Detention ponds

While authorities in the USA stipulate detention times for certain areas, the general use of this technology to settle out suspended solids and for the treatment of other pollutants from runoff in South Africa appears remote, as the incoming runoff usually has a high clay content. Siltation occurs in all dams. However, from a purification point of view, it is not considered economically feasible in detention facilities to settle out the products of erosion (i.e fine silts and clays). Detention times would need to be very long, and therefore require large areas of land. Retention facilities should rather be considered for their beneficial use as water bodies and integrated with the natural drainage corridors which allow other natural processes to occur (e.g. wetlands).

Wetlands

Background

Walmsley (1987) defined wetlands as "water dominated areas with impeded drainage where soils are saturated with water and there is a characteristic *fauna* and *flora*". Other items such as *vleis*, water sponges, marshes, bogs, swamps, pans, river meadows and riverine areas are often included in references to wetlands. Their ecological importance has often been emphasised, and many municipalities and industries are using artificial wetlands to treat waste water (Gillette 1993).

Wetlands purification functions

The principle function of the vegetation in wetlands is to create additional environments for microbial populations. The stems and leaves in the water obstruct flow, facilitate sedimentation and increase the surface area for the attachment of microbes, and constitute thin films of reactive surfaces.

Wetland plants also increase the amount of aerobic microbial environment in the substrate. This is incidental to the unique adaptation of wetland plants to thrive in saturated soils. Most terrestrial plants cannot survive in waterlogged soils for any appreciable length of time due to the oxygen depletion which normally follows flooding. Unlike their terrestrial relatives, wetland plants have specialised structures which enable them to conduct atmospheric gases, including oxygen, down into the roots. This oxygen leaks out of the root hairs, forming an aerobic rhizosphere around every root hair, while the remainder of the subsurface water volume remains anaerobic. This juxtaposition of aerobic/anaerobic environments is crucial to the transformation of nitrogenous compounds and other substances.

Microbial organisms

Microbes (bacteria, fungi, algae and protozoa) alter contaminant substances in order to obtain nutrients or energy to complete their life-cycles. The effectiveness of wetlands in water purification is dependent on developing and maintaining optimal environmental conditions for the desirable microbial populations. Most of the desirable microbes are ubiquitous and are likely to be found in most waste waters with nutrients and energy; hence inoculation of specific strains is generally not necessary.

Substrate

The primary role of the substrate, whether soil, gravel or sand, is to provide a support for the plants and a surface for attachment by microbial populations. The substrate can also be selected on the basis of its chemical characteristics, where pollutant removal is achieved through complexing - a chemical and physical process allowing more complex substances to be formed, which then remain in the substrate zone (Batchelor 1993).

Plant selection

The diversity and complexity of natural wetland vegetation is principally the result of interactions between the following three important factors:

- hydrology;
- substrate; and
- climate.

In constructing a wetland - if the intention is to attempt to reproduce a "natural" wetland - a thorough knowledge of local wetland vegetation is a distinct advantage. If, however, the intention is to use the wetland for water purification, there are a number of universal species that can be used. By far the most commonly used genera are *Phragmites*, the common reed and *Typha* (referred to locally as the bulrush). Other genera that have been used successfully are various *Scirpus* and *Cyperus* species.

Advantages of constructed wetlands

Constructed or created wetlands simulate processes occurring in the natural wetland system. These include

- flood attenuation (if properly designed); and
- water-quality improvement through the removal of substances such as suspended solids, nitrogen, trace metals, bacteria and sulphates.

These are only a few of the substances wetlands are able to remove. Their effective functioning is dependent on the pressure of environmental conditions conducive to the required processes. They are not dependent on external energy or chemical inputs. Wetlands also require little maintenance.

In addition to their water purification functions, wetlands provide habitats and life-support systems for a wide range of flora and fauna, particularly birds, plants, reptiles and invertebrates. Wetlands can be aesthetically pleasing and offer an opportunity for recreation and education. See Figure 6.25.

Figure 6.25: Part detention, part retention facility, including an artificial wetland

Protection of the environment during the construction phase

Erosion protection

One of the most unstable periods in any development occurs during the construction phase. Runoff from sites should be collected in temporary check dams (see below). Straw bales can be positioned at kerb inlets to prevent silt entering the underground drainage systems while construction is taking place. Figures 6.26 and 6.27 illustrate the examples of temporary erosion protection.

