Modelling free surface backwater effects in WALLRUS

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Abstract
This paper adresses the problem of modelling free surface backwater effects in WALLRUS, and describes the solution adopted in version 1.

Introduction
When the Wallingford Procedure was originally developed it was conceived primarily as a design and analysis method for **new** storm drainage systems. For this reason WASSP was constructed out of three design methods (MRM, Hydrograph and Optimising) and a Simulation method which gives the designer the opportunity to appraise the performance of the designed system for rainfall events rarer than the design event. In designing a system with the Hydrograph method, a pipe (or channel) is sized on the peak inflow to the pipe for a range of events with the same return period but increasing duration. The calculation of the peak inflow depends only on the flows calculated in all the pipes upstream of the pipe under design: no account is taken of the flows in any of the downstream pipes. This is the essence of a design method which prescribes the size of a pipe. If the design method were to take into account in some manner the direct effect of the flows in the downstream pipes then an iterative method would be required which would be difficult and tedious to apply. It is preferable therefore to size pipes in the traditional manner and then to test the performance of the designed system to assess its capability to keep the frequency of surface flooding at a tolerable level. In simulating the performance of the designed system it would be reassuring for the engineer if the flows generated by the design event reproduced those calculated by the design method and, in particular, did not surcharge any of the pipes. For this reason the Simulation method in WASSP uses the same free surface routing technique (Muskingum-Cunge) as in the Hydrograph design method. It can, of course, be argued that if the Simulation method could also reproduce the effect of flows on pipes upstream for the design event, that is, calculate the free surface backwater effects, then there would be the opportunity for the engineer to adjust the sizes of the pipes to improve the design. With WASSP however it was felt that such a refinement would have been too confusing for most engineers at the time.

Although the original intention of the Wallingford Procedure was to deal with the design of new systems, the increasing awareness of the need to rehabilitate existing systems has lead to the Simulation method being used primarily as an integral component of the hydraulic analysis procedure, defined by phase 2b in the Sewerage Rehabilitation Manual. The early days of the release of WASSP saw a number of modifications to the original code in an attempt to improve its capability to describe the wide variety of structures and facilities in existing systems. With the emphasis on simulation rather than design came the need to include such features as spatially varying rainfall, better description of overflows and tanks, allowance for sediment, and free surface backwater effects, among others. All of these features have been introduced to the Simulation method. This paper concentrates on the problems of introducing the calculation of the free surface backwater effects, and the advantages and limitations of the way it has been implemented.

Free surface backwater effects

Strictly this is a problem of how free surface flows in a dendritic drainage system are affected by downstream effects. When the flow is subcritical and steady it is well known that the water level along a channel is affected by the water level at the downstream boundary. So, for example, if the downstream water depth is greater than the critical depth and the water level is increased the water levels upstream will increase accordingly. The effect of the high downstream water level dies out exponentially upstream so that at some distance upstream the effect of the high downstream water level is negligible. Suppose now that the flow from upstream is unsteady, then the effect of a high downstream water level will affect not only the water levels upstream but also the discharges. Alternatively, if the flow from upstream is steady but the downstream water level is changing in time then the discharges upstream will also vary in time, though at a point sufficiently far upstream the discharge will remain steady. For example, if the downstream water level were forced to rise sufficiently fast then there could be a temporary reversal of flow upstream.

Provided a drainage system is dendritic, reasonably steep and consistently designed, then for rainfall events less than the design event flows are generally little affected by downstream influences. The problems come with rapidly rising water levels, such as in a tank, wet-well, surcharged manhole or submerged outfall, and in flat pipes. For example, in a sequence of flat pipes the upstream water level may be very sensitive to the downstream level. Indeed it is important to note that a pipe full discharge cannot be defined for a flat pipe, so therefore, unlike a steep pipe, a condition that a flat pipe is surcharged cannot only depend on the discharge exceeding the pipe full discharge: the downstream water level is always going to be important. It is possible, for example, to get a non-zero discharge through a flat pipe without surcharging it, but this depends intimately on the downstream water level (and the geometry of the pipe).

The Simulation method in WASSP calculates free surface flow along a pipe assuming that the downstream effects are unimportant. As explained above this is for consistency with the design methods. However flat pipes and rapidly rising water levels are features of many existing systems. To overcome the deficiencies in the Muskingum-Cunge routing technique WASSP introduces a modification for the routing parameters for flat pipes and, more significantly, the level pool effect upstream of a surcharged manhole. In the case of flat pipes the routing parameters are calculated on the basis that the pipe has a minimum gradient of 1 in 10000. In recent versions of the software a further modification of the parameters for pipes with small gradients has also been introduced. The level pool effect is a more radical innovation. The basic idea is that because the routing technique does not include any downstream effects then, when the water level in a surcharged manhole rises rapidly, water is retained in the pipe(s) upstream. In effect the pipe(s) act as an extension of the surcharged manhole by storing water to a level approximately that in the manhole. As the water level rises in the manhole so the total volume stored is greater than in the manhole alone. This damps down the rate of rise of the water level and reduces the maximum water level achieved during the event. Although the calculations assume a level water surface upstream of the manhole it provides a realistic approximation to the actual behaviour of the water level. The major drawback of the technique is that the discharge in the pipe(s) upstream is unaffected by the rate of rise in the manhole. Therefore the flow into the manhole will still normally be larger than in the prototype.

