Development of a model simplification procedure for integrated urban water system models – conceptual catchment and sewer modelling

Mémoire

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Résumé

La modélisation intégrée du système d'assainissement urbain offre la flexibilité nécessaire pour développer des solutions qui bénéficient le plus au système global, en mettant l'accent sur la quantité et la qualité de l'eau, Les modèles intégrés offrent des avantages par rapport aux modèles traditionnels des sous-systèmes individuels en facilitant l'analyse efficace des interactions entre ces différents systèmes individuels (c.-à-d. les bassins versants, les égouts, les stations d'épuration et les eaux réceptrices) dans une seule plateforme de modélisation. La complexité réduite de ce type de modèle diminue le fardeau de calcul par rapport à leurs homologues détaillés, ce qui permet une plus large gamme d'évaluations telles que l'analyse de scénarios, l'optimisation par contrôle en temps réel et l'analyse d'incertitude par approche Monte Carlo.

Le potentiel de créer ces types de modèles intégrés représentatifs a été démontré dans de multiples études, mais les méthodes existantes pour développer ces modèles ne sont pas bien établies ni bien documentées et nécessitent donc un grand effort pour chaque nouveau cas d'étude. De plus, l'absence d'une méthode standardisée pour représenter la partie du modèle qui simule la quantité d'eau limite l'application de ces modèles pour des études de qualité de l'eau. Bien que la recherche soit nécessaire pour développer et optimiser toutes les méthodologies impliquées dans le développement de modèles intégrés de systèmes d'eaux usées urbaines, ce projet se concentre sur les modèles conceptuels simplifiés des bassins versants et des égouts pour la quantité d'eau.

L'objectif de cette étude était de développer une procédure structurée pour traduire des modèles hydrologiques et hydrauliques détaillés en modèles conceptuels simplifiés utilisés dans la modélisation du système intégré des eaux usées urbaines. L'objectif était d'améliorer la répétabilité, la flexibilité et l'efficacité de l'approche générale, indépendamment de la plateforme de modélisation choisie. Cette tâche a été réalisée en extrayant les principales étapes et considérations tout en construisant deux modèles conceptuels simplifiés d'une étude de cas au centre d'Ottawa, au Canada.

La partie urbaine centrale (6 400 ha) d'un modèle détaillé PCSWMM de la Ville d'Ottawa, contenant une combinaison d'égouts séparés, partiellement séparés et combinés, a été utilisée comme modèle de référence dans cette étude de cas. La tâche principale consistait à déterminer comment traduire ce modèle détaillé en modèle conceptuel simplifié de manière structurée, systématique et répétable en utilisant WEST comme plateforme. La procédure développée suit une séquence similaire à celle des protocoles examinés dans la revue de la littérature, tout en tenant compte des spécificités liées à l'agrégation des bassins versants et des égouts. Les quatre phases principales sont la définition du projet, le développement du modèle, la calibration et la validation.

Deux versions du modèle conceptuel ont été créées : le premier a d'abord été créé avec un certain niveau d'agrégation, tandis que le deuxième était plus agrégé que le premier modèle, avec environ la moitié du nombre de bloques et de réservoirs. Les deux modèles ont été calibrés et comparés au modèle détaillé.

Les résultats des simulations ont montré que le volume total et la dynamique des débits calculés par les modèles conceptuels ont bien émulé ceux du modèle détaillé (<< 10% de différence), tout en fournissant une réduction significative du temps de calcul (10 à 80 fois). La réduction du temps de simulation pour le modèle le plus agrégé n'était pas équivalente au niveau d'agrégation augmentée, principalement parce qu'il y a une quantité de code qui est présente dans les deux codes et prend donc le même temps de calcul.

Comme généralement anticipé, des différences plus grandes, mais acceptables, ont été observées en validation. Ces différences ont été attribuées à plusieurs facteurs, tels que le manque de calibration avec des données sur une période longue, les représentations simplifiées des structures spéciales, les différences entre les mécanismes utilisés dans les modèles détaillés et conceptuels pour représenter le durée de pluie, et la configuration du code de modèle. Dans l'ensemble, la validation a été une réussite étant donné que la calibration a été effectuée à l'aide d'événements de courte durée alors que la validation a utilisé une longue série de données.

En général, la procédure conçue a permis de réduire le travail manuel associé à la construction d'un modèle et à bien structurer la façon de construire des modèles conceptuels. Des connaissances pour chacune des différentes phases de modélisation ont également été acquises tout au long du processus du développement des deux modèles. Dans la phase ‹‹ Définition du projet ››, les objectifs du modèle conceptuel ont guidé la méthode de développement et de calibration du modèle. Les bassins versants et les égouts ont été délimités simultanément dans la phase de ‹‹ Développement du modèle ››, tout en tenant compte des emplacements des structures hydrauliques clés, des pluviomètres et des structures de débordement. La phase de ‹‹ Calibration ›› a permis l'avancement le plus systématique étant donné qu'un bon ordre de calibration a été défini et un ensemble limité de paramètres a été ciblé pour chacune des étapes de calibration. La phase de ‹‹ Validation ›› s'est révélée essentielle pour repérer des lacunes dans les hypothèses de base et les valeurs calibrées, afin de déterminer si le modèle est prêt à être utilisé ou doit être modifié.

Une procédure efficace et structurée qui traduit les représentations des bassins versants urbains et des égouts de modèles détaillés en modèles intégrés conceptuels a été développée et appliquée avec succès à une étude de cas. Comme démontré dans ce projet, l'application de la procédure structurée mènera au développement efficace de modèles intégrés représentatifs, ce qui augmentera leur utilisation potentielle pour tester des scénarios réalistes. Pour raffiner et améliorer la procédure formulée, il est recommandé de l'appliquer à d’autres études de cas.

Abstract

Modelling urban wastewater networks within integrated systems, focusing on both water quantity and quality, introduces flexibility to develop solutions with greatest benefit to the overall system. Integrated models provide benefits over traditional single sub-system models by facilitating efficient analysis of interactions between the individual components of urban water systems (i.e. catchments, sewers, treatment plants, and receiving waters) within a single modelling platform. The reduced complexity of this type of model decreases the computational burden compared to their detailed counterparts. This allows for a wider range of assessments such as scenario-testing, RTC optimization, and Monte Carlo uncertainty analyses.

The potential to create these types of representative integrated models was proven in multiple studies, however, the current methods to develop these models are not well-established nor well documented, and therefore require significant work for each case study. Furthermore, the lack of a standardized method to represent the water quantity portion limits the wide-scale application of such models for water quality studies. Although research is required to further develop and optimize all methodologies involved with building Integrated Urban Wastewater System (IUWS) models, this project focuses on the simplified catchment and sewer conceptual models for water quantity.