Figure 6.26 (a): Construction sites can be prevented from polluting the surrounding area by the use of straw bales, mulching and geo-mats. Aggregates placed at exits from sites prevent the transport of pollution

Figure 6.26 (b): Construction sites can be prevented from polluting the surrounding area by the use of straw bales, mulching and geo-mats. Aggregates placed at exits from sites prevent the transport of pollution

Figure 6.27: Stone aggregate can be placed on the roadside while the shoulder grass establishes itself

Protection and rehabilitation

The erosion cycle - detachment, transportation, deposition - is a natural phenomenon. However, development usually alters the natural pattern. Erosion control is a measure to substantially reduce erosion and thereby decrease the sediment input into the stream system. The aim is to reduce the accelerated erosion typically caused by poor agricultural techniques and other land uses. Measures may include practices such as contour farming and terracing (applicable to both the rural and urban settings), strip cropping, crop rotation, no-till farming, grassing drainage ways, gully and stream bank erosion control, and stabilisation of critical areas.

Technologies available to the designer include the following:

Silt fencing and straw bale barriers

Silt fences and hay/straw bale barriers are two types of filter barriers. They are temporary structures which are installed across or at the toe of a slope. They are used to control sheet flow and are therefore not effective in areas of concentrated flow, such as ditches or waterways. See Figure 6.28.

Figure 6.28: The straw-bale barrier has allowed pioneer plants to establish themselves

Temporary check dams

Small temporary check dams constructed across a ditch or small channel reduce the velocity of concentrated stormwater flows. They also trap small amounts of sediment. Temporary check dams are useful on construction sites, or for temporary stabilisation of erosion areas where protection is required for the establishment of vegetation.

Riprap

Riprap is a heavy stone facing on a shorebank used to protect it and the adjacent upland against wave scour. Riprap depends on the soil beneath it for support and should be built only on stable shores and bank slopes.

Other technologies

The use of geofabrics, matting, netting, mulching and brush-layering are other technologies which attempt to protect the soil from rain impact and impede the flow of stormwater runoff.

The alternative biological approach is often integrated with the structural technologies. Many of the indigenous flora can be effectively used to form vegetation buffer strips and other natural barriers, sponges and stable riverine corridors (Oberholzer 1985).

Street cleaning

Street cleaning can be an effective method of removing litter and sand-sized particles. Overall pollutant removal by street sweeping is not, however, very efficient, with an upper limit of 30 per cent removal being reported in the USA for well-run programmes and a more typical removal of 10 to 30 per cent (Sartor et al 1984).

Organics and nutrients are not effectively controlled, but regular - daily or twice daily - street cleaning can remove up to 50 per cent of the total solids and heavy metal yields in urban stormwater (Field 1985).

Runoff from unmanaged urban environments can be highly polluted. Efforts to reduce this pollution must be coordinated between those responsible for refuse removal, sanitation, and industrial effluent.

Waste disposal sites

The siting of waste disposal sites is regulated by the minimum requirements guidelines published by the Department of Water Affairs & Forestry (1994a, b and c). For the drainage engineer, the importance of siting relates to the environmental impact the sites may have on the ground and surface water bodies. As waste disposal sites are regarded as a bulk service, they are not discussed further in this document, except to illustrate the adverse effects of uncontrolled or unmanaged dumping (see Figures 6.29 and 6.30).

Figure 6.29: Unmanaged domestic refuse is a serious health risk

Figure 6.30: Uncontrolled dumping at municipal waste sites can have a serious impact on surface and sub-surface water systems

Sanitation

Waterborne sanitation

Illegal stormwater drainage into sewer gulleys is endemic throughout South Africa. The increase in flow into sewage works after storm events is widely recognised (Institute of Water Pollution Control 1973). While no estimates of flow are suggested, one empirical estimation for increased flow under wet weather conditions is equal to one and a half times the peak dry weather flow. However, because of the variations observed in many sites, it is advisable to place gulleys away from where stormwater flows or collects, and gulleys should be as few in number as practicable.

