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Discussion

Comment on 'Analysis and modeling of flooding in urban drainage systems'

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In the paper by Schmitt et. al (2004), the authors describe their model and demonstrate its use to support the urban drainage components of European Standard EN 752. This standard dictates that urban drainage systems should be designed to safely convey discharges from events with return periods of 10–50 years. Such regulations demand that dual drainage principles be considered in the planning of urban stormwater removal systems. The authors propose their model in the analysis of dual drainage systems, or a linkage of distinct surface and subsurface components to convey stormwater.

The authors are remiss in stating in Section 3 that dual drainage modeling was 'first described by Djordjevic et al. (1999).' While the work of Djordjevic et al. (1999) is significant in its own right, it is preceded by over 20 years of research and development in the concept of dual drainage in the UK, South Africa, Slovenia, Austria, Serbia, Turkey, Japan, and the US. During this preceding era, there was early recognition of the need for this concept and the causative problems, followed by a broad vista of research into proposed solutions. More recently, faster computational platforms, GIS tools, new data collection sensors and platforms, and increased computer storage capacities have accelerated the research into dual drainage. The authors have neglected to cover the many works in this area and consequently have failed to properly place their research in the context of the existing literature. For example, the authors neglect to reference a paper in the same special issue of the Journal (Mark et al., 2004). Thus, their claim that the 'new and crucial point in this approach…is the coupling of the shallow water equation model of surface flow with the dynamic sewer flow model' (section 3.2.4) is not well substantiated.

The purpose of this critique is to review the history of dual drainage and related concepts for urban storm water drainage and management. I limit this to issues related to stormwater quantity without any consideration of water quality.

1. Definitions

For the purpose of this critique, I use the definition of dual drainage put forth by AMK associates (2004) and others (e.g. Stephenson, 1987; 1989; McBean et al., 1985; Wisner and Kassem, 1982; Ellis et al., 1982; Wisner et al., 1981). Urban stormwater drainage systems are composed of two distinct and

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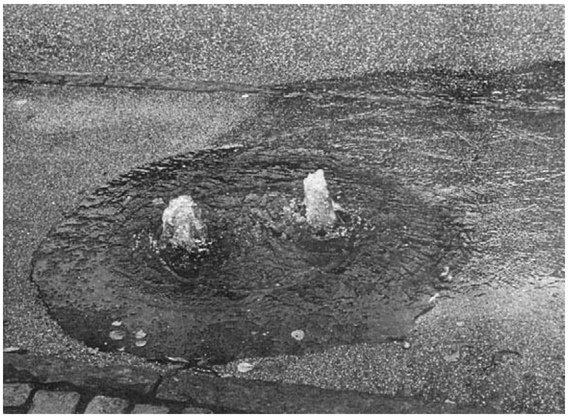

Fig. 1. Surface flooding at manhole no. 2. (Source: Jacobsen and Harremoes, 1984; reproduced with permission).

mostly separate components: (1) a surface, or 'major' system composed of streets, ditches, and various natural and artificial channels, and (2) a subsurface storm sewer network or 'minor' system. This minor system is designed to carry the runoff from a storm of 2–10 year return frequency, while the surface system is designed to handle events of 25–100 year return frequency. These systems are linked via street curb inlets which convey designed amounts of storm runoff into the storm sewer system. Manholes also link the two systems during surcharge. Street flooding is a special case of sewer surcharge in which water is allowed to exit the manhole and pond on the surface or flow down the street in response to topographic gradients as shown in Figs. 1 and 2.

The surface and sewer systems are not constrained to follow parallel flow paths or even flow in the same direction. While Schmitt et al. (2004), Section 3 seem to indicate that dual drainage systems are defined as only those related to surcharging sewer systems, none of these other authors use such a limited definition. For this short paper, I will use the terms major and minor system interchangeably with the surface and storm sewer systems, respectively.

2. Recognition of the dual drainage problem and design considerations

While other early references may exist, Heaney et al. (1975) and later AMK Associates (2004) report

Fig. 2. Downstream movement of storm sewer overflow from manhole no. 2. (Source: Jacobsen and Harremoes, 1984; reproduced with permission).

that perhaps the first mention of dual drainage for urban areas is found in the design manuals of the city of Denver, Colorado (Denver, 1969). These design criteria describe the linkage of the major and minor systems. However, the major system criteria are limited to providing proper street flow gradients and capacities for the safe conveyance of surface flows.