The objective of this study was to develop a structured procedure to translate detailed hydrologic and hydraulic models into the simplified conceptual models used in IUWS modelling. The aim was to improve repeatability, flexibility and efficiency of the general approach, regardless of chosen modelling platforms. This task was achieved by extracting the key steps and considerations while building two simplified conceptual models of a case study in central Ottawa, Canada.

The central urban portion (6,400 ha) of a calibrated detailed PCSWMM model of the City of Ottawa, containing a mix of separated, partially-separated and combined sewer areas, was used as the reference model in this case study. The main task involved determining how to translate this detailed model into simplified conceptual models, using WEST as the platform, in a structured, systematic and repeatable way. The resultant developed procedure follows a similar sequence as the protocols reviewed in the literature review, while taking into consideration specifics related to aggregating catchments and sewers. The four main phases of this thesis are Project Definition, Model Development, Calibration and Validation.

Two versions of the lumped model were created; the first was created with a certain level of aggregation, while the second was a further aggregation of the first model, resulting in about half the number of blocks and reservoirs. Both models were calibrated and compared to the detailed model as well as to each other.

The simulation results showed that the volume and dynamics (ie. the shape of the hydrographs) of the conceptual models emulated those of the detailed model well (<<10% differences), while providing a significant reduction in simulation-time speed-up (10 to 80 times faster than the detailed model). The simulation time reduction in the more aggregated model was not equivalent to the increased level of aggregation, mostly due to the fixed amount of basic calculation required in each model. As generally expected, larger but acceptable differences were found during the validation period compared to the calibration period. These differences were attributed to several factors, such as the lack of a long-time series calibration, oversimplified representations of special structures, the different mechanisms in the detailed and conceptual models used to represent wet weather flow, and the configuration of the model code. Overall, the validation was successful given the fact that the calibration was performed using events whereas the validation used an extended time series of 45 days.

In general, the devised procedure helped reduce the manual labour associated with building a model and structured the approach to build the conceptual models. General findings from the various identified phases were also documented throughout the model building process. In the Project Definition phase, the conceptual model's objectives guided the method of model development and calibration. The catchments and sewers were delineated concurrently in the Model Development phase, while taking into consideration the locations of the key hydraulic structures, raingauges and overflows. The Calibration phase allowed for the most systematic advancement of the model build, given that a good calibration order was defined and a limited set of parameters was targeted in each successive run. The Validation phase proved critical in pinpointing deficiencies in the initial assumptions and calibrated values, thus determining whether the model is ready for use or needs to be modified through one of the preceding phases.

An efficient and structured procedure that translates catchment and sewer representations from detailed to conceptual models in IUWS was developed and successfully applied to a case study. As demonstrated in this project, applying the proposed structured procedure will lead to the efficient development of representative IUWS models, thus increasing their potential use to test real-life scenarios. To challenge and improve the formulated procedure, applying it to multiple case studies is recommended.

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CSO	Combined sewer overflow
DWF	Dry weather flow
GIS	Geographic information system
GMP	Good modelling practice
GUI	Graphical user interface
GWI	Groundwater inflow or baseflow
IC	Institutional and commercial
IE	Inhabitant equivalents
IOS	Interceptor outfall sewer
IUWS	Integrated urban wastewater system
IWA	International Water Association
LR	Linear reservoir
MH	Maintenance hole
MSL	Model-specific language
NSE	Nash-Sutcliffe coefficient
ODE	Ordinary differential equations
PEP	Percent error in peaks
PVE	Percent volume error
RDII	Rainfall-derived inflow and infiltration
RES	Residential
RTC	Real-time control
SCADA	Supervisory Control and Data Acquisition
WEST	Wastewater treatment plant Engine for Simulation and Training
WWF	Wet weather flow

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Chapter 1 Introduction

The importance and advantages of evaluating and managing the operation of Urban Wastewater and Stormwater Systems (UWS) as integrated, global systems are commonly recognized but not often applied in practice. Traditionally, UWS have been modelled, designed, managed and operated as separate sub-systems. This approach has resulted in individual sub-systems that may be optimized to meet specific objectives and individually operate reasonably well but, in context of the overall system, run the risk of imposing excessive constraints, limiting the effectiveness of other sub-systems, or having missed opportunities for more effective solutions (Mitchell et al., 2011, Solvi et al., 2007).

Considering an Integrated UWS (IUWS) approach introduces the flexibility to develop and invest in solutions that minimize overall risk as well as provide greatest positive impact to the system as a whole and at affordable levels of investment. As regulatory frameworks move more towards considering holistic water quality and ecological health-based objectives, regulatory agencies gain interest in the integrated decision-making process. The need for the supporting tools, such as computer models, thus follows suit. Integrated models use a simplified and conceptual version of existing sub-system models, and available data to build an overall integrated model in one common platform. This model serves as the basis for system optimization and as a convenient tool to efficiently screen and assess multiple alternatives (Benedetti, 2006, Freni et al., 2008).

The true benefit of using IUWS modelling lies in the ability to assess systems based on water quality and not only quantity. However, the lack of a standardized method to efficiently represent the water quantity portion limits the wide-scale application of such models for water quality analyses. Although research is required to further develop and optimize all methodologies involved with building IUWS models, a focus on the development of the simplified catchment and sewer models is the first step towards improving the overall modelling approach. In any case, ensuring accurate water quantity representations is required before embarking on water quality modelling.

The potential to create reasonably representative conceptual models was proven in multiple studies (Solvi, 2007, Benedetti, 2006, Mannina and Viviani, 2009, Meirlaen et al., 2002, Wolfs, 2016, Vojinovic and Seyoum, 2008); however, the current methods are neither widely used nor well-established and require significant effort when developing each specific conceptual model. A research tour was conducted in November 2016 in Europe, in which many leading researchers in this field (L. Benedetti, D. Muschalla, M. Kleidorfer, V. Wolfs, and P.S. Mikkelsen) were consulted about the relevance of this problem statement. Although research foci varied, all researchers agreed that no such universal method exists.

Given the absence of a clear procedure to represent catchments and sewers required in integrated models, this project focused on the development of such a procedure, formulated based on synthesising and structuring pertinent approaches identified in the literature review. The main task involved determining how to translate a detailed model into simplified conceptual models, using WEST as the platform, in a structured, systematic and repeatable way. A focus on improving the robustness, flexibility and efficiency of the general approach to conceptually represent the hydrology and hydraulics in IUWS models will therefore result in the largest benefit in terms of increasing reproducibility, reducing simulation calculation times, and advancing their use to efficiently test a variety of real-life scenarios.

