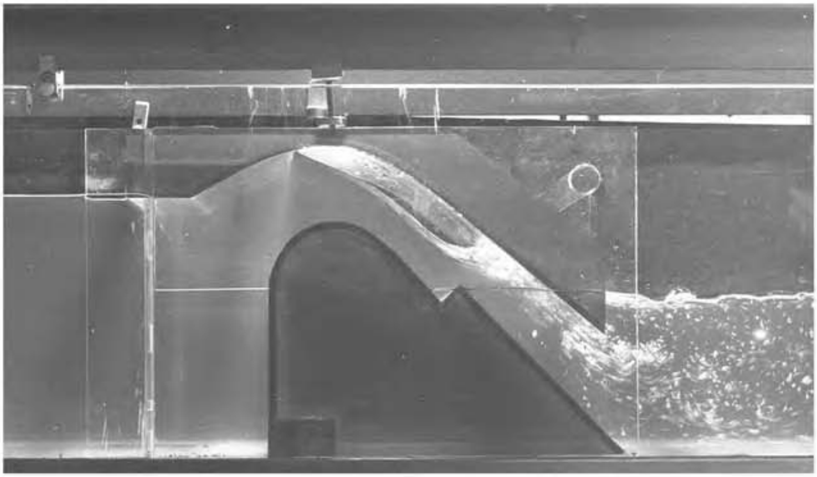
Phase II – Deflected flow (Figure 7.13b and c) As the flow increases, the upstream water level rises further and seals the barrel. The evacuation of air continues and a partial vacuum is created. This raises the head of water over the crest and so increases the discharge



(a) Phase I

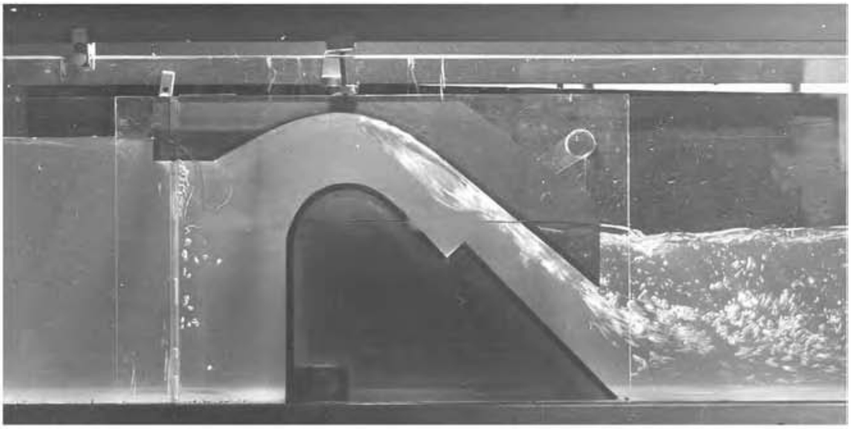


(b) Phase II begins

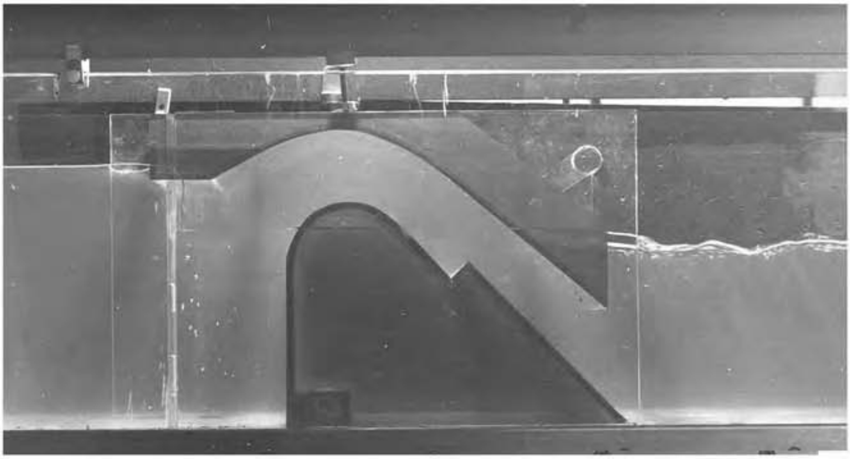


(c) Phase II

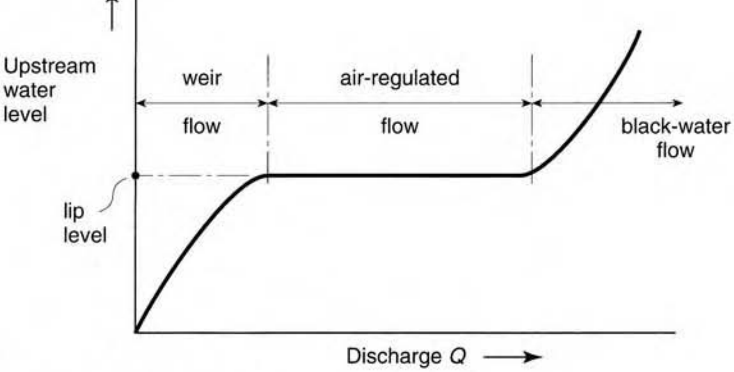
7.13 Air-regulated siphon.