Discussing similar criteria, McBean et al. (1985) noted that design manuals in Canada (Environment Canada, 1976) recognized that dual drainage system responses could not be easily modeled within a single simulation run. The greatest difficulties blocking this capability in a single model run were the inability of then-current techniques to handle the mismatch of flow directions between the surface and subsurface systems, and that surcharged storm sewers can create lags and increased flow durations. Wisner and Kassem (1982) noted that already by the late 1970's, several municipalities in Canada required the inclusion of major-minor systems in the design of urban drainage strategies. Pratt (1985) discussed similar design measures in Australia.

Several years after the Denver design manuals were developed, Kidd and Helliwell (1977) described the urban runoff process as a two-phase phenomenon, incorporating a surface phase with a sub-surface phase. They recognized the complexities of the interactions between these two phases by stating:

> *'Unfortunately, there is no clear-cut interface between the two phases'.*

Given this deficiency, the traditional approach to modeling the complex interactions between the major and minor systems consisted of two stages (Ellis et al., 1982). In the first stage of designing an urban drainage system for say, a 100 year event, the minor system is designed to convey the discharge from a five-year event. Sewer pipes are sized until an acceptable level of performance is achieved. Next, the five-year hyetographs are subtracted from a 100-year design event hyetographs and the subsequent rainfall is input to the hydrologic model. The resultant surface flows are used to design the components of the major drainage system. Assuming a common outfall point, the flows from the major and minor systems are added to produce a total system response. The problem with this approach is that it leads to incorrect responses because the input regimes are not designed to recognize each other's presence (Ellis et al., 1982). Excessive infiltration and evaporation volumes and problems with surface storage result from this two-stage approach. There is no recognition of the fact that one rainfall event simultaneously generated runoff responses to both the major and minor systems.

3. Dual drainage modeling: research and development

Early attempts to design and evaluate urban stormwater systems according to dual drainage concepts entailed engineering-type solutions and detailed manual computations.

Thompson and Lupton (1978) performed one of the early attempts to model storm sewer surcharge and surface flooding in the context of urban dual drainage. They recognized that storm sewers can overflow and the excess volume can either return via the original manhole or travel overland to another entry point in the sewer system. In their system, overflows are treated as a separate system within a 'water transfer facility'. Here, the user specifies a water level above which the overflow volumes are allowed to travel downhill. The user also specifies a travel time and the outfall location of the storm sewer overflows.

In another early engineering-type effort, Price and Howard (1978) reported a detailed analysis of the movement of stormwater in excess of the minor system capacities along overland flow paths. They attempted to account for the fact that these overflows can often create flooding downstream in an area designed for a higher return period flow. In these areas, the overflows will cause flooding to occur at a lower-than-designed return period. To model these effects, they produced a secondary network of surface flow paths which added considerable complexity to the simulation problem. In their paper, the authors also included a dramatic photograph of overflows from a surcharged storm sewer system that subsequently flow down a city street.

Wisner et al. (1981) linked a dual drainage system to a series of depressed parks to store flows from the major system to further reduce the peak discharge from an urban area. Such a technique can lead to reduction of post-development flows to a level that is below the pre-development levels, thus achieving a superior level of storm water management. To implement this strategy, detailed plans were manually constructed showing the sub areas, inlet catch basins, directions of major system flow, and discharge points into the designated parks. They were also to compute the capture by street curb inlets and the by-pass or carry-over flow not entering the minor system. Specific inlet control devices were recommended to restrict major system flow into the minor system so as to avoid overloading the storm sewers.

Akan et al. (1982) allowed flow volumes in excess of the storm sewer capacities to flow downstream as bypass or carryover flow to the nearest collector. This method required the labor-intensive step of manually determining the surface drainage patterns.

Noting that the traditional two-stage approach to dual drainage resulted in erroneous system responses, Ellis et al. (1982) modified the parameters of the US EPA Storm Water Management Model (SWMM; EPA, 1971) to reflect a more balanced response. Previous two-stage applications of the SWMM model resulted in a double accounting of infiltration. Ellis et al. (1982) achieved reasonable results by reducing the infiltration rates for the design of the major system.