The following chapter (Chapter 2) provides a review of relevant literature related to existing procedures for modelling catchments and sewers in an IUWS context. Specific research goals and tasks of this project are then stated in Chapter 3. Required modifications made to the chosen modelling platform are summarized in Chapter 4. A description of the devised procedure, as well its application to a case study are found in Chapter 5 and Chapter 6, respectively. Obtained results, discussions, and study limitations are discussed in Chapter 7 and Chapter 8. Finally, general conclusions and recommendations from this project are presented in Chapter 9.

Chapter 2 Literature review

Three main topics are reviewed in the following literature review. First, an introduction to integrated modelling is provided, in which IUWS modelling history, applications, types and related obstacles are discussed. Second, approaches and methods used in literature to develop IUWS models, and specifically the catchment and sewer components, are reviewed. Finally, specifics to modelling in the selected platform, WEST, are discussed.

2.1 Introduction to integrated modelling

As the concentration of people in urban centres increases (United Nations, 2010) and threat of severe climate change impacts rise (NASA, 2017), the stress on urban wastewater infrastructure follows suit. Governments are thus forced to find new ways to adapt to the complex and ever-changing situation. In terms of wastewater management, practitioners and researchers increasingly recognise the need to assess systems as a whole instead of optimizing each component individually. This shift means acknowledging the multifaceted interactions between the diverse urban wastewater components (water distribution, wastewater networks, storm drainage, treatment facilities), as illustrated in Figure 1.

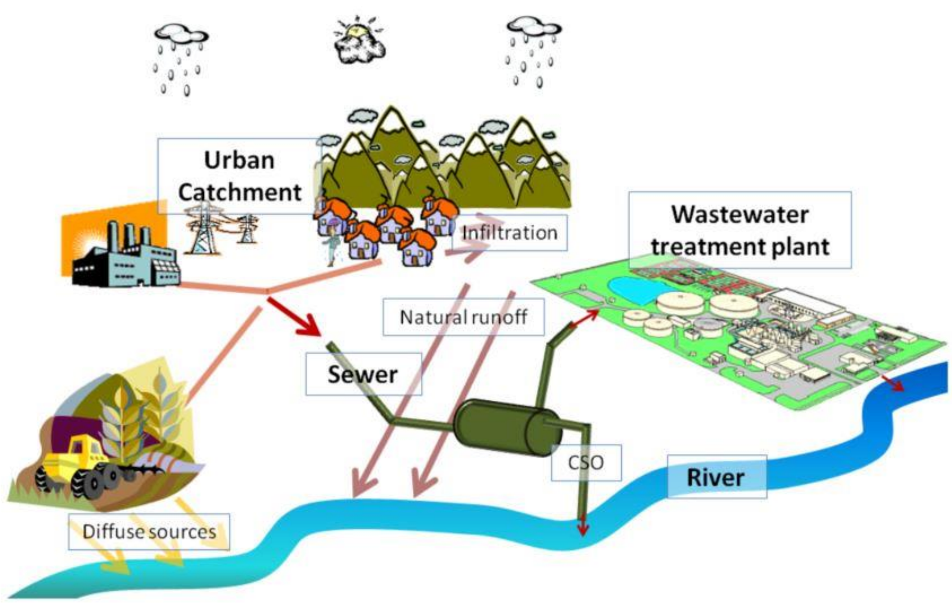

Figure 1: Illustration of the diverse integrated urban wastewater system components (Köhler, 2008)

Simulation models are often used to help in the analysis of these complex urban wastewater systems. Traditionally, engineering practices involve assessing each subsystem (catchments, sewers, treatment facilities, and receiving water bodies) separately. Although this method may lead to individually maximized solutions, the optimal management of the entire system is not necessarily achieved. An integrated approach to dealing with CSOs and the resultant pollution on receiving water bodies is needed to guarantee improved receiving water quality (Bach et al., 2014).

The following sections review the aspects of integrated modelling that are relevant to the conducted research project. First, a brief history of integrated modelling is presented, followed by applications of such models. Different types of integrated models and conceptual water quantity models are then reviewed. Finally, common obstacles limiting the acceptance or use of integrated models are discussed.

2.1.1 Brief summary of the history of integrated modelling

Applying water quantity models for water management has evolved over the years. Initially, very simple non-physically based models, with simplified equations that could be manually solved were used (Bach et al., 2014). As computers developed, slightly more complex models arose, but they were still very simplistic compared to modern standards. Later, as computation power increased, more and more detail was included. Including the most amount of detail as possible then became the main objective of most modelling projects. Recently, simpler models have regained attraction, specifically for integrated water management purposes, due to several advantages over detailed models (Wolfs, 2016). Firstly, the significantly shorter calculation times of conceptual models made it easier to run long-term simulations or applications that required many iterations (e.g. uncertainties, risk, optimization, etc.). Second, commercial products for detailed models were not as flexible as conceptual models to deal with abnormal situations or configurations. Lastly, as integrated thinking and modelling began to evolve, the open-code model structure of conceptual models proved advantageous over the closed-code structure found for most detailed models.

Although assessing systems in an integrated fashion was not always considered a mainstream approach, increased efforts to represent the important interactions between the different components in urban drainage systems began in the early 1990s (Bach et al., 2014). Research studies began covering different angles of simplified integrated analyses, such as integrated real-time control studies (Schütze et al., 1999), and integrated sewer system, treatment plant and river models (Vanrolleghem et al., 1996a). With the development of the Activated Sludge Model No. 1 (ASM1) (Henze et al., 1987), which formalizes the water quality calculations into mass balances and the Gujer matrix, a few notable integrated urban drainage models were subsequently developed. With the introduction of the European Union Water Framework Directive in 2000, river-basin analyses, with the goal of defining and developing solutions to achieve good water quality, became the new focus for water resources planning and management. Researchers and practitioners began turning more towards integrated approaches to meet the newly identified requirements. The following year, the River Water Quality Model No. 1 (RWQM1) (Reichert et al., 2001) emerged and was paired with the ASM1 model into commercial software for integrated modelling, such as WEST (Vanhooren et al., 2003) and Simba (Alex et al., 1999). Once these commercial packages were made available, the scope of integration also broadened to include other fields such as stormwater management planning and economic optimization, as well as defining the associated uncertainty of the analysis. While new ideas, models and methods were developed, very little in the way of guideline documents and protocols for integrated modelling emerged (Muschalla et al., 2009, Vanrolleghem et al., 2003, Bach et al., 2014).

2.1.2 Applications of integrated modelling

Although the criteria in Ontario and Canada are, in general, not yet water-quality based for wastewater and combined sewer overflows, both the European Union and the USA have moved towards pollution-based criteria for water resources planning and management. Both directives demand the assessment of the overall impact of urban water systems on river-basin management. An integrated approach to account for all pollution sources is consequently necessary. Thus, modelling these systems in an integrated manner is the logical step.