(d) Phase III



(e) Phase IV



(f) Discharge characteristic

7.13 Continued.

through the siphon. A point is reached when the flow through the siphon exceeds the incoming flow. The water surface close to the lip is drawn down and air is sucked into the barrel to compensate for the evacuation taking place on the downstream side. This process is not cyclic but continuous. Both air and water are drawn continuously through the structure. In this manner the siphon adjusts rapidly and smoothly to the incoming flow and is said to be self-regulating. As the flow passes over the weir it is deflected by a step and springs clear of the structure. This encourages air entrainment and evacuation at low flows and it not intended to create an air seal as in the case of some black-water siphons.

Phase III – Air-partialised flow (Figure 7.13d) As the flow increases, the water level inside the hood rises to a point where the air pocket is completely swept out and the siphon barrel is occupied by a mixture of air and water. Changes in the discharge are now accommodated by variations in the quantity of air passing through the siphon and not by an increase in the effective head over the weir crest.

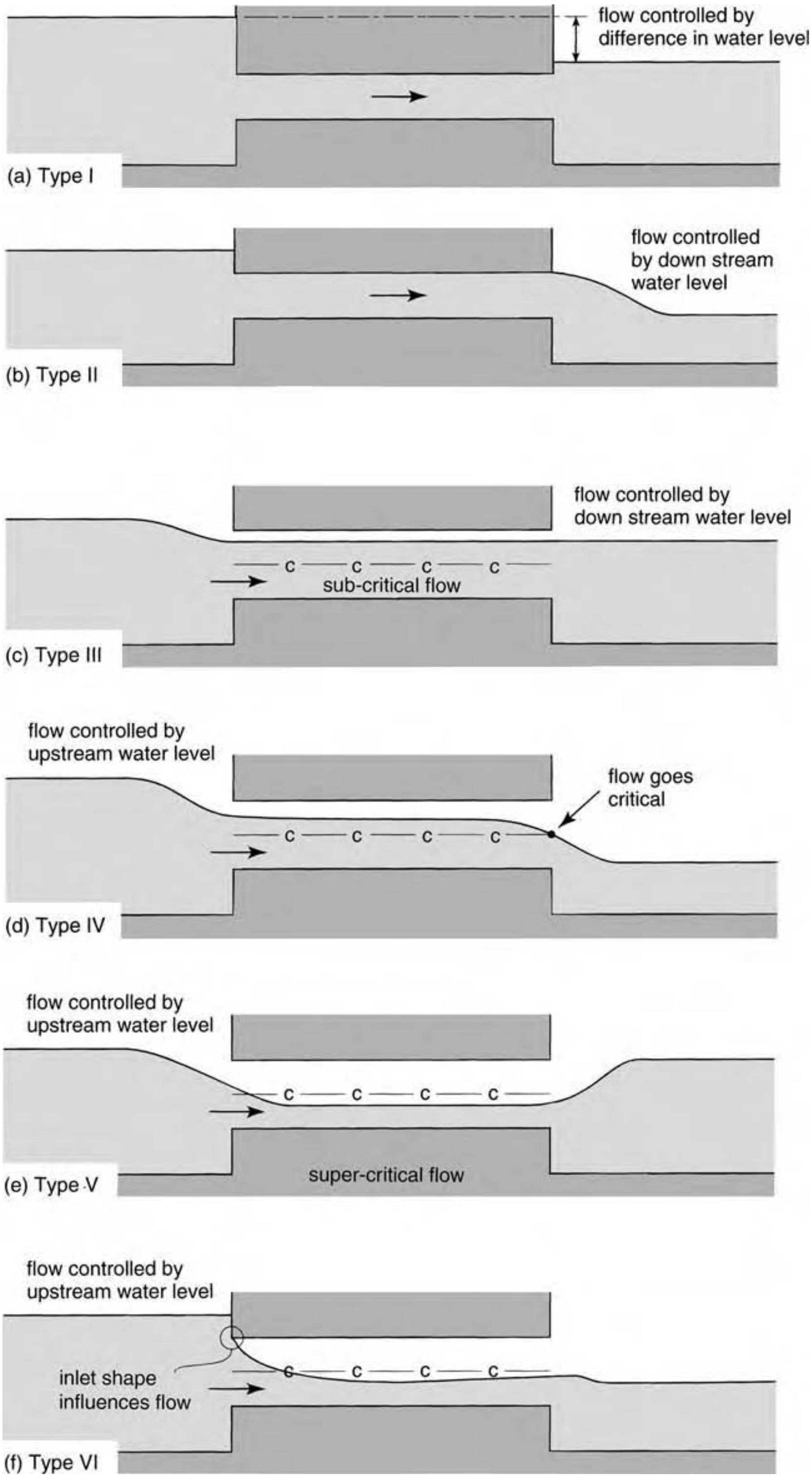
Phase IV – Black-water flow (Figure 7.13e) Increasing the flow beyond the air-partialised phase produces the more common black-water flow in which the barrel is completely filled with water. The discharge is now determined by the head across the siphon, that is, the difference between the upstream and downstream water levels.