Pethick (1984) modified the surface flooding mechanism of the existing Wallingford Storm Sewer Design and Analysis Package (WASSP) to meet specific conditions in Port-of-Spain, Trinidad. Among these modifications was the treatment of surface flooding from surcharged storm sewers. He added a fictitious linear routing element to convey the overflows from surcharged sewers. Flows in such linear elements were added to the sewer flows at a downstream point to give a total system response. A few years later, Chiang and Bedient (1986) used two models in sequence to simulate the interactions of the major and minor drainage systems in Houston, Texas. They used the HEC-1 model from the US Army Corps of Engineers to route surface flows that did not enter the storm sewer system. In the late 1980's, work in South Africa progressed on modular hydrologic-hydraulic models that were capable of describing urban drainage scenarios. In this work, Stephenson (1987; 1989) and Coleman and Stephenson (1990) developed the Wits Storm Kinematic Modular Management Model (WITSKM). A hallmark of this model was its ability to redirect flows along different routes. However, manual methods were required to identify the flow paths.

Around this time, modelers began to recognize the need to accurately define surface flow paths in urban areas. In his commentary on the work of Pethick (1984), Huber (1984) noted the importance of defining complex surface flow paths:

> *'The routing can be done in parallel to accommodate surcharge flow from channels. Great effort must often be made when using this technique to identify the surface flow pathway. Although quite successful as a routing technique, it is difficult to predict surface flooding depths accurately'*.

This concern would later be addressed through the use of advanced terrain analysis techniques adapted to urban areas.

The late 1970s and early 1980s saw the beginning of significant advances in the hydrologic and hydraulic modeling of urban drainage systems. In some models, the complete equations of motion were solved for free-surface and surcharged flow in the storm sewer system. However, several of these simply assumed that surface flooding volumes from surcharged systems were contained in fictitious reservoirs above the surcharged manhole and that no inter-manhole surface flows occurred (Bettess et al., 1978; Fread, 1984; Price, 1982; Pansic and Yen, 1982; Ammarell and Meadows, 1989; Green, 1984a,b).

Jacobsen and Harremoes (1984) presented a comparison of two storm sewer models for the computation of surcharge. They were able to test these two models on a well-instrumented storm sewer line that frequently surcharged and produced street flooding as seen in Figs. 1 and 2. They concluded that the head loss parameters are very important and are model specific rather than universal. In related research, Guo and Song (1990) investigated surge in urban storm sewers and in-line storage elements, a phenomena that can lead to manhole-cover blow-offs and street flooding. They used a mixed transient flow model to simulate the surge movements in the main sewer line in Chicago, Illinois.

Other models emerged that introduced strategies for the simultaneous solution of the flow equations in minor and major drainage components. Roesner and Shubinski (1982) showed that updated versions of EXTRAN could be used for integrated surface and storm sewer flow routing, given that the problem is properly specified. They provided example simulations showing surcharge and surface flooding conditions. During surface flooding, the excess amounts were allowed to exit the manhole and flow along the street channel to the next down-hill inlet to the sewer system. Kinematic routing was used to convey the surface flooding volumes.

Wisner and Kassem (1982) noted that then-existing models were not suitable for the design of dual drainage systems since they assumed that all catchment runoff is transferred directly into the storm sewer system. They further stated that any model for the analysis and design of dual drainage systems should be based on the simultaneous solution of the major and minor system flow equations. In response to this need, they developed the University of Ottawa Storm Water Management Model (OTTSWMM). In OTTSWMM, the major and minor networks need not be parallel or even flow in the same direction. Storm sewer routing was modeled as free surface flow. If the minor system surcharged, the user could specify that OTTSWMM would limit access into the storm sewers, or incrementally enlarge the pipes to carry the flow. For more complex surcharge analysis, OTTSWMM could be linked to the full dynamic wave routing within the Extended Transport module (EXTRAN; Roesner et al., 1988) of the EPA SWMM model (Huber and Dickenson, 1988; EPA, 1971). In later applications of OTTSWMM, Wisner et al. (1984) were able to confirm that while using curb inlet restrictions reduces surcharge, their use also increased flows in the major drainage system. OTTSWMM was the basis for the Dual Drainage Storm Water Management Model (DDSWMM; AMK Associates, 2004), used widely in Canada today.

That same year, Kassem (1982) developed a comprehensive mathematical algorithm for the simultaneous modeling of the major and minor drainage systems. His approach contained a finite-difference formulation of the kinematic wave approach for unsteady free surface sewer flow, and a full solution of the St Venant equations for surcharged storm sewer flow.