The only satisfactory way to do the calculations properly is to solve the complete equations for unsteady gradually varying flow in an open channel. These equations, known as the Saint-Venant equations, are expressions of Newton's laws of conservation of mass and momentum. Unfortunately the equations are non-linear and difficult to solve for a number of reasons. Therefore it is customary to approximate the original analytical equations before they are solved numerically. Such an approach has to be done with care in that the approximations may remove the possibility of calculating particularly relevant phenomena. So, for example, the Muskingum-Cunge is one such an approximation which, like the kinematic wave approximation, removes the possibility of including free surface backwater effects. The basic level of approximation which includes an allowance for backwater effects is the assumption that the inertial terms in the momentum equation can be neglected. The interesting thing about this approximation is that the equations for the stage (or water level) and discharge can be manipulated to produce a differential equation in which discharge is the dependent variable and stage only appears as a variable in certain coefficients. The equation is the well-known convection-diffusion equation with the convection speed and diffusion coefficients functions of discharge and stage.

$$\frac{\partial Q}{\partial t} + c(Q,h)\frac{\partial Q}{\partial x} - d(Q,h)\frac{\partial^2 Q}{\partial x^2} = 0$$

There are a number of efficient and accurate ways of solving this equation for suitable boundary conditions. Once a discharge has been calculated for a particular time step then the stage (or water level) along the pipe can be defined using the original, approximate form of the momentum equation.

$$\frac{\partial h}{\partial x} + \frac{Q|Q|}{A^2F^2} = 0$$

In effect this second step is very similar to doing an instantaneous backwater profile without the velocity head term.

The advantages of this technique are that it avoids the vagaries and instabilities of solutions for the complete equations and it preserves volume. The main disadvantage with the implementation of the technique is that within the design of the software it has to be applied to each pipe separately like the Muskingum-Cunge technique. The main reason for this is that the software identifies groups of surcharged pipes and solves for the associated water levels and discharges accurately. Because the groups of surcharged pipes can change from time step to time step it is important to decouple the calculation of free surface flow from pressurised flow. This is straightforward with the Muskingum-Cunge technique. However when applying the convection-diffusion equation to an individual pipe it is important to solve the equation with an appropriate downstream boundary condition. The most relevant condition for the single pipe is one which takes into account the rate of rise of water level in the downstream manhole based on the continuity of mass equation.

$$\frac{\partial Q}{\partial x} = - B\frac{\partial h}{\partial t}$$

The implementation of this boundary condition requires the use of the rate of rise of water level in the downstream manhole at the previous time step and not at the current time step. This is because the discharge at the new time level is calculated before the water level. Generally the discharges at the new time level are calculated in all relevant pipes at the new time level and only then are the water levels calculated, beginning at the outfall and working back upstream. The boundary condition can be made to work reasonably well provided the water level in the downstream manhole does not rise (or fall) too rapidly. Where the water level rises rapidly oscillations are set up in the discharges for the pipe. If the water level in the downstream manhole depends intimately on the discharges entering it from the pipe, such as in a manhole or tank with small cross-sectional area or with a throttle on the outfall, then it is apparent that unless special precautions are taken the oscillations could get out of hand. There is therefore a special implementation of the downstream boundary condition in the software to dampen down the possibility of oscillations.

There will however be occasions when oscillations occur in using the backwater option. In such cases the user will generally be able to minimise these by taking one or both of the following actions:

reduce the major computational time step (e.g. down to 5 secs)

increase the effective storage at the manholes or tanks downstream of the pipes with the backwater option

Conclusions

It has to be admitted that, although the free surface backwater technique works reasonably well in most circumstances and it is an improvement on not having such a facility, it is not entirely reliable and should be used with care. Considerable thought has been given to improving the facility but no better way has been found to date. It is thought that further improvements can only be obtained by completely redesigning the algorithmic structure of the computation techique in the Simulation method. This would however lose the advantages of speed and convenience give by the present method, and any new method would in fact be very similar to the looped model, called SPIDA, which has been developed by Hydraulics Research. It could be that this model, which has not been made available on general release yet because of its own residual difficulties as a user friendly tool, will eventually become a complementary tool to WALLRUS for those who want to look at flat systems with significant storage. It will of course be the obvious tool to use for looped systems as WALLRUS has not been designed to be used on such systems.

1.3 **Backwater Calculations - Dr. R.K. Price HRL**

R. Ashley - Dundee Institute of Technology

Regarding the comparisons with output from Flucomp, discharges looked similar, but do you have any information on water level comparisons?

Ans: Not with me, but we did find similar correlations. I certainly agree that water levels are more sensitive to backwater effects than the discharge values. Our examples are very simple, problems are usually encountered where there are rapidly fluctuating levels.

B. Sharman - North West Water Ltd

There has been lots of publicity regarding the benefits of the backwater calculations, yet your graphs seem to show that they make little difference. Is it all worth it?

Ans: Without backwater, calculation assumes only normal depth of flow, and this has proved to be inadequate for a number of users.

R. Ashley - Dundee Institute of Technology

Has the backwater calculation routine been coupled with the sediment modelling facility in WALLRUS, where very different water levels could occur for the same discharge?

Ans: The two "facilities" are not coupled together as such.