Applying IUWS modelling for strategic planning and management of urban water systems has been demonstrated in multiple case studies. In additional to adhering to water-quality based legislation, IUWS models are often necessary to perform scenario investigations and determine multi-objective optimizing strategies (Vanrolleghem et al., 2005). Solving municipality emission problems with integrated approaches, and thus IUWS modelling, is also beneficial in priority-setting and decision-making exercises for infrastructure improvements (Fletcher et al., 2013, Krebs et al., 2014, Bach et al., 2015)). Other uses of such models include optimisation of process or development of control strategies within a treatment plant (Vanrolleghem et al., 1996a), and demonstration of the benefits of RTC for improving river water quality (Butler and Schütze, 2005). IUWS models are especially suited for projects where the focus is the catchment outlet (i.e. treatment plants or outfalls) (Coutu et al., 2012, Vanrolleghem et al., 1996b). These models are also used for a wide range of Monte-Carlo based uncertainty analyses (Benedetti et al., 2008, Benedetti et al., 2010). Complex and computationally heavy models are not well suited for the above-mentioned application; simplified models are therefore required to enable such analyses in an efficient manner.

2.1.3 Types of integrated models

Due to the broadened scope of integration in urban drainage systems, a specific definition of IUWS modelling is not evident. The general principles in IUWS modelling have been summarised by Bach et al. (2014) as:

- Modelling multiple components (e.g. physical, biophysical, etc.) and their interactions;
- Considering short-term, long-term and delayed impacts of both water quantity and quality processes over a time period; and

- Capturing both local and global perspectives to make better informed decisions about policies, strategies, and solutions.

Bach et al. (2014) also make a distinction between the various levels of integrated models. The type of model that is most often used in urban wastewater management are called Integrated Urban Drainage Models in the above-mentioned paper, and termed IUWS models in this project. These models integrate sub-systems (catchment drainage and wastewater generation, sewer networks, treatment facilities and receiving water bodies), focusing on the treatment and transport processes. Further broader scopes of integrated models may include the total urban water cycle, or all disciplines with a water-centric focus (e.g. societal models, energy models, economic models, etc). On the reverse side, a more detailed integrated model may only look at integration within one subsystem (e.g. multiple processes in a treatment plant).

Two main approaches to building integrated models exist and were reviewed by Volcke et al. (2006):

- Using one set of variables for all subsystems (i.e. supermodels); and
- Using different sets of variables for each subsystem and using interfaces (i.e. transformers) to connect the subsystems.

The first concept was introduced in Vanrolleghem et al. (1996b), in which a more holistic approach to wastewater treatment plant design was suggested. The supermodels have the advantage of simpler transformations between sub-model state variables; however, because all variables need to be calculated under all environmental conditions, these models are slower simulating compared to their interfaced counterparts. In addition, these models were often developed in specific simulation platforms, therefore expertise gained from other models cannot be easily adapted for their use. The interfacing approach couples well known existing models and therefore has the advantage of utilizing all the previous expertise from the specific models. In addition, because each subsystem only contains a specific set of variables, these models are faster. Linkage difficulties may however arise from the required complex non-standard interfaces that must be written for each specific case study. Furthermore, when new variables are introduced in a submodel, the interfaces must be updated. Although each type of model has its strengths and limitations, the suitability of either depends on the requirements and objectives of the project by Volcke et al. (2006):

Depending on the chosen IUWS modelling approach, different types of conceptualization of water quantity representations may be used. The following section reviews the main types of water quantity models used to simulate the catchment and sewer networks in IUWS models.

2.1.4 Water quantity models

There are many different types of quantity models that exist, each with varied characteristics, objectives and features (Wolfs, 2016, Bach et al., 2014). Some of the key features that vary in these models include model structure, data requirements, spatial and temporal detail, process nature, etc. Classifying the different types of models based on these features simplifies an analysis of their uses. Although models are often divided into stochastic and deterministic models (models that account for natural variability versus single output models, respectively), only deterministic models are reviewed in this thesis. As outlined in his PhD, Wolfs (2016) refers to the division suggested by Abbot and Refsgaard (1996):

- Distributed physically-based models;
- Lumped conceptual models; and
- Empirical models.

Although this division combines specific model features to define three categories, most distributed models are physically-based, while most lumped models are conceptual. Physically-based models are most often used in hydrodynamic software, such as InfoWorks, SWMM, and Mouse DHI, and are solved using different numerical integration approaches in each program. The Saint-Venant equations, which calculate the flow and energy based on conservation of mass and momentum, are linearized equations of the three dimensional Navier-Stokes equation for describing motion of viscous fluids (Te Chow, 1959). Full solutions that require significant computational power and time are needed to solve these equations.

Empirical models fall on the other side of the spectrum. Physical processes are not represented, nor do model parameters represent any physical characteristic. These models are generally simple and are categorized into two groups by (Abbot and Refsgaard, 1996): statistically-based approaches, such as regression and correlation methods, and models developed with machine-learning techniques.

Conceptual models draw from both spectrums of models: they are an abstraction of the physical process on a larger scale (Wolfs, 2016). These models still use the continuity principles (closed mass balance), but the momentum equation is replaced by defined relationships that are often empirical. In these models, most conceptual parameters do not relate directly to reality, and therefore need to be calibrated. Many different types of conceptual models exist, the simplest being the storage-outflow models, as seen in KOSIM-WEST (Solvi, 2007). Due to the required timely calibration of conceptual models, approaches that link the inflow to the outflow are often integrated into conceptual models. For example, the Kalinin-Milyukov approach (National Institute of Hydrology, 1986) was incorporated into KOSIM-WEST (Solvi, 2007). Due to their simplicity, conceptual models often suffer limited accuracy or limited applicability; therefore, many models have added additional routines to mimic important phenomena such as backwater. One such example is the combiner-splitter routine developed by Solvi (2007). Although this approach requires additional calibration of introduced parameters, it has been proven to provide acceptable results compared to physically-based models like SWMM (Vanrolleghem et al., 2009).

2.1.5 Obstacles limiting acceptance of integrated modelling

As reviewed in previous sections, integrated models could be used to support effective decision making. However, these models are seldom used for practical applications due to certain obstacles. The following items have been highlighted in multiple studies as important limitations that prevent the use of such models in practice. This section is meant to outline some of the challenges that could be addressed to advance the use of integrated models.

The authors of a review paper on hydrological modelling of urbanized catchments (Salvadore et al., 2015) highlight the limitations of overly-lumped models to accurately represent spatially-variable phenomena. The authors are in favour of high-resolution (detailed) models to accurately depict urban hydrology, and suggest resorting to cloud computing to decrease simulation run-times. The authors suggest that modular approaches could introduce flexibility in the model structure. Furthermore, they state that lumped models lose the benefit of geographic information systems (GIS) integration and use. Conceptual models often, but not always, don't exploit the available data and powerful tools found in GIS. The paper also states that spatial and temporal scale of physical practices often do not correspond to spatial and temporal discretization of hydrological models (i.e. conceptual models use detailed physical phenomenon at a lumped scale).