In an important development, Djordjevic et al. (1991) developed a method to simultaneously solve the equations of storm sewer and street flows. They used the diffusive wave approximation of the full St Venant equations to model both flow phases. Their work showed that the flows in the storm sewers can be significantly affected if the excess volumes are allowed to flow along the street rather than being stored in a fictitious basin above the surcharging manhole.

Takanishi et al. (1991) reported on the development of two models that account for surface, river, and storm sewer flows in urban environments. Sewer flows were treated as one-dimensional, while overland flows are modeled as two-dimensional (2D). The authors were able to simulate surcharge at various system points and subsequent inundation.

Pankrantz et al. (1995) compared three dual drainage modeling approaches to solve complex street flooding situations in the city of Edmonton, Canada. The authors computed runoff volumes using three hydrologic models: the SWMM Runoff Block, the OTTHYMO-89 model, and the PC OTTSWM model. EXTRAN was used in all three cases to rout flows through the storm sewer network. They concluded that after calibration, all three models provided adequate simulations of street flooding in low areas.

After a series of typhoons hit Taiwan, Hsu et al. (2000) linked a complex, 2D, diffusive-wave surface flow model to components of the EPA SWMM model and a pumping station model to generate detailed dynamic information of surcharge-induced surface flooding. Both the rainfall-runoff module and the EXTRAN dynamic-wave routing module of the EPA SWMM model were used. They used a computational element of $120 \times 120\ m^2$. In their testing, the authors were able to simulate the system surcharge and resultant surface flooding using data from a typhoon in 1998.

4. GIS tools and to support urban dual drainage modeling

While significant advances were being made in the mathematical linkage of surface and sewer hydraulic models, commensurate research and development was needed for these models to realize their full potential. After linking diffusive-wave models of street flow and storm sewer flow, Djordjevic et al. (1991) made a future-looking observation of this need by stating:

> '*The present model makes sense only if reliable input data are available. The role of GIS to provide the adequate information on the surface contour lines could be significant*'.

GIS tools and terrain analysis algorithms ushered in a new era of watershed modeling, and gradually impacted the analysis of urban storm water drainage with all its complexities. These new tools paved the way for more comprehensive solutions to dual drainage problems, since one of the major issues is that storm sewer systems do not always follow the surface drainage patterns (Hsu et al., 2000; McBean et al., 1985) and overland flow paths are modified by man-made features (Djokic and Maidment, 1991).

Initial efforts looked at GIS tools to derive urban terrain descriptions and to define parameters of existing urban hydrologic models. Along the way, new models based on GIS elements and using automatically defined urban flow paths were developed.

In an early effort to do urban dual drainage runoff modeling using GIS-type computational elements, Ichikawa and Sakakibara (1984) developed a gridded rainfall-runoff model using 10m cells. Storm sewers were linked to the surface system via manholes at specified cell locations. All surface flows were assumed to enter the sewer system at the manhole locations with no by-pass or carryover flow. Flow simulations on small urban watersheds agreed will with observed data. Their use of very small computational elements is significant in that it set the stage for the 1m to 5m grid size recommended years later by Prodanovic et al. (1998) and Mark et al. (2004).

Thorpe (1988) reported new techniques to define surface contour maps in the urban environment complicated by roads, over-passes, and drains. Efficient contour interpolation programs were developed that resulted in visually pleasing contours that approached the quality of traditional maps derived through labor-intensive manual procedures. In this way, non-hydrological research efforts were beginning to provide terrain representations deemed essential by Djordjevic et al. (1991) for advanced mathematical modeling of surface and storm sewer flows.

Bergmann and Richtig (1990) continued the theme of Ichikawa and Sakakibara (1984) by developing a gridded overland flow model linked to both a channel routing capability and a storm sewer model. They used a hydraulic channel routing model and a simple hydraulic sewer model. Results of their model tests were forthcoming at the time of their paper.

Djokic (1991) and Djokic and Maidment (1991) interfaced an expert system and the Arc/INFO GIS to evaluate the connectivity and capacity of the storm sewer network for a local jurisdiction. Individual drainage areas for each inlet were defined manually due to the complexity of the urban flow paths and the imprecise terrain information.