The flow changes from one phase to another quite gradually and smoothly and there is no distinct or abrupt change over point. During phases II and III, the upstream water level remains relatively constant at a level close to that of the upstream lip. This feature makes this structure an excellent water level regulator. Only when the black-water phase is reached does an increase in discharge cause a significant rise in the upstream water level (Figure 7.13f).

7.12 Culverts

Culverts are very useful structures for taking water under roads and railways. They are circular or rectangular in shape and their size is chosen so that they are large enough to carry a given discharge, usually with minimum energy loss (Figure 7.14). They are important structures and can be as much as 15% of the cost of building a new road.

7.14 Culverts.



7.15 Culvert flow conditions.

Although they are very simple in appearance culverts can be quite complex hydraulically depending on how and where they are used. Sometimes they flow part full, like an open channel and other times they can flow full, like a pipe. Six different flow conditions are recognised depending on the size and shape of a culvert, its length and its position in relation to the upstream and downstream water level (Figure 7.15).

The simplest condition occurs when a culvert is set well below both the upstream and downstream water levels and it runs full of water (type I). It behaves like a pipe and the difference between the water levels is the energy available which determines the discharge. This full pipe flow can still occur even when the downstream water level falls below the culvert soffit (this is the roof of the culvert) (type II). The culvert is now behaving like an orifice and the flow is controlled by the upstream water level and the size of the culvert. In both cases the discharge is controlled by what is happening downstream. When the water level falls the discharge increases and when it rises the discharge decreases. If the flow in the channel does not change then any change in the downstream water level will have a corresponding effect on the upstream water level.

The four remaining flow conditions are for open channel flow. Three occur when both the upstream and downstream water levels are below the culvert soffit (type III, IV and V). The difference between III and IV is the slope of the culvert. III produces sub-critical flow and so the discharge is controlled by the downstream water level. When the downstream level rises the discharge reduces or the upstream level rises to accommodate the same flow. In IV, the flow is still sub-critical but the downstream water level is low and so the flow goes through the critical depth at the outlet. This means that the flow is controlled by the upstream level. Because the flow has gone through the critical depth any changes downstream do not affect the flow in the culvert or upstream. Condition V produces super-critical flow and so the culvert is again controlled by the upstream level. A rise in the downstream level will have no effect until it starts to drown the culvert.

The final condition occurs when the upstream water level is above the soffit, the downstream level is below and there is a sharp corner at the entrance causing the flow to separate (type IV). Open channel flow occurs in the culvert and is primarily due to the shape of the entrance. But if the entrance is rounded then this could change the flow to pipe flow. Clearly this would improve its discharge capacity.

Because of their complexity, and particularly the importance of the shape of the entrance, most culvert designs are based on model tests rather than on fundamental formulae. But this does not mean that every culvert must be tested in this way. There has already been extensive testing of culverts over many years and so designers look to the standard handbooks when deigning new culverts (see references for details).

7.13 Some examples to test your understanding

1 A broad-crested weir 3.5 m wide is to be constructed in a channel to measure a discharge of 4.3 m^3/s. When the normal depth of flow is 1.2 m, calculate the height of weir needed to measure this flow assuming that the flow must go critical on the weir crest (0.4 m).

2 A broad-crested weir is 5.0 m wide and 0.5 m high is used to measure a discharge of 7.5 m^3/s. Calculate the water depth upstream of the weir assuming that critical depth occurs on the weir and there are no energy losses (1.45 m).