Sofia Drainage Area Planning - Detailed Modelling with WaPUG standards

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1. *Introduction*

During the first 10 years of the Bulgarian democratic transition, the political and economical instability, which was very common in Eastern Europe, had a severe negative effect on the entire social and economical life from which the water industry was not exempt. The disproportional urbanization combined with lack of funding in water and wastewater services resulted in severe problems for the Bulgarian water utilities. The situation got worse for the capital city of Sofia in 1995 when the lack of investment and the unfavorable hydrological conditions brought a serious water crisis to the city. It was then obvious that a new modern approach, a combination of management and technology, was needed to provide to the City high quality water services. As a result in October 2000 Sofiyska Voda AD (SV) took over the operation of the water and wastewater services in Sofia, through a 25-year concession agreement signed between the Municipality of Sofia, United Utilities and International Water Ltd.

SV inherited exceptionally large and complicated potable water and sewer systems, combined with lack of basic technical information and computer-based technologies. The high levels of service required by the concession agreement and the political requirements for implementation of latest EU technical and environmental standards, forced the company to deliver large scale hydraulic models of both sewer and potable water systems. Over the last 3 years the modelling units of the Asset Management Department with the support of United Utilities and Ewan Associates delivered water and wastewater strategic models as a result of wide range of different surveys and analysis. Subsequently, these are being enhanced to provide detailed models.

The strategic model of the Sofia sewerage system (Type I according to WaPUG CoP) was finished in March 2003. The subsequent analysis of the strategic sewer system – main collectors and sub collectors – identified a serious number of hydraulic and operational deficiencies. For example –

- lots of flooding locations – more than 21 flooding areas were defined using the model and surveyed on site,
- high rates of infiltration – about 50%,
- CSO deficiencies – almost 70% of the CSOs don't meet the design standards,
- sedimentation – more than 30% of strategic network suffer low velocities and high sedimentation.

The results of these studies proved the urgent need for more detailed and sophisticated models, which are to be used for creating the company strategy for the whole 25 year concession term.

This paper highlights the work of the Asset Management Department (in particular the sewerage modelling team) in transferring the technologies and creating the basis for sewerage modelling in Bulgaria.

2. City of Sofia – catchment description

Sofia, the capital of Bulgaria, is located in the Northwest part of the country. The City area is about 22,560 ha, which consists of many different urban types. Government buildings, museums, churches and social infrastructures dominate the City centre. Most of the population – about 1.3 million - live in high-rise apartment blocks with more than 8 floors but family houses are very common in the suburbs.

The economy in Sofia consists mainly of light industries, with intensive agricultural land use in the surroundings. The trade flow is currently estimated at about 55,000 m^3/day and statistical analysis shows increase by 45,000 m^3/day by the end of year 2020.

The City has a unique climate due to the proximity of Vitosha Mountain (2290 m AD) on the southern border of Sofia and to the North of the City lies the Balkan range. Meteorological phenomenon, like unusual rainfall spatial variation and temperature inversions are very common for the region. All these conditions in combination with snowmelt, significantly affect the sewer system performance.

There are 12 watercourses running through the city and none of these are particularly large. The largest river has 95-percentile flow of approximately 2.00 m^3/s, which is less than the estimated average dry weather sewer flow of 2.30 m^3/s. Most of the watercourses run through culverts and channels, which incorporate additional capacity for the high flow rates caused by snowmelt and rainfall during spring and intensive summer storm events.

The construction of Sofia sewerage system started in 1897, and has grown over the years with the city development. The approximate length of the network is 1,625 km, and the number of manholes known so far is nearly 29,400. The sewerage system was built according to a centralized scheme where all the sewers drain to one single wastewater treatment plant (WWTP), situated near the small village of Kubratovo. There are 7 strategic drainage catchments: Kakach, Suhodol, Vladaiska, Perlovska, Slatinska, Trunk 2 and WWTP, defined by the boundaries of the natural watercourses. There are no significant pumping stations within the catchment as all the sewers drain by gravity to the Kubratovo WWTP.

The majority of pipes are made out of pre-cast concrete, but older brick-wall sewers could be found in the City centre. Due to Bulgarian law and the present design norms the pipes should have diameter not less than 300 mm, but there are areas constructed using smaller pipes according to the Old Bulgarian legislation.