Huber et al. (1991) experimented with the integration of the rainfall-runoff component (Runoff Block) of the EPA SWMM with Arc/INFO and AUTOCAD, a commercial design and drafting software package. Their chief goal was to assess the

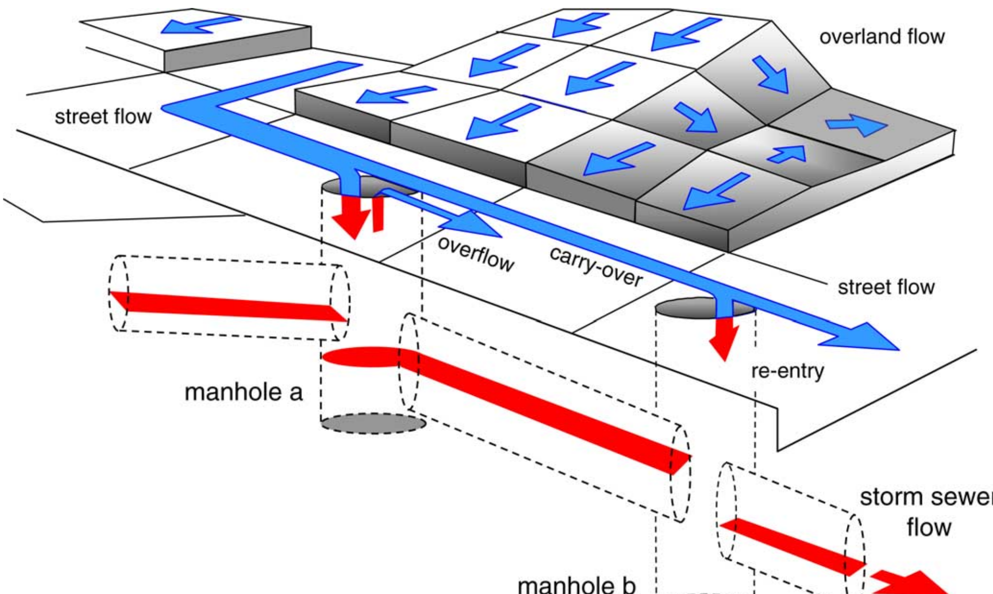

Fig. 3. Idealized surface (blue) and storm sewer (red) flow components in dual drainage systems. (Source: Smith, 1993. Copyright John Wiley & Sons Limited. Reproduced with permission).

ability of both systems to define input variables such as flow lengths and areas as needed by SWMM. The authors noted that either package could serve as the preprocessor for SWMM, and that user familiarity would probably be the deciding factor.

Noting that in urban areas the storm sewer network is not constrained to follow the surface flow paths, Smith (1992, 1993) developed a simultaneous solution of the equations for rainfall-runoff conversion, overland flow, street flow, and storm sewer flow in the context of gridded GIS data layers as shown in Fig. 3. Runoff volumes in excess of the minor system were allowed to flow downhill to other storm sewer inlets. Time shift routing was used for the sewer flows following the recommendations of Constantinedes (1983). Smith and Vidmar (1994) later derived automatic GIS-based procedures for defining small drainage basins and surface flow paths for urban areas. They modified traditional terrain analysis procedures to account for man-made low-relief features such as streets which can intercept and redirect surface flows apart from the dominant topographic gradient as described by Djokic and Maidment (1991). A 12 m grid size was used to describe the land use and urban topography. The work of Smith (1992, 1993) and Smith and Vidmar (1994) preceded by 10 years the need expressed by Mark et al. (2004):

> *'By the application of GIS features like a DEM and a simulation module, modeling of real storage and routing of surface flooding can be achieved*'.

Elgy et al. (1993) reported on progress to use GIS to define input necessary for two complex, physically-based storm drainage models. They recognized the need to account for the flow diversion effects of streets and buildings. To accomplish this, they used a gridded terrain model with 1×1 m^2 resolution to describe the dominate terrain gradients. All terrain cells covered by building foot prints were artificially raised by five meters and all streets were lowered by 0.5 m. Flow simulations based on GIS-derived model parameters agreed well with simulations based on manually-derived parameters.

Prodanovic et al. (1998) reported on their approach to solve the problem of full interaction between the surface and subsurface flow components. They presented a detailed description of the GIS processing steps required to implement a dual drainage model. They stressed the importance of standard and specialized GIS procedures to define surface pathways.

5. Summary

There exists a rich history of research and development into the complexities of dual drainage for urban stormwater management. The last two decades have seen a steady progression in the linkage of mathematical models for surface and storm sewer flows. These models are now realizing their full potential via the swift advances in GIS tools and terrain analysis techniques, combined with rapid advances in the ability to develop detailed terrain models in urban areas.

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