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A FUTURES APPROACH TO WATER DISTRIBUTION AND SEWER NETWORK (RE)DESIGN

Submitted by

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to the

University of Exeter

as a thesis for the degree of

Doctor of Philosophy in Engineering

April 2013

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ABSTRACT

When designing urban water systems (i.e. water distribution and sewer systems) it is imperative that uncertainty is taken into consideration. However, this is a challenging problem due to the inherent uncertainty associated with both system loading requirements and the potential for physical components failure. It is therefore desirable to improve the *reliability* of each system in order to account for these uncertainties.

Although it is possible to directly evaluate the reliability of a water distribution systems (WDS) (using *reliability measures*), the calculation processes involved are computationally intensive and therefore unsuitable for some state-of-the-art, iterative design approaches (such as optimisation). Consequently, interest has recently grown in the use of *reliability indicators*, which are simpler and faster to evaluate than conventional direct reliability methods.

In this thesis, a novel *measure* (the R_{UF}) is developed to quantify reliability in urban water systems with a view to enhance their robustness under a range of future scenarios (Policy Reform, Market Forces, Fortress World and New-Sustainability Paradigm). The considered four future scenarios were synthesized in the EPSRC supported multidisciplinary 4 year project: Urban Futures. Each investigated urban future scenario is characterised by a distinct household water demand and local demand distribution (emerging due to different urban forms evolving in future scenarios). In order to assess the impact of urban futures, R_{UF} has been incorporated into Urban Water System (UWS) dynamic simulations for both WDSs and Foul Sewer Systems (FSSs) using open source codes of EPANET and SWMM.

Additionally, in order to overcome extensive computational effort, resulting from the use of traditional *reliability measures*, a new holistic *reliability indicator*, the hydraulic power entropy (I_{HPE}) has been developed and compared to existing reliability indicators. Additionally, the relationship between the new reliability indicator and the above mentioned R_{UF} *reliability measure* is investigated. Results suggest that the magnitude of the I_{HPE} in network solutions provides a holistic indication of the hydraulic performance and reliability for a WDS. However, the performance of optimal solutions under some Urban Futures indicates that additional *design interventions* are required in order to achieve desired future operation.

This thesis also proposes a new holistic foul sewer system (FSS) reliability indicator (the I_{FSR}). The I_{FSR} represents sewer performance as a function of excess pipe capacity (in terms of available *increase* and also *decrease* in inflow). The indicator has been tested for two case studies (i.e. different sewer network layouts). Results suggest that the magnitude of I_{FSR} has positive correlations with a number of identified key performance indicators (i.e. relating to capacity, velocity, blockages).

Finally, an Integrated Design Approach (IDA) has been developed in order to assess the implications of applying *design interventions* on both a WDS *and* downstream FSS. The approach holistically considers present and future operation of each interconnected system. The approach was subsequently demonstrated using two proposed *design interventions.* Results suggest that, for the considered *design interventions*, there is trade-off between the simultaneous improvement of both WDS and FSS operation and reliability.

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to my supervisors Professor Fayyaz Ali Memon and Professor David Butler. Their guidance, expertise and encouragement have been invaluable, not only while completing my PhD. thesis, but throughout my entire academic studies at the University of Exeter.

I am also truly thankful to Dr Raziyeh Farmani for her technical guidance and suggestions.

It has been a great pleasure to work alongside all of the current and past members of the Centre for Water Systems who have helped to create an inspiring research environment. My particular thanks go to Dr Sarah Ward, Dr Josef Bicik, Dr Mark Morley, Dr Maryam Imani and Mr Innocent Basupi.

This work was supported by the UK Engineering and Physical Science Research Council as part of the Urban Futures Project (EP/F007426/1).

Finally, this dissertation would not have been possible without the love, support, patience and understanding that my family and wife Sammy have shown over the past three years.

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LIST OF ABBREVIATIONS

B-P	Butler-Pinkerton (chart)
D-S	diameter-slope
DS	downstream
DWF	dry weather flow
FSS	foul sewer system
FSR	foul sewer reliability
FW	fortress world (Urban Future)
HC	hydraulic constraint
IDA	integrated design approach
HPE	hydraulic power entropy
HWI	household water interaction
KPI	key performance indicator
MF	market forces (Urban Future)
NPV	net present value
NSGAII	non dominated sorting genetic algorithm II
NSP	new sustainability paradigm (Urban Future)
PR	policy reform (Urban Future)
R_{UF}	reliability measure
SATT	sewerage available to transport
UF	Urban Future
US	upstream
UWS	urban water system
WDS	water distribution system

LIST OF NOTATIONS

Symbol	Description	Units
b_i	trench width	m
C_o	average per capita consumption	m^3/s
c_{mh}	individual manhole cost	£
c_e	cost per unit of electricity	£/kWh
C_E	unit excavation cost	£/m^3
C_F	estimated future average per capita consumption	m^3/s
C_H	maximum global surplus FSS capacity	-
C_L	minimum global surplus FSS capacity	-
C_o	existing average per capita consumption	m^3/s
C_{Hi}	proportional foul sewer pipe highest surplus capacity	-
C_{Li}	proportional foul sewer pipe lowest surplus capacity	-
C_{FSS} $(\dot{C}_{FSS})$	(normalised) capital cost for WDS (re)design solution	£
C_{HWI} $(\dot{C}_{HWI})$	(normalised) capital cost to change HWI	£
C_{WDS} $(\dot{C}_{WDS})$	(normalised) capital cost for WDS (re)design solution	£
$C_p(D)$	pipe cost as a function of diameter	£
$C_b(D)$	trench width as a function of pipe diameter	m
C_{MH}	capital cost to construct manholes	£
C_{PIPE}	capital cost to construct piping infrastructure	£