Other limitations of conceptual modelling are reviewed by Bach et al. (2014). One of the most detrimental limitations of integrated modelling is the lack of user friendliness in most commercially available packages designed for IUWS modelling. These platforms often fail to assist users who become frustrated with trial and error and lots of manual labour. Unfortunately, the industrial market to further develop integrated modelling platforms is small at this time.

Model complexity is raised as another large obstacle in advancing the use of IUWS models. The multiple subsystems and the complexity of their interactions make the development of IUWS models very time-consuming. In addition, the lack of data (including spatial coverage of precipitation) complicates the process. Either large amounts of data are required for calibration to makeup for the lost physical descriptions, or existing, calibrated detailed models are needed to develop conceptual models (Meirlaen et al., 2001). Furthermore, the conceptualized representations of networks and physical processes in lumped models are often hard to follow for a second user. Finally, there is a lack of understanding of the ways in which these complex IUWS models can be used in practice (e.g. decision-support tool versus on-line operational tool).

Communication between various industries, stakeholders and practitioner poses another obstacle in the acceptance of IUWS modelling. To tackle this issue Bach et al. (2014) suggests improving communication from modellers to stakeholders by following a systematic approach wherein the objective is clearly stated, and all aspects of the approach, results and conclusions are transparent.

Thus, future research should focus on standardizing a more transparent process when developing integrated models. Such a procedure will hopefully lead to increased user-friendly platforms, simplify the model complexity issues, and improve communication of the benefits of the performed work and the presentation of results.

2.2 Modelling protocols

The following sections review approaches related to modelling protocols starting from the most generic to the more specific. First the generic environmental modelling procedure is reviewed, followed by a summary of integrated modelling protocols. Subsystem modelling protocols are then reviewed, and finally an overview of methods used to lump and aggregate models is described. Comments about the benefits of using standardized approaches in modelling practice are subsequently discussed.

2.2.1 Generic modelling protocols

Generic protocols for water and environmental modelling are reviewed in Carstensen et al. (1997), Refsgaard et al. (2005), and Refsgaard et al. (2007). Terminology for the general model-building process is suggested by Carstensen et al. (1997), in which the following steps are outlined (see Figure 2): problem formulation, prior-knowledge collection, frame definition, model structure selection, parameter estimation, model diagnosis, and model testing. Refsgaard et al. (2005) reviewed other technical model-building guidelines, and outlines a new guideline that organizes and builds from summarized key elements of the reviewed guidelines. This new guideline is decomposed into 5 steps:

1. Model study plan
2. Data and conceptualization
3. Model set-up
4. Calibration and validation
5. Simulation and evaluation

Many sub-tasks are presented under each step, however a condensed version of the depicted process, along with its interactions with the water management process, is presented in Refsgaard et al. (2007) in Figure 3.

The first step of this generic protocol calls for identifying the problem and its context, setting the objectives and evaluating the various modelling requirements. Other overall modelling approach questions are also answered in this step. The second step is intended for collecting and assessing the validity of data that will be used to build, calibrate and validate the model. Spatial and temporal detail are considered while selecting the model codes and conceptualising the system in this step. The third step involves setting-up the model based on the selected model code and conceptualized system. Performance criteria are also confirmed in this step. The fourth step is devoted to model calibration and validation. In this step, a calibration strategy is defined and calibration parameters are selected. Finally, in the firth step, the sought simulations and analysis are performed.

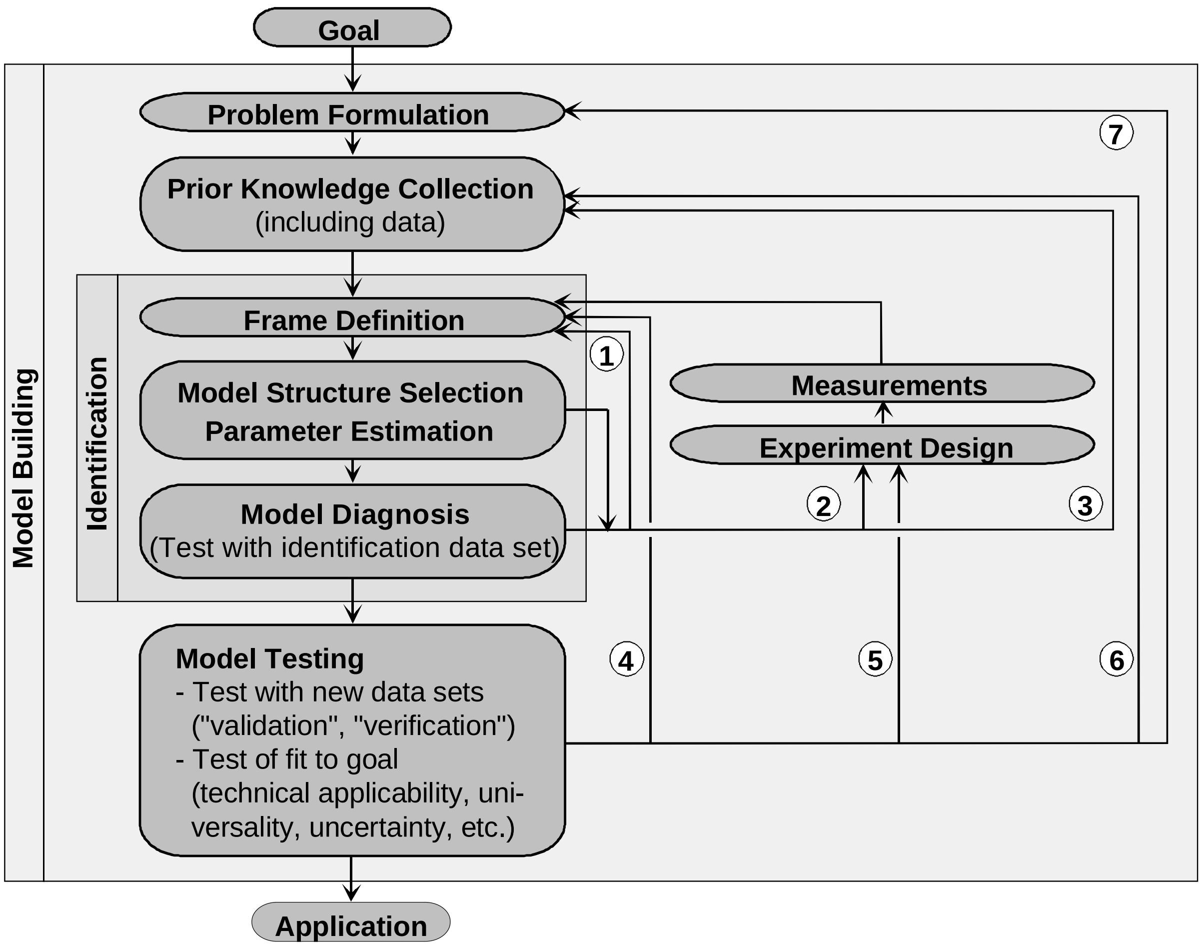

Figure 2: Model building process from Carstensen et al. (1997)