3. Sofia Drainage Area Planning - Detailed Modelling with WaPUG standards

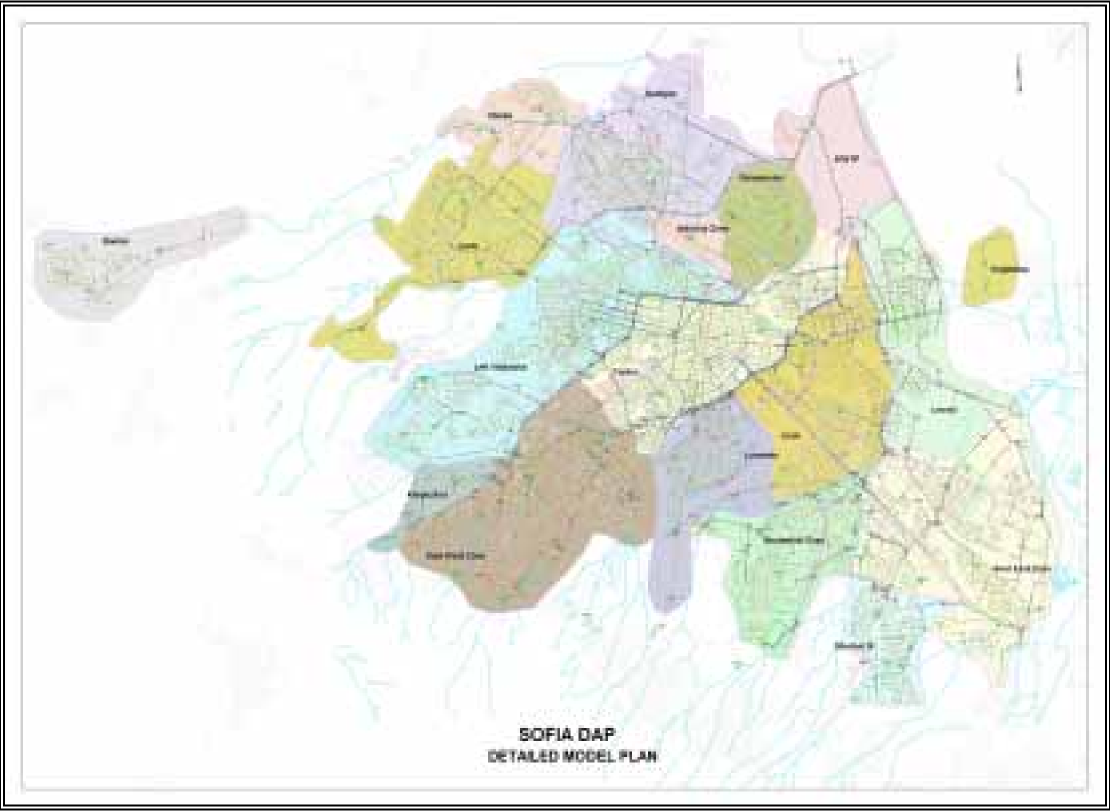
3.1. Model definition and level of simplification

The high levels of service that Sofiyska Voda AD offers to the citizen of Sofia require a modern approach and advanced technologies to be used with the purpose to create a long-term company strategy. The Strategic Model of Sofia sewerage system was just the beginning of a large-scale study of which the next step is to provide detailed models.