On-site sanitation

The protection of the environment from possible pollution by on-site sanitation systems such as pit toilets and soakaways is crucial. Pollution may be caused by infiltration of the leachate from the pits into the groundwater, or by surface runoff through a sanitation system which is positioned in a surface-water drainageway. The preservation of groundwater resources (many South Africans use wells, springs and boreholes) is particularly important. In this regard, recommendations of the Department of Water Affairs & Forestry (1995) are relevant.

Water supply

In developing communities, consider the drainage of excess water from water points. Erosion can occur (see Figure 6.31).

Figure 6.31: This water point has been placed in a low-lying area. Drainage of runoff and water spilled from the point has not been allowed for, and a health hazard has resulted

Selection of cemetery sites

The following ten criteria are deemed essential (Fischer 1992) when planning the position of a cemetery:

- soil excavatability for ease of excavating the graves;
- soil permeability which affects the pollutants' ability to be transported into groundwater;
- the position with respect to domestic water supplies, specifically if groundwater resources are being used;

- the position with respect to drainage features, so that stormwater runoff does not convey pollutants to streams or pose a threat of exposing graves. The position of the 1:50 floodline or a more stringent floodline should be part of the investigation;

- site drainage, which influences the ingress of rain into the soil and therefore the graves, with the possibility of pollutants then being conveyed from the site through the soil;

- site topography, which influences access to graves as well as surface and subsurface drainage;

- basal buffer zone, which relates to the depth of soil (buffer) between the deepest grave and the water table (permanent or perched);

- grave stability relates to the stability of the soil around the grave from the time of excavation to the time of interment;

- soil workability, which refers to the ease of compaction; and

- cemetery size, which relates to the requirements of future grave sites and development pressures.

Cemetery pollution

According to Fischer (1992) cemeteries pose a pollution threat in that many of the existing cemeteries in SA contaminate our water resources. Microbiological pollutants (including bacteria, viruses and parasites) remain active within the water table at much greater distances from their source than was previously assumed.

At present no legislation exists to control the planning of cemeteries in South Africa. Linked to the issue of land availability, the potential of pollution from cemeteries requires a thorough technical evaluation.

MAINTENANCE ISSUES

Detention facilities

The nature of problems encountered with a stormwater facility depends on its type, function, location and general environment. Many of the problems can be avoided by proper design and construction procedures. Table 6.4 lists some of the problems commonly experienced with these facilities.

The control of weed growth and invader plants, and the mowing of lawns is necessary for aesthetic and health (mosquito control) reasons. To ensure that the bottom of a dry pond remains dry, it should be sloped (typically at 5 per cent) to the outlet or to a sub-channel linking the inlet to the outlet. The sub-channel may confine silt and enable storm runoff from minor events to bypass the pond. Subsurface drainage may be required to prevent swampy conditions when a surface channel cannot be conveniently installed.

Aquatic weed growth can be reduced in wet (retention) ponds by designing the ponds to have a minimum depth of water of 1,2 meters (after allowing for sedimentation). Aeration and disinfection of the water may also be necessary to maintain the required quality. The proper design of grids over outlets (limiting the opening to about 314 mm^2) assists in reducing outlet blockages. Reliable emergency spillways that cannot block should be provided. The pollution of wet ponds, where the initial runoff cannot be routed to bypass the facility, can be reduced to some extent by installing grease and sediment traps upstream of the pond inlet.

However, reduction or elimination of the pollutants at their source is generally the preferred option.

The failure of a facility's embankment may result from piping, either because of poor soils (e.g. dispersive soils), inadequate filter designs, animals which burrow into the embankment, or tree root systems. Legumes should not be used as plant cover for earth embankments as this results in a concentration of nitrogen in the roots, which attracts rodents.

When sports fields are used as detention facilities, playing surfaces are generally raised slightly above the surrounding area to facilitate drainage and clearing of general debris and siltation. See Figure 6.32.