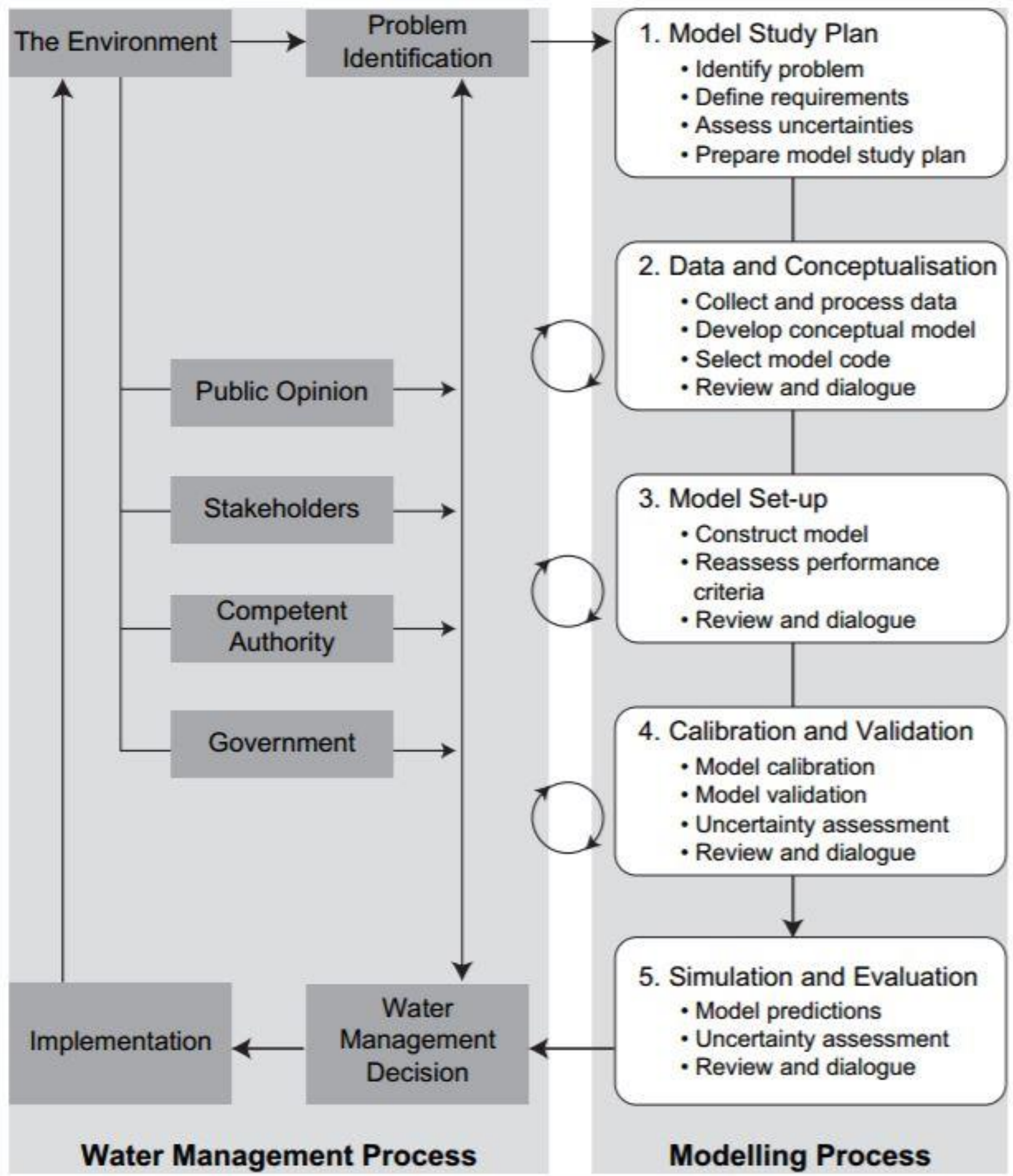

Figure 3: 5-step model-building process with water management process interactions (Refsgaard et al., 2007)

2.2.2 Integrated modelling protocol

Some earlier publications that reviewed IUWS modelling protocols include Marsalek et al. (1993), Beck (1997), and Poch et al. (2004). A generally agreed-upon methodology was introduced at INTERURBA I (Lijklema et al., 1993), which others later updated (Rauch et al., 1998, Vanrolleghem et al., 1999, Schilling et al., 1997). Most of these methodologies are very similar, but vary in the level of detail (Bach et al., 2014). The Central European Simulation Research Group (Hochschulgruppe—HSG) developed a synthesised transparent generic integrated modelling protocol (Muschalla et al., 2009, Muschalla, 2008) by taking into consideration the other developed methodologies. This protocol follows an objective-oriented approach and is suitable for many types of modelling projects, such as IUWS modelling. The HSG guideline looks at the entire model-building procedure and breaks it into a systematic and structured six-step approach:

1. System analysis
2. Processes and criteria
3. Modelling approaches and data demand
4. Analysis of data and model
5. Model calibration and validation
6. Model application: analysis of scenarios

Each step is reviewed in the journal article, and insights specific to integrated modelling are provided. A visualization of this approach was provided in Bach et al. (2014), and is presented in Figure 4. In the Systems analysis step, the motivation for completing the conceptual model and the modelling objectives are determined. The main processes, variables, and system boundaries as well as the modelling criteria are defined in the Processes and criteria step. Data sets are collected, modelling approaches are selected and subsequently the basic model structure is described in the third step. The Analysis of data, and the Model calibration and validation steps require the most amount of work. The former requires assessing all available data sets and completing required measuring campaigns. Ensuring that the models and interfaces perform as anticipated is also done simultaneously in these steps. The Calibration and Validation step has its own internal sequence, starting with the estimation of the parameters. If possible, each subsystem is then separately calibrated and validated, starting with the hydrology and the hydraulics, followed by the quality processes. A system-wide calibration, with a focus on the receiving water bodies, is then performed. Finally, scenarios are tested in the last step.