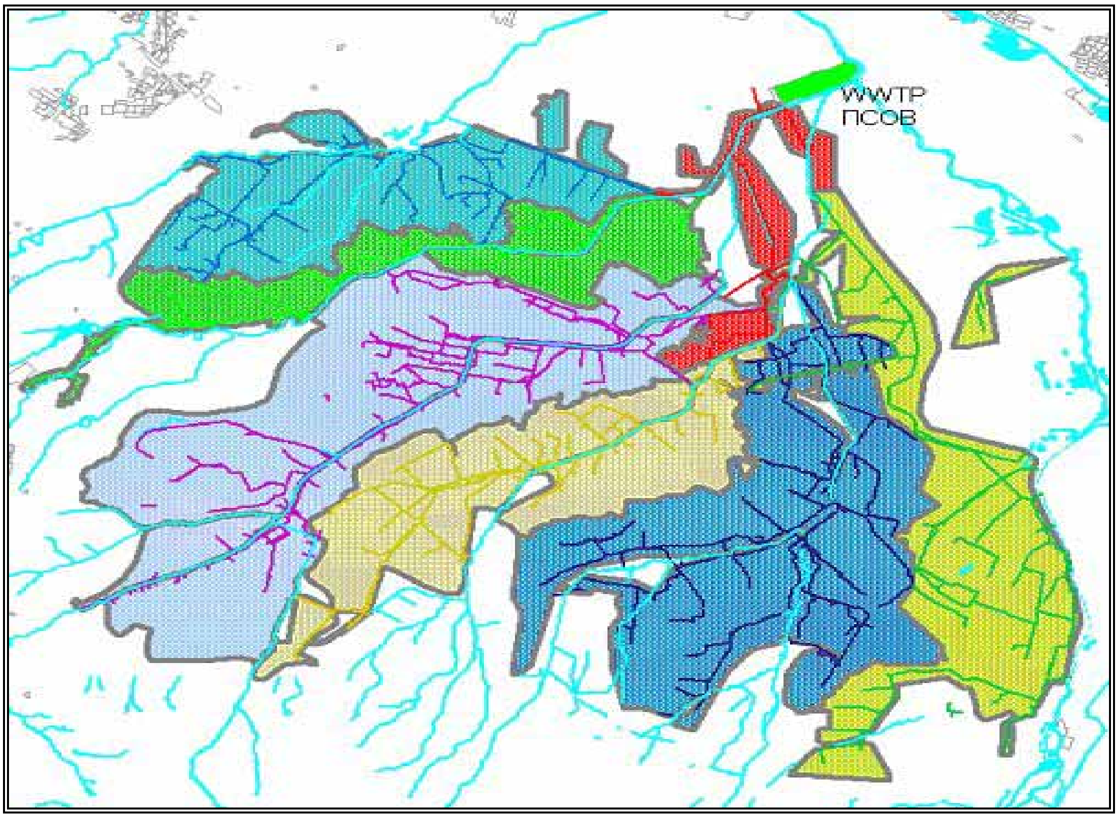
The detailed model of Sofia was initially considered to be "Model Type II – Drainage Area Planning Model" according to WaPUG CoP definitions. The original strategic scheme of 7 main catchments has been amended with 18 detailed modelling catchments, defined by a connectivity analysis of the network The widely accepted WaPUG CoP simplification criteria adopted and namely: "The number of modelled manholes would be typically between 6 to 20 per 1000 population". Using that, engineering judgment and local knowledge the following scope of the study has been accepted:

Catchment Name	Area, ha	Population, hd	Nodes In Catchment	Number of Nodes In Model	Number of Manhole Surveys
Bankia	720	9,512	555	403	136
Center	1,093	150,761	3,785	2,395	811
Industry Zone	159	93	114	81	41
Istok	1,120	94,451	3,088	1,896	581
Karpozitsa	214	9,307	277	201	73
Left Vladaiska	1,929	157,450	4,063	2,483	719
Levski	1,022	31,093	1,211	722	138
Liulin	1,083	119,815	1,953	1,235	392
Lozenets	807	35,830	1,184	670	252
Mladost III	533	61,330	908	557	165
Nadejzda	1,216	89,355	2,703	1,423	411
Obelia	422	20,737	272	229	72
Orlandovtsi	491	12,520	683	526	128
South East Zone	1,821	104,901	2,299	1,653	511
South West Zone	2,017	120,127	2,640	1,944	618
Studentski Grad	1,199	67,397	1,608	1,032	293
Vrajdebna	233	3,482	47	46	18
WWTP	595	1,506	180	144	10
Total	**17,468**	**942,590**	**27,550**	**17,640**	**5,367 (+3,048)**

Table 1: Detailed Model – Initial plan and level of simplification



Picture 1: Sofia Detailed Model – Catchments boundaries



Picture 2: Sofia Strategic Model – Catchments boundaries

The results of the Sofia strategic model– historical verification, flooding assessment, infiltration study, critical sewer assessment and operational events database – were the leading criteria, during the model definition process. The findings of the currently running field surveys have led to an extension for particular models. Some areas need to be modelled in more details and the Sofia detailed model was finally defined as a combination of Model Type II and Model Type III – "Detailed Design Model" (WaPUG CoP). A series of modelling procedure have been generated to standardise the build and merge of the 18 subcatchment models.

Following the need for more detailed information, a wide range of different studies and surveys is currently running at Sofiyska Voda AD. The following data collection is in progress, some of these are described in more details below:

- Population distribution
- Future development plans
- Rainfall
- Impermeable Area Survey data
- Historical rainfall
- River flow and level data
- Customer billing data
- Trade effluent data
- Manhole data
- Flow data
- Operation schedules
- Hydrology and hydrogeology data
- Ancillary surveys
- Inlet works survey

The scale of the model and the need of modern methodology based on WaPUG standards convinced the company management to choose Wallingford Software's InfoWorks modelling package, due to its version control capabilities, linkage to GIS and InfoNet, verification utilities and user-friendly interface.