Figure 6.32: These sports fields will act as a detention facility should the watercourse on the right of the picture not be able to convey the flood. Note that the playing surfaces are raised to aid drainage after such an event. The crest of the side weir between the watercourse and the sports fields is designed to accept the excess flow, but is made aesthetically pleasing with a meandering cycle path

Where porous pavements are used in parking areas or roads to encourage infiltration or reduce traffic noise,

Table 6.4: Problems commonly experienced with storage facilities (after APWA Special report No 49 1981, and DeGroot 1982)	
PROBLEM TYPE	COMMENTS
Weed growth	Easy access to the site will enable the maintenance department to combat weed growth. Designers should establish acceptable pioneer grasses (e.g. *Cynodon dactolon* - fine kweek, *Stenotaphrum secundatum* - buffalo grass) and reeds and marsh plants where applicable.
Maintaining grass	Bank slopes should be gentle enough to allow access by maintenance equipment.
Sedimentation and urban litter	Increased maintenance required, but confined to a specific site.
Mosquito control	Regular mowing required - keeping grass short facilitates evaporation and provides access for predators of mosquito larvae.
Outlet blockages	Particular detail required for outlet works and may incorporate straw bale filters and trash racks.
Soggy surfaces	Landscape the basin so that depressions can be utilised as retention areas for artificial wetlands.
Inflow water pollution	Regular maintenance during wet season. Consider wetland filters at inlets.
Algal growth	Attempt to create a sustainable ecology.
Fence maintenance	Consider public access points to the facility.
Unsatisfactory emergency spillway design	Dam design requirements.
Dam failures and leaks	Dam design requirements (e.g. dispersive soils).
Public safety during storm events	Flood warning systems are an integral part of the total design.

the surfaces should be regularly cleaned of debris to prevent clogging.

Design details

Minimum pipe diameters

The suggested minimum pipe diameters are

- 300 mm in a servitude; and
- 375 mm in a road reserve.

Minimum velocities and gradients in pipes

The desirable minimum velocity range is 0,9 - 1,5 m/s. Low velocities will not prevent siltation, so the maintenance of pipe networks needs to be considered at the design stage (see Table 6.5).

Anchor blocks

Concrete anchor blocks (20 MPa concrete strength) should be provided, as in Table 6.6.

Figures 6.33 to 6.36 illustrate some common maintenance problems with stormwater facilities which can be avoided by careful planning and design.

Table 6.5: Suggested minimum grades for pipes (City of Durban 1984)

PIPE DIAMETER (mm)	DESIRABLE MINIMUM GRADIENT (1 IN ...)	ABSOLUTE MINIMUM GRADIENT (1 IN...)
300	80	230
375	110	300
450	140	400
525	170	500
600	200	600
675	240	700
750	280	800
825	320	900
900	350	1 000
1 050	440	1 250
1 200	520	1 500

Table 6.6: Suggested spacing for anchor blocks (City of Durban 1984)

GRADIENT (1 IN...)		SPACING FOR 2,44 m PIPE LENGTHS
2	(50%)	every joint
2 - 3,33	(50% - 30%)	alrternate joint
5	(20%)	every 4 th joint
10	(10%)	every 8 th joint

Figure 6.33: Inlet grids need attention

Figure 6.34: Kerb inlets require maintenance

Figure 6.35: The use of underground drainage systems in unpaved roadways should be justified

Figure 6.36: Stormwater drainage must occur off the roadway if kerbing is not installed

ENVIRONMENTAL HEALTH AND SAFETY

The role of education and community involvement

Wood consumption for cooking and heating purposes can be greatly reduced by the use of efficient stoves (Ellis 1987), in lieu of open fires. Less wood consumption leads to less denudation of the landscape.

The establishment of woodlots, although a long-term project, will help alleviate the wood shortage. Again, these woodlots must be protected and managed, so the communities having access to the resource must have the necessary institutional capacity to do this.

Veld fires are a common occurrence during the winter months in many areas in South Africa. No land-user may burn veld or allow burnt veld to be grazed without the written authorization of the executive officer (Forestry Act No 72 of 1968). While it is generally agreed (Booysen and Tainton 1984) that veld burning (typically every 3 - 5 years) improves the quality of the veld, regular yearly burning reduces the basal cover of the grass and therefore subjects the soil in the area to rain beat and possible erosion. Not only does the burning pollute the atmosphere, but resources such as thatching materials (*Hyparrhenia filipendula*, *H. dissoluta* and *H. hirta*) may be lost. Although grasses usually recover before the rains, when burned in the middle of winter, fires in early spring may expose the soil to potential erosion. A preferred technology is mowing; this, however, is more expensive.