C_{PMP}	pumping installation capital cost	£
C_{TANK}	construction cost of WDS tanks	£
C_{TOTAL}	(re)design solution capital cost	£
C_{OP}	pumping NPV operational cost over system lifetime	£
C_{OP}^{*}	annual operational cost of pumping	£
d	foul sewer pipe depth of flow	m
d^{*}	randomly generated decimal variable	-
d_o	individual household water consumption	m^3/s
d_{WDS}	individual household WDS water demand	m^3/s
d_{FSS}	individual household FSS water demand	m^3/s
D_{des}	WDS or FSS design demand	m^3/s
D_E	future demand from existing population	m^3/s
D_f	sewer demand multiplier for Urban Future *f*	-
D_F	estimated future global demand	m^3/s
D_o	existing global demand	m^3/s
D_N	future demand from additional (new) population	m^3/s
$D_{N,i}$	new future demand assigned to node *i*	m^3/s
$D_{E,i}$	existing future demand assigned to node *i*	m^3/s
$D_{o,i}$	demand originally assigned to node *i*	m^3/s
$D_{T,i}$	total future demand assigned to node *i*	m^3/s
D_{FSS}	global FSS demand (inflow)	m^3/s

D_{WDS}	global WDS demand	m^3/s
$D, [D_i]$	diameter [of pipe *i*]	m
Dwf_i	average dry weather flow in foul sewer pipe *i*	m^3/s
E_p	total pump energy used over 24h	kWh
F_F	future fulfilment function	-
F_E	future exceeded function	-
G_{max}	total number of simulations performed	-
h	demand *increase* component of future *exceeded* function	-
$h_{ava,i}$	available pressure head at node *i*	m
$h_{req,i}$	required pressure head at node *i*	m
$H,\ (H_i)$	pressure head (at node *i*)	m
H	demand *increase* component of future *fulfilment* function	-
h_i	depth of manhole *i*	m
I_{HPE}	Hydraulic power entropy indicator for WDS	-
I_{FSR}	Foul sewer reliability indicator	-
I_{RI}	Todini’s resilience index for WDS	-
I_{NR}	Raad’s network resilience for WDS	-
I_{CRE}	combined resilience-entropy index for WDS	-
I_{ENT}	informational entropy for WDS	-
IN	set of input nodes for WDS	-
l	demand *reduction* component of future *exceeded* function	-

L	demand *reduction* component of future *fulfilment* function	-
L_i	length of pipe i	m
n	foul sewer pipe Manning roughness coefficient	-
n^*	time of cash flow for calculating net present value	yrs
n_E	number of “edge” nodes	-
n_h	number of households served by WDS or FSS	-
N_{PC}	number of nodes selected for polycentric growth	-
N_{ED}	number of nodes selected for edge growth	-
N_C	number of conduits in FSS	-
N_n	number of nodes in WDS or FSS	-
N_p	total number of pipes in WDS or FSS	-
N_R	number of WDS supply nodes (reservoirs/tanks)	-
$N_{P,i}$	number of pipes entering node *i*	-
N_{PMP}	number of pumps	-
N_s	number of simulation time steps	-
P_o	population served by WDS or FSS	-
P_F	estimated future population	-
P_N	additional (new) future population	-
p_{ij}	hydraulic power entering WDS node i from pipe j	kW
P_k	rated pump power	kW
P_T	total WDS hydraulic power supplied by all input sources	kW

$P_{in,i}$	WDS hydraulic power from input source *i*	kW
$P_{ava,i}$	available hydraulic power at demand node *i*	kW
$P_{req,i}$	required hydraulic power at demand node *i*	kW
q_i	demand at WDS node *i*	m^3/s
q_{ij}	flow into WDS node *i* from pipe *j*	m^3/s
$Q, [Q_i]$	WDS or FSS pipe or node flow [in pipe *i*]	m^3/s
$Q_{min,i}$	minimum feasible flow in foul sewer pipe *i*	m^3/s
$Q_{max,i}$	maximum feasible flow in foul sewer pipe *i*	m^3/s
$Q_{L,i}$	lowest constrained flow in foul sewer pipe *i*	m^3/s
$Q_{H,i}$	highest constrained flow in foul sewer pipe *i*	m^3/s
r	discount rate for calculating net present value	%
R^2	coefficient of determination	-
R_{MF}	reliability measure (Market Forces)	-
R_{FW}	reliability measure (Fortress World)	-
R_{NSP}	reliability measure (New Sustainability Paradigm)	-
R_{PR}	reliability measure (Policy Reform)	-
S_i	slope of foul sewer pipe *i*	-
$\boldsymbol{S}$	set of nodal demands describing all network in/outflows	m^3/s
S_s	number of successful (feasible) simulations	-
T	total flow entering WDS network from all sources	m^3/s
T_i	total flow passing through WDS node *i*	m^3/s

V	foul sewer pipe flow velocity	m/s
$V_{e,i}$	excavation volume for construction of pipe *i*	m^3
V_{min}	foul sewer minimum (sedimentation) velocity	m/s
W_i	demand assignment weighting of node *i*	-
W_T	cumulative demand assignment weighting of all nodes	-
X_i	stochastic normal future demand for node *i*	m^3/s
$X, \hat{X}$	logarithmic proportion in the form *XlnX*	-
α	WDS demand coefficient	-
$\dot{\alpha}$	population weighted WDS demand coefficient	-
β	FSS demand coefficient	-
$\dot{\beta}$	population weighted FSS demand coefficient	-
δ	design demand factor	-
γ	proportion of households with altered HWI	-
γ^*	specific weight of water	N/m^3
γ_P	proportional change in population	-
γ_C	proportional change in average per capita consumption	-
γ_D	proportional change in global demand	-
η	pump efficiency	-
φ	average household occupancy	-