3.2. Field Surveys

The last 3 years of modelling experience clearly defined the need of high quality data for the sewerage system. As an important part of the sewerage modelling team more than 25 field surveyors were completely trained and equipped based on the latest international data collection standards and strict United Utilities Health & Safety policy. To create a modern sewerage system database the following field surveys are currently running at Sofiyska Voda AD:

- Manhole Survey (MS)
- Flow Survey (FS)
- Impermeable Area Survey (IAS)
- CCTV / Structural assessment

3.2.1. Manhole Survey (MS)

On commencement of the strategic study in November 2001 the only sewer network data available was a network GIS database, which had been populated from old sewer records, some of which were 100 years old. During the strategic modelling about 5,000 manholes were successfully measured.

Due to data quality requirements and lack of information about present network status, nearly 9,000 manholes were surveyed over the term of detailed modelling. The MS revealed many network deficiencies and oddities, and the most common are:

- Missing manhole covers;
- Collapsed manholes;
- About 5% to 8% of the manholes had been covered by new roads, impermeable areas within private properties and buildings or buried in the ground;
- "Canned" manholes – the chamber is covered by a concrete plate in purpose to avoid debris and blockages, that makes difficult internal survey;
- Connectivity issues – very often the basic GIS data do not correspond to field survey findings and that leads to conflicts with GIS unit about the accuracy of the information;
- Large ancillary chambers – often the size of the chamber makes levelling and measurement of the chamber elements very difficult and many attempts are required to achieve reasonable results.

One of the most unusual characteristics of Sofia sewerage system is the enormous number of different pipe shapes. The reason is that the majority of the sewer network had been designed and constructed as a combined system. During the City's development over the last 100 years, due to the changing design standards and economical reasons, more than 100 different types of pipe shapes have been used in network construction. For example:

- Circular – from 200 mm to 2400 mm – applicable for a local network and collectors;
- Egg shaped – **3** types – applicable for both local network and collectors;
- Tunnel shaped – **3** types of symmetric and asymmetric shapes - applicable for collectors;
- The so-called "Mouth" shaped – **3** types - applicable for collectors;
- Open channels – **4** types known so far;
- ATYPE – sectional pipes made out of precast reinforced concrete units, symmetric and asymmetric – **84** different types known so far – mainly applicable for collectors. Each must be modelled separately.

The data obtained from MS is currently organized using the Wallingford Software's InfoNet 2.0 package, which made possible and easy the analysis of the information and its subsequent transfer to the SV GIS database based on ArcView 3.2 and InfoWorks.

3.2.2. Flow survey (FS)

The results of the studies obtained using the strategic model of Sofia sewerage system revealed the complicated nature of the network and the need for more detailed information. Connectivity issues, infiltration, variable water consumption / sewer return rates, sedimentation and many other problems were identified over the last 3 years. Therefore a detailed short-term FS plan was adopted including more than 340 flow monitors and 90 rain gauges.

The scale of this campaign forced SV to split it into 3 parts over the next 3 years. The first part, already finished, was carried out for 6 weeks between 20/04/2004 – 01/06/2004 and managed by an international team of engineers from Sofiyska Voda AD and Ewan Associates Ltd. 104 flow monitors and 25 rain gauges have been installed in 5 catchments.

The results of the campaign highlighted again the issue of the feasibility of installing flow monitors at poor sites. Many authors back up the idea of reducing the number of flow monitors as many of those always give unsatisfactory data and make verification more difficult and time consuming. The last 3 years of modelling experience in Sofia forced the SV modellers to make a reasonable compromise following the idea to collect as much data as possible. The unstable site conditions were the main issue – sediment transportation and debris after storm events interrupted the proper monitor readings at some places. There are many oddities typical of Sofia sewerage system, which make the choice of FS sites more difficult than as usual:

- 5% - 8% "buried" manholes which frequently make impossible finding of alternative sites
- Low velocities less than 0.60 – 0.20 m/s under DWF;
- High sedimentation and sediment transportation;
- Many different types of pipe shapes, which led to difficulties in accurately calibrating flow monitors. Therefore a high proportion of advanced monitors is required.
- No access to manholes in private and government properties;
- Site security issues – theft and vandalism;
- More than 2400 potential (at higher water levels) bifurcations;
- Need to duplicate monitoring sites in different surveys.

As a part of the long-term flow survey programme 17 permanent rain gauge sites have been set up at the start of the strategic modelling. Rainfall data analysis revealed a seasonal rainfall pattern where storms travel across the catchment – Northwest to Southeast between November – March and South to Northeast for the rest of the year. At the same time a series of intensive rainfall events have been observed during the last 2 years, which parameters were considered more heavy than the standard design rainfall that is 10 year storm with 335 l/s/ha of 5 min maximum intensity, leading to investigation for design storm events. The Sofia's unique climate defined the need of using a dense rain gauge network with purpose to capture the spatial variation effect on the rainfall data.