Awareness of hazardous situations and flood-warning systems

Flood-warning systems are an integral component of the design of any hydraulic structure, and are a local authority responsibility. Stormwater management should aim to eliminate flood hazards.

Effective forecasting and warning of impending flooding will enable a community to prepare and therefore reduce the danger to life and property. Flood warnings are usually more effective in large catchments, where long response times allow intervention by the authorities and the public. However, local areas subject to flood hazards can be signposted and safety measures incorporated into the land-use design. (See Figure 6.37.)

Figure 6.37: Flood-warning systems

Recreational use of facilities

Watercourses need to be managed and maintained in urban environments. Flood plains are particularly valuable facilities for indigenous fauna and flora. One particular maintenance problem is the management of alien invader plants (see Figure 6.38). Maintenance by the relevant authorities may place a high burden on the funding available for general parks and recreational maintenance. The commitment to maintain these natural corridors should be communicated to all involved and not be the burden of the authorities only. Many campaigns (Collect-a-can, for example) encourage public participation in maintaining our natural areas.

Figure 6.38: This nature trail has a problem with pampas grass (Cortaderia jubata), an alien invader

General precautions for development on dolomites

Figure 6.39: Dolines are almost always the result of man's intervention in natural drainage systems. This sinkhole has been caused by a road culvert

The following recommendations have been made by the Council for Geoscience (Calitz 1993):

House structures

- All man-made ponds, drainage ways, stormwater conduits and road surfaces should be made impervious.

- Runoff from structures should be conveyed in impervious conduits away from the structures. If gutters are required by the local authority, the downpipes should discharge into a lined or precast furrow. This furrow should discharge the water 1,5 m away from the from the foundation, preferably onto a grassed ground surface sloping away from the structure. Where no gutters are utilised, it is recommended that an apron 1,5 m wide be provided along the external walls of the structure where water will discharge from roofs. This will allow the runoff from the roof to be distributed away from the structure foundation.

Installation and maintenance of services

- Bulk services should be routed in road reserves or servitudes with a minimum width of five meters.

- Sewer- and water-reticulation systems in the road reserves or other servitudes. If these services are placed mid-block, a building line restriction of a minimum width of 5 m should be imposed. Place water and sewer connections of any two erven on their common property boundary. Shared sewer connections should be considered if this arrangement leads to a reduction of the length of piping and/or minimises the disturbance to the environment.

- Each erf should have a rodding eye or similar access point to the sewer connection, in addition to an inspection eye.

- All stormwater, water and sewer pipes must be watertight.

- Avoid the use of clay pipes. When using polyethylene (HDPE) or polyvinyl chloride (uPVC) pipes, the use of compression-type joints is preferred. The use of heat fusion, glue fusion or mechanical bonding requires good workmanship and may rupture with small differential movements in the soil.

- The roots of trees planted in close proximity to the line of water-bearing services often cause leaks. Due regard should be taken when positioning trees and other plants.

- Trenches and excavations, once opened, should be closed as soon as possible. Proper compaction of the backfilling is recommended to obviate the trench acting as a soakaway drain.

- The excavated material may be unsuitable for use as pipe bedding or initial backfilling material because of the possibility of the presence of coarse chert.

- Water pipes entering buildings should be fitted with flexible couplings or kinked with a Z-form to allow for relative movement.

- Corrodible pipes should be protected.

- Where pipes cross roads, consideration should be given to the use of sleeves or culverts (ease of access for maintenance).

- Once the service has been installed and backfilled, the ground surface profile should be restored to its natural slope.

- All laid drainage pipes and sewerage should be tested for leakage at time of installation and thereafter at regular intervals (CSIR, NBRI Info sheet X/BOU 2034).

See also: Donaldson 1963; Buttrick and Van Schalkwyk 1995; Buttrick and Roux 1993; and Roux 1991.