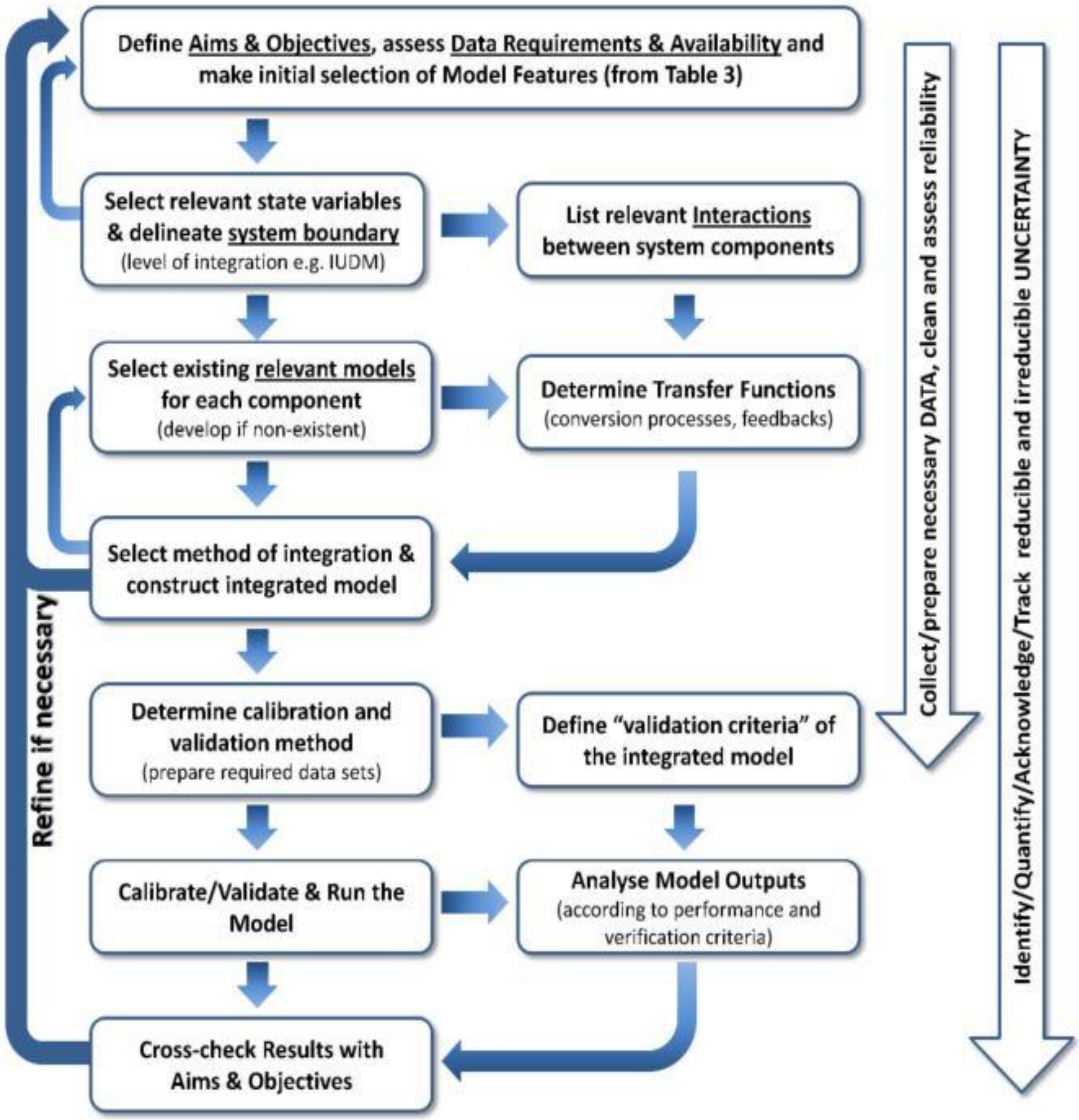

Figure 4: HSG approach to developing IUWS models, visualized by Bach et al. (2014)

2.2.3 Subsystem modelling protocol

Many guidelines that review the procedure to develop the subsystem representations in integrated models focus on one subsystem in particular: the treatment facility. As reviewed in the Muschalla et al. (2009) paper, many papers provide approaches for preparing calibrated models of activated sludge wastewater treatment plants: the STOWA calibration protocol (Hulsbeek et al., 2002), the BIOMATH calibration protocol (Vanrolleghem et al., 2003), and the WERF protocol (Melcer, 2004). The GMP procedure was developed by the good modelling practice (GMP) Task Group (Rieger et al., 2013). This group of international experts was formed by the

International Water Association (IWA) with the objective of synthesizing all key aspects of other available wastewater treatment modelling protocols into a unified generic protocol. The group compared existing protocols and found that most contained many similarities to the generic approach, and the few differences that existed were primarily related to the level of detail and foci of the protocols. The unified generalized approach was broken down into 5 steps, that are very similar to those introduced in the generic and integrated modelling procedure:

1. Project definition
2. Data collection and reconciliation
3. Model setup
4. Model calibration and validation
5. Simulation and result interpretation

The WaPUG Code of practice for the hydraulic modelling of sewer systems (WaPUG, 2002) provides a good overview of the entire sewer model building approach, including simplification strategies. The Code of practice identifies that differing standards and techniques are applicable depending on the intended purpose of the model. In this guideline, IUWS models would fall under their definition of Skeletal planning models: reasonably accurate models of trunk sewers and tributary areas built for trunk or outfall flow simulations. Although a generic modelling procedure is not specifically outlined, the following larger tasks are reviewed:

1. Project definition
2. Definition of data requirements and collection
3. Model building and testing
4. Model verification (i.e. calibration and validation)

Many guiding principles for specific tasks, such as simplification methodologies, are reviewed in the WaPUG document, however a sequential procedure is not defined. Relevant tasks that are reviewed include selection of modelling software, interactions with other subsystems, model simplifications, representation of special structures (e.g. hydraulic structures), initialization of models, and criteria for calibration. Although these guidelines do provide meaningful insight into each model building phase, they may be more suited to planning level models, which still use physically-based models but do some level of aggregation.

Other regional or internal technical protocols have been developed and are used internally by modellers. Although these often focus on software-specific constraints, issues, and solutions, these types of protocols can often provide relevant additional information on how to build or apply models. One such protocol is by Wolfs (2016), in which he defines his own model configuration procedure, which has many similar steps to generic approaches, however it is specific to the "CMD" software that he developed. This procedure is also classified into discrete steps:

1. Collection of required data
2. Definition of conceptual model topology (equivalent to catchment and sewer connection delineation)
3. Identification and calibration of model structures
4. Configuration of elements into model script (required step for CMD software)
5. Simulation of events

In summary, there are many software programs that have been developed to model IUWS. New and better methods are not necessarily needed; instead, time should be spent on spreading the knowledge of how to efficiently use each software, and how to apply proper modelling procedures within the chosen platform. The GMP protocol is a great guiding tool developed for wastewater treatment modellers, from which all the generic steps could be implemented when building IUWS models. Combining knowledge from these types of systemized protocols with the knowledge about IUWS modelling and aggregation approaches could act as the basis for formulating a procedure for catchment and sewer modelling in integrated models.