3.2.3. Impermeable Area Survey (IAS)

A very detailed IAS is currently in progress. The variety of runoff surfaces and land use types are typical for Sofia. It is very common to see a small quarter of family houses with sloped roofs and gardens, surrounded by a large area of high-rise apartment blocks and modern infrastructure. There are more than 3 types of cobbled roads, asphalt roads, semi surfaced roads, etc., which are very typical for the City. According to Bulgarian legislation, the road drainage infrastructure (street gullies, ditches, etc.) and the sewerage system are responsibilities of different City authorities. Hence, lack of gullies, blocked gullies and ditches and long runoff paths are very common and significantly affect the entire runoff process. Therefore very detailed surveys were required for modelling purposes.

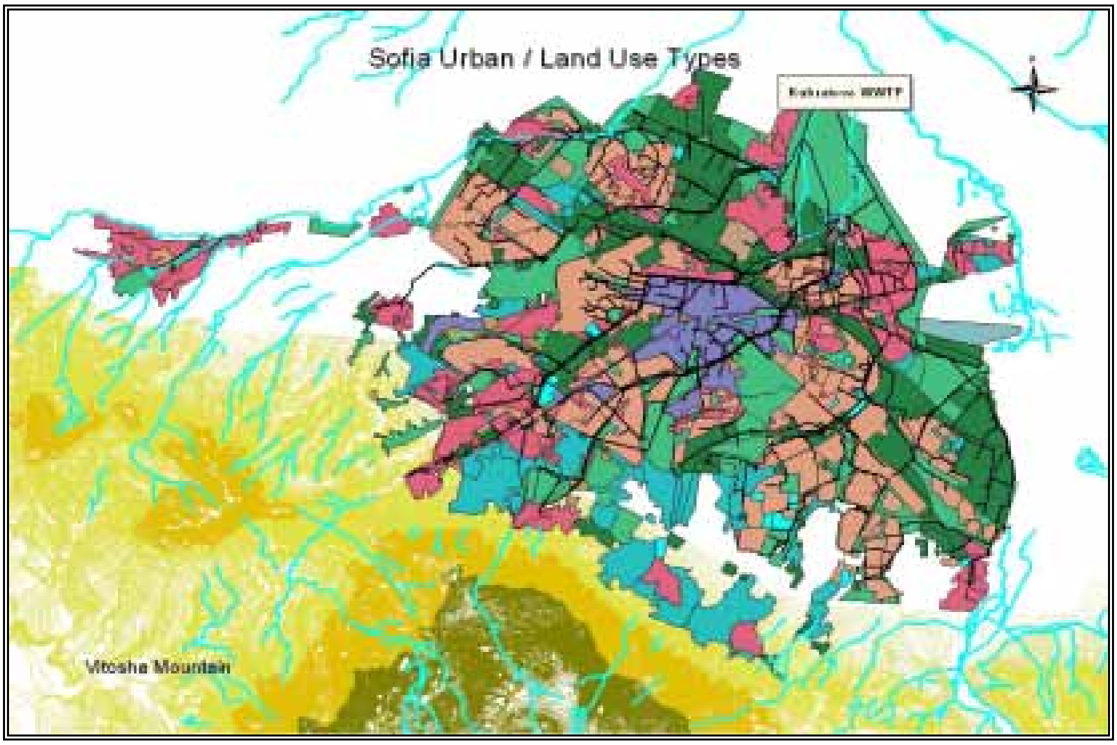
Completely trained field crews managed by an experienced engineer are carrying out the IAS. A widely accepted UK coding system has been adopted in Sofiyska Voda AD. The field maps are being digitised in ArcView shape files, which are the basis for area takeoff functionality in InfoWorks.

Picture 3: IAS – ArcView layer

Impervious Surface Type	System	Surface	Colour
Drains to Soak away	Any	0	Yellow
Paved / Road draining to Foul / Sanitary System	Foul	1	Brown
Roof draining to Foul / Sanitary System	Foul	2	Red
Paved / Road draining to Storm System	Storm	1	Green
Roof draining to Storm System	Storm	2	Blue

Table2: IAS coding system

The different land uses in Sofia have been analysed and 11 different types were defined. A digital ArcView layer has been created to automate the land use import into InfoWorks.