GLOSSARY: Terms used in stormwater management

- **CUTA**: Committee of Urban Transport Authorities, Department of Transport, PO Box 415, Pretoria 0001.
- **Design period**: Design period is usually the length of time a structure or asset will be expected to have a useful life, or the amortisation period if loans have been procured to finance the construction of the structure or asset.
- **Design storm**: The properties of a storm include the depth, spread and duration of the rainfall as well as variations in rainfall intensity in space and time over the catchment area during the storm. In the choice of a design storm cognisance should be taken of all these parameters.
- **Detention facility**: A structure which temporarily stores excess stormwater for a length of time. The outlet of the structure is designed to release the stored water into the downstream watercourse at a rate less than the flow rate into the facility during storm events.
- **Drainage area**: That part of a catchment above a specified point that contributes to the runoff at that point.
- **Drainage system**: See "stormwater drainage system".
- **Dry pond**: A detention pond that remains dry during dry weather flow conditions.
- **Dry weather flow**: Flow occurring in a water course not attributable to a storm rainfall event, but to groundwater flow where the water table intersects the stream channels of a catchment. These dry weather flows do not fluctuate rapidly because of the low flow velocities.
- **Evapotranspiration**: The evaporation from all water, soil, snow, ice, vegetation and other surfaces plus transpiration of moisture from the surface membranes of leaves and other plant surfaces.
- **Flood plain**: The flood plain of a river is the valley floor adjacent to the incised channel, which may be inundated during high water (Linsley et al 1975). CUTA defines the floodplain as the area inundated in a river by the major flood.
- **Flood plain fringe**: The flood plain fringe is that area in a river defined as being below the level reached by the regional maximum flood and above the level reached by the major flood. Note: The US National Flood Insurance Programme has definitions of "floodway" and "fringe area" that differ from those of CUTA.
- **Flood zone or floodway**: Defined by CUTA as the area inundated by the regional maximum flood (RMF).
- **Groundwater runoff**: That part of the infiltrating water that percolates downward until it becomes groundwater. Eventually, after an indirect passage, it enters a stream that intersects its path and becomes dry weather flow or base flow.
- **Hyetograph**: A graph indicating the distribution of rain relative to time.
- **Hydrograph**: A graph of stage or discharge relative to time.
- **Interception**: Precipitation stored on vegetation as opposed to rain in surface depressions (termed depression storage).
- **Major drainage system**: A stormwater drainage system which caters for severe, infrequent storm events. Supported by the minor drainage system.
- **Minor drainage system**: A stormwater drainage system which caters for frequent storms of a minor nature.
- **Nomograph**: A chart or graph from which, given a set of parameters, other dependant parameters can be ascertained.
- **Off-stream facility**: A stormwater facility which is situated away from the normal drainage way. A typical example is shown in Figure 6.32. The sports fields alongside a drainage way will act as a detention facility should the bank of the drainage way be overtopped by flood waters.
- **On-site facility**: Detention facility located on a watercourse and through which normal dry weather flow passes.
- **Outfall**: See "stormwater outfall".
- **Recurrence interval**: Recurrence interval or return period is the average interval between events. The recurrence interval is usually expressed in years and is the reciprocal of the annual probability. That is, the event having an annual probability of occurrence of 2% (0,02) has a recurrence interval of 50 years. This does not imply that such an event will occur after every 50 years, or even that there will necessarily be one such event in every 50 years, but rather that over a much longer period (like a 1 000 year period) there will very likely be 20 events of equal or greater magnitude.

- **Retention facility**: A structure which retains runoff indefinitely should the capacity of the structure be sufficient to contain such runoff. Excess flow into the structure will be discharged via a spillway.

- **Runoff**: The water which constitutes streamflow may reach the stream channel by any of several paths from the point where it first reaches the earth as precipitation. Water which flows over the soil surface is described as surface runoff and reaches the stream soon after its occurrence as rainfall. Other water infiltrates through the soil surface and flows beneath the surface to the stream.

- **Stormwater drainage system**: All the facilities used for the collection, conveyance, storage, treatment, use and disposal of runoff from a drainage area to a specified point.

- **Stormwater outfall**: The point at which runoff discharges from a conduit.

- **Subsurface runoff**: The flow derived from water infiltrating the soil and flowing laterally in the upper soil strata. It reaches the receiving streams or bodies of water fairly soon after a rainfall event, without joining the main body of groundwater.

- **Surface runoff**: That part of the runoff that travels over the ground surface and in channels to reach the receiving streams or bodies of water.

- **Sustainable development**: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

- **Watercourse**: Stream or channel. May or may not have a permanent flow of water.

APPENDIX A

Storage-Indication working curve method or Modified Puls method.

The standard flood routing equation is

$$\left(\frac{I_1 + I_2}{2}\right)\Delta T - \left(\frac{Q_1 + Q_2}{2}\right)\Delta T = S_2 - S_1 = \Delta S \qquad \text{(A1)}$$

This can be transposed to

$$\left(\frac{I_1}{2}\right) + \left(\frac{I_2}{2}\right) + \left(\frac{S_1}{\Delta T}\right) + \left(\frac{Q_1}{2}\right) - Q_1 = \left(\frac{S_2}{\Delta T}\right) + \left(\frac{Q_2}{2}\right) \qquad \text{(A2)}$$

where

I_1 and I_2 are the inflow rates at times T_1 and T_2 respectively;

Q_1 and Q_2 are the outflow rates at times T_1 and T_2 respectively;

S_1 and S_2 are the storage values at times T_1 and T_2 respectively;

ΔT is the time increment between time T_2 and T_1.

In equation (A2) all the values on the LHS are known. Initially I_1, Q_1, S_1 and I_2 are known, yielding $\left(\frac{S_2}{\Delta T}\right)+\left(\frac{Q_2}{2}\right)$. By developing the relationship between Q and $\left(\frac{S}{\Delta T}+Q\right)$, Q_2 can be interpolated from the value $\left(\frac{S_2}{\Delta T}\right)+\left(\frac{Q_2}{2}\right)$ and S_2 can be interpolated from the relationship between Q and S. In the next time step the terms Q_2 and $\left(\frac{S_2}{\Delta T}\right)+\left(\frac{Q_2}{2}\right)$ become Q_1 and $\left(\frac{S_1}{\Delta T}\right)+\left(\frac{Q_1}{2}\right)$ respectively, so that the third storage value and discharge value can be deduced, and so on.

APPENDIX B

Proportional and inverted V-notch weirs

The relationships for proportional weirs are as follows:

$$Q = C_D . \sqrt{2ga} \; . \; b \left(h - \frac{a}{3} \right) \tag{B1}$$

where the discharge coefficient C_D can be assumed to be approximately 0,62

and

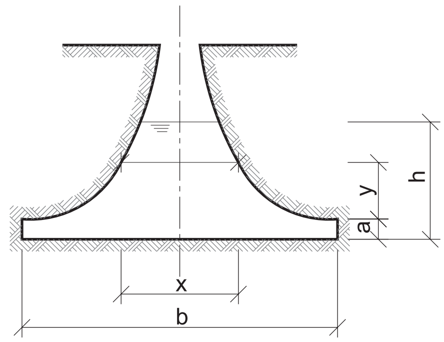
$$\frac{x}{b} = 1 - \frac{2}{\pi} \tan^{-1} \left(\sqrt{\frac{y}{a}} \right) \tag{B2}$$

where

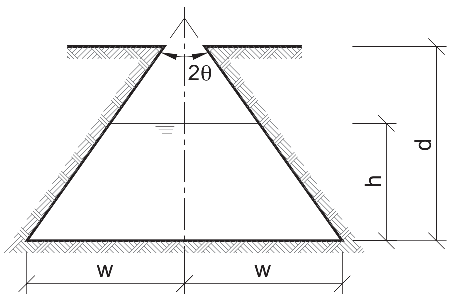
Q is the flow in m³/s

a, b, h, x and y are in meters and shown in Figure B6.

DOWNSTREAM ELEVATION
PROPORTIONAL WEIR



DOWNSTREAM ELEVATION
INVERTED V-NOTCH WEIR



The relationship is as follows:

$$q = \frac{2}{3} . C_D . \sqrt{2g} \; . \; 2Wh^{3/2} - \frac{8}{\;} . C_D . \sqrt{2g} . \tan \theta . h^{5/2}$$

for 0 < h < d

For flows through this weir above a depth of 0,22d but less than 0,94d (where d is the V-sloped section height), Murthy (1990) found that the discharges are proportional to the depth of flow. See Figure B6.

Figure B6: Proportional weirs

APPENDIX C

Broad crested weir

The most commonly used formula for estimating flow over a broad crested weir is formula (C1). As long as the flow is critical and parallel along its length, the equation is a good estimate.

$$q = 1{,}70 H_2^{3/2} \qquad \text{(C1)}$$

Where

q = flow per unit width of weir.
H_2 = total specific head at the weir.

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