Picture 4: Sofia Land Uses – ArcView digital layer

Picture 5: Sofia Urban types / Land Uses

3.3. Critical Sewer Assessment

On commencement of detailed model planning the Sofia sewerage system was analysed and sewers were classified in accordance with their criticality. The WRc methodology has been adopted and during the analysis it has had to be revised.

The criteria for depth and diameter were not appropriate for Sofia as pipes are generally larger, e.g. minimum size for design is 300 mm. For example, using the economic rationale underlying the WRc method, for depth / diameter adjustments were made for a peak economic factor of 6 times normal replacement values. All other factors have remained the same. This approach finally has led to 25% to 30% critical sewers for the area of Sofia.

3.4. Water Consumption / Return to Sewer Rate Study

A high water consumption rate variation across the city was observed during an independent study carried out by University of Architecture, Civil Engineering and Geodesy (UACEG) with the support of Sofiyska Voda AD. Its relationship with sewer return rates still is not scientifically defined. Rates between 173 l/hd/day typical for the compact city and 480 l/hd/day for suburban territories with agricultural land use have been observed. Still the design sewer return rate is in use, which is 90% of 310 l/hd/day for the city of Sofia. The obvious inconsistency in observed and design rates led to establishing a new research for identifying a scientific relationship between those rates.

A detailed study incorporating both sewer and potable water models commenced in April 2004. Mladost III detailed catchment has been used as a pilot study. The latest FS data obtained for that catchment and the results based on potable water modelling measurements have been analysed and a sewer return rate of 84% has been initially estimated for that area. This study will finish after the detailed models are completed.

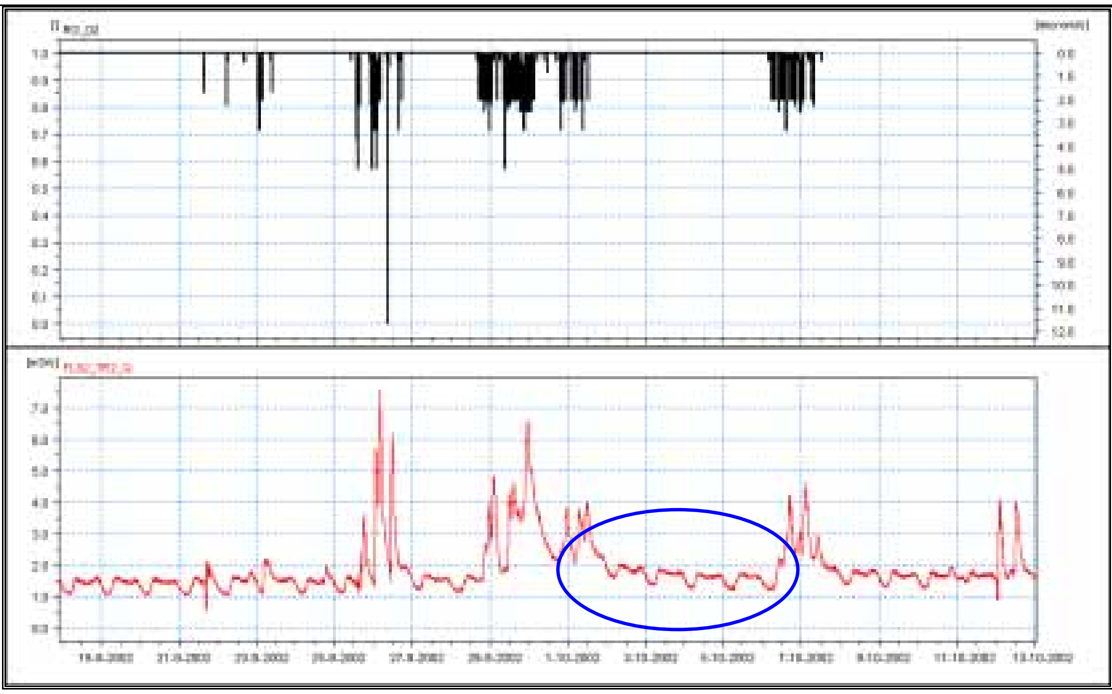
3.5. Sewerage Modelling and the Bulgarian Design Norms

As an advanced and expensive tool the full value of the hydraulic model should be exploited in creating long-term investment solutions, for designs and for design approval process. The so-called “Rational” Method is the official method for sewerage systems design, according to the Bulgarian legislation. Its static runoff computational core, generally based on statistical assumptions between 1970 -1985 considered being inappropriate for analysing and design of large-scale sewer systems. Sofiyska Voda AD, as the first Bulgarian water utility that has the opportunity to create and use hydraulic models, started a public debate for legalizing the modelling approach.

The latest results from simulations for the long term investment program clearly identified that some previous projects are significantly over designed – 15% to 20% on average (for some particular projects – more than 30%). Obviously that leads to unjustifiable high expenses for the company. Hence, a revision of the design standards (water demand for example that currently is 310 l/hd/day, as the observed average water consumption is only 173 l/hd/day) and legalization of the hydraulic models as a tool for design and new project approval, are important targets for Sofiyska Voda AD.

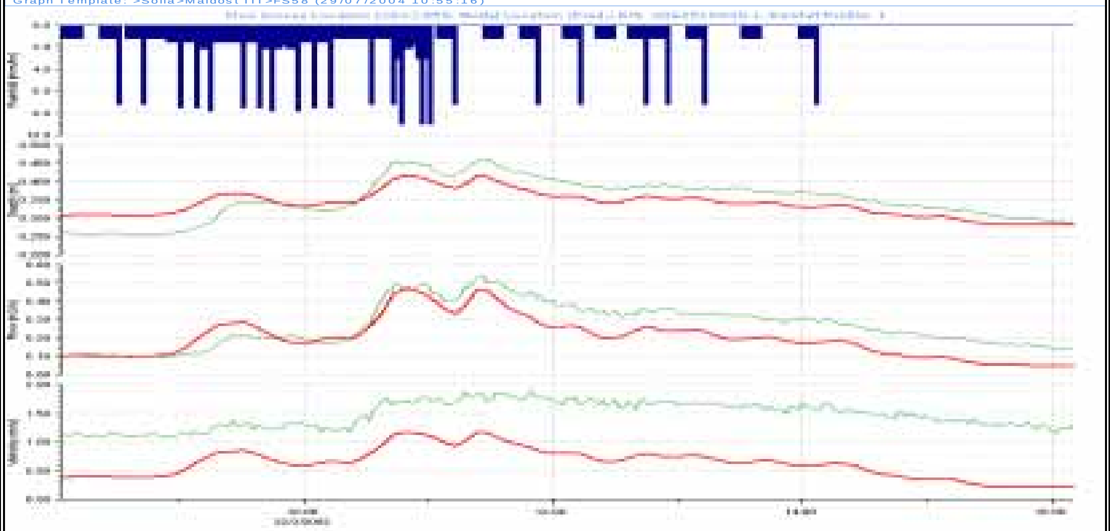
3.6. Sewerage Modelling – the choice of runoff model

On commencement of the detailed model planning a wide range of studies and surveys have been carried out to obtain the information needed for detailed model planning. The runoff analysis clearly identified the so-called “slow runoff component” (SRC). Its duration at the WWTP inlet has been estimated as 2 to 4 days. The reason has been considered to be a rainfall-induced infiltration combined with a runoff delay, both caused by the high percentage of permeable areas across the city, problems of gullies and overland flows. Further analysis was carried out, using the short term FS data that has been used for calibration of the Strategic Model. The results revealed the same nature of the phenomenon, for all the areas where IAS surveyors have observed high percentage of permeable areas.



Graph 1: An example of Slow Runoff Component (SRC) observed at WWTP inlet

Produced by alexlitchev (16/08/2004 14:14:51) Page 1 of 1
Flow Survey: >Sofia>EVENT A (16/09/2003 14:05:28)
Sim: >Sofia>Maldost III>Run Group>TEST_NAPI>Event A_NAPI (04/08/2004 16:33:48)
Graph Template: >Sofia>Maldost III>FS58 (29/07/2004 10:55:16)



	Rainfall			Depth (m)		Flow (m3/s)			Velocity (m/s)	
	Depth (mm)	Peak (mm/hr)	Average (mm/hr)	Min	Max	Min	Max	Volume (m3)	Min	Max
Rain	0.003	9.000	1.352							
Obs.				0.253	0.463	0.096	0.542	7820.822	1.080	1.880
Event A_NAPI				0.281	0.416	0.047	0.468	5920.134	0.200	1.170

Graph 2: Typical peak and volume under prediction for catchments where high percentage of pervious areas has been observed

Problems like under predicted peak flows and volumes have been solved with calibration in the strategic phase of the project. Such an approach is considered as unacceptable for detailed modelling and for the subsequent use of the models. Obviously for long duration storm simulations, not taking into account the lower initial losses towards the end of the storm could cause significant volume errors. Therefore the New UK Runoff Model was considered most suitable for the Sofia drainage area.

3.6.1. New UK Runoff Model – implementation issues

The main problems in using the New UK are the lack of basic data for Sofia and the empiric nature of the model equation:

$$\mathbf{PR = IF \cdot PIMP + (100 - IF \cdot PIMP) \cdot NAPI \cdot PF^{-1}},$$

where:

IF – effective impervious area factor
PF - moisture depth parameter (mm)
$\mathbf{NAPI = \Sigma_{1..30} \cdot P_{-n} \cdot C_p^{n-0.5}}$ – net antecedent precipitation index

The initial tests of the model against FS data have shown a good fit, but it was obtained using calibration of the parameters. There are no appropriate observations and statistical analysis for Sofia. For example:

- $\mathbf{C_p}$ **–** the decay coefficient in NAPI equation. It is strongly related to the **Soil Class** that could be obtained from geological maps available in UK. There is no such official soil classification for the City of Sofia, so the SV modellers had to create a map, based on the soil physical description in the original UK documents and had a study of soil types carried out in conjunction with National Geological Institute.

- **IF –** effective impervious area factor. The values recommended by Wallingford Software are statistically derived for the UK. The initial tests, carried out at the beginning of the project, show that the values should be revised for the area of Sofia.

- **P**F **–** moisture depth parameter. Wallingford Software has recommended 200mm, where no initial loss model is used. There is no suitable and ready-to-use statistically derived value for the City of Sofia. Currently a study is being commenced with the National Hydro-Meteorological Institute (HMI) to collect required data.

- **Design NAPI –** still there is no standard computer-based procedure for generating design rainfall events, design timeseries and rainfall parameters in Bulgaria. However, the Bulgarian HMI with the support of Sofiyska Voda AD have developed a sophisticated rainfall disagregation model, which has been used to generate design timeseries from historic daily rainfall totals. This was made for the first time in Bulgaria and there is still a process of acceptance of this design approach.

In most cases SV modellers have had to make best estimate approximations or to undertake empirical research to estimate basic data that is taken for granted in the UK.

3.7. Design Storms / Annual Timeseries Rainfall (ATSR)

The analysis of the sewer network required a range of design rainfall events and timeseries. Design storms were generated for 15min, 30min, 60min, 90 min, 120 min, 240 min, 480 min, 720 min and 1440 min durations for a 10 year return period by extracting the rainfall depth from 1976 Intensity – Duration – Frequency (IDF) curves for relevant duration and applying a standard profile.

The standard profile was taken from a statistical approach used in the Flood Studies Report whereby more than 100 storms were plotted as cumulative depth and normalised in depth and time. Then these were reversed using the IDF depth and duration.

The Annual Timeseries Rainfall (ATSR) was estimated as the most average for each month for the period 1991 – 2001.

Jan	1996	Feb	1995	Mar	2000
Apr	1997	May	1999	Jun	1991
Jul	1999	Aug	2001	Sep	1991
Oct	1991	Nov	1996	Dec	1993

Table2: Typical months

The table shows the typical months: the HMI model was used to disaggregate daily totals to 2 min totals where data was not in appropriate format.

The design storms and ATSR are used for simulating long-term investment scenarios and for assessing the frequency of spills from Sewer Overflows to the river system.

4. Conclusions

The Sofia DAS is the first of its kind in Bulgaria. The ambitious project was defined as a key factor for the company success and a sophisticated methodology was needed to achieve the high targets set in the concession agreement.

The WaPUG standards and UK modelling experience were successfully transferred to meet the Bulgarian conditions and oddities. Sofiyska Voda AD succeeded in creating a professional modelling unit comprised of local engineers that now is fully capable of carrying out the project. Ewan Associates Ltd. delivered the modern technologies and knowledge, staff training and the project management. The UK Company is a strategic partner of Sofiyska Voda AD.

Local oddities and specific issues have led to revision and adaptation of the applied WaPUG / WRc standards. During the critical sewer assessment the WRc depth/diameter criterion was considered not appropriate and has had to be revised in order to reflect the local conditions.

Many specific issues have been experienced during the field surveys such as the existence of a great number of pipe shapes, various road and roof surface types, rainfall spatial variation and flow survey difficulties.

The high standards and the procedures generated during the detailed model planning have required sophisticated software and InfoWorks by Wallingford Software has been chosen for being the most appropriate one for the project. The complicated runoff process observed across the city identified the New UK Runoff Model as the most suitable. Implementation issues, such as a lack of basic data and observation results, made the company to undertake a series of extra studies in conjunction with scientific research institutes such as the National Hydro-Meteorological Institute (HMI), Geological Institute (GI), University of Architecture, Civil Engineering and Geodesy (UACEG), etc., to provide basic data that is the key factor for a successful modelling process.