2.2.4 Lumping and aggregation of models

Due to the increased complexity and associated computational burden of detailed sewer network models, simplifications are necessary. Few articles focus on simplification and aggregation of detailed catchments to lumped catchments. Of the few studies that exist, most are not related to integrated modelling and do not look at the same degree of lumping that is required for this type of modelling. Nonetheless, useful insight can be extracted from these works to develop a guiding aggregation procedure relevant to integrated modelling. Most studies agree that a generalized aggregation method does not exist, nor is it possible to define a specialized method that works for all cases. Expert knowledge of the system is therefore required to perform such a task. Most studies also conclude that calibration is required to adjust aggregated parameters in the lumped model, for modelled processes act differently at various scales.

The following section reviews considerations extracted from multiple studies related to catchment and sewer aggregation. Two additional and specific approaches that offer suggestions to lumping catchments and sewers are described in the next section.

2.2.4.1 Considerations for model aggregation and lumping

Wolfs (2016) reviews the shortcomings of conceptual modelling and states that no formalized generic procedure exists, meaning that modellers are forced to depend on self-programmed algorithms to determine how to conceptualize their systems. One of his main conclusions about aggregation is that the process of aggregation on different scales is challenging and many factors affect the method. Hence, the degree of lumping for models depends on the intended use, the desired accuracy, data availability and the behavior and dynamics of the system itself. The author concludes that expert knowledge is required to delineate catchments and sewers, because defining a conclusive list of criteria to determine these divisions is not possible. Thus, determining the balance between simplifications and resultant accuracy is left to the modeller of each specific case. In his project, the catchments were created by tracing up-stream and downstream-flow paths from selected nodes in the developed software. Some hydraulic structures that were mentioned to consider in the delineation process included pumps, valves, weirs, sluice gates, trunk junctions and bifurcations. Hydraulic structures and conduits between catchments or overflow structures that acted similarly were merged into one defining model component in his project.

A study on the effects of spatial resolution in urban hydrologic simulations (Ghosh and Hellweger, 2011) also states that a general consensus about how aggregation affects the model predictions is not evident in literature. The study aimed to understand mechanisms that lead to scale effects and results. They compare models of varying spatial resolution, including artificially generated systems, in which parameters were aggregated based on area-weighted averages. The study concluded that the effect of scaling results in varying model outcomes, and depends on various modelled processes and storm characteristics. In general, physical parameters had to be altered/calibrated to achieve decent fits for different storms.

Cantone and Schmidt (2009) researched small and larger case studies to show the risks of the two most common simplification techniques: aggregating catchment parameters based on area-weighted methods and skeletonizing sewer systems. The study concluded that conduit storage is often lost and not accounted for through aggregation; however, in agreement with the aforementioned researchers, errors due to aggregated parameterization could be compensated for by calibration of certain parameter values. The study also showed that calibration of parameters to fit certain storm events may result in non-representative responses for storms of varying duration and magnitude. As such, calibrating with multiple and successive events is necessary.

Tikkanen (2013) conducted a study on hydrological modelling of large urban catchments using ArcGIS. This research also concluded that no clear procedure has been presented in literature on how to choose certain parameter values in an aggregated stormwater model. The authors also stated that aggregated parameter values were found to be inaccurate compared to calibrated values. Furthermore, it was determined that parametrization of heterogeneous subcatchments for low-resolution models was challenging and inaccurate. Hence, the effort needed to create network parameterization proved highly dependent on the quality of the input data. As such, the importance of performing a sensitivity analysis on different parameters was highlighted. The authors suggested a systemized GIS-based method to delineate catchments, however it was highly dependent on using high-resolution digital elevation maps and very detailed and accurate sewer data. Finally, the authors conclude that a complete automation of catchment delineation is not possible due to typical data defects, sewer network complexity, and variability in input data.

A method to scale up descriptions of hydrological responses is explored by Viney and Sivapalan (2004). The authors attempt to develop a correlation between the conceptual model parameterization and the underlying process-based small-scale descriptions, however the work is only applicable to lumped models operating at a daily time step.

A study was conducted by Cantone and Schmidt (2011), in which the hydrologic response of a highly urbanized catchment was analyzed. The authors established that the hydrologic response of large urban catchments is inherently linked to the configuration and structure of the sewer network conveying flow in the catchment. Hence, the defining catchment parameters must represent the combined sewer and hydrologic responses. The non-uniformity of rainfall over catchments was also raised, and the potential negative impact of coarsely spaced raingauges on predicted resulted was highlighted.

Rodriguez et al. (2003) raised similar points, stating that the contribution of the overland flow over the surface (i.e. streets) is often not explicitly accounted for in urban hydrological models; however, they represent a significant portion of the flow paths. Furthermore, careful attention must be paid when using travel time as a basis for lumping detailed models, because response times were shown to decrease consistently with increasing magnitudes of rainfall.

The issue of scale is discussed in Dehotin and Braud (2008), wherein the authors state that the optimal scale (i.e. detail of representation) of the model depends on the model objective but also on the extent of the available data. With respect to conceptual model parameters, the authors agree that detailed model parameters must be modified (calibrated) to represent large-scale phenomena.

Several studies give insight on the method to define parameters for aggregated catchments. Vojinovic and Seyoum (2008) state that values are generally estimated by trial and error during the calibration process. The authors suggest that parameters could potentially be estimated from derived equations that could correlate model parameters to the drainage system characteristics. An attempt to develop such equations would be to derive, via calibration, a large number of model parameters that corresponds to larger gauged systems, and then to derive a mapping function which can provide the parameter values for a given combination of catchment characteristics. Although there have been some attempts to achieve such a goal, many studies, like those introduced above, conclude that determining this type of universal direct correlation is not possible. The authors of a recent study completed by Siegrist et al. (2016) identify that no industry standards exist for defining the calibration parameters of a lumped area, however this selection often affects the accuracy of a model. Furthermore, due to the many variables that influence a model's flow response, evaluating a model's performance is often subjective, thus the calibration process advances iteratively.

2.2.4.2 Suggestions on tackling aggregation

WaPUG (2002) reviews practices for sewer modelling, including simplification methods for sewers. Three common methods for sewer model simplification are outlined in this guideline:

- Pruning: Excluding small diameter pipes from the periphery of the system;
- Merging: Grouping many similar consecutive pipes together to a single pipe;
- Equivalence: Replacing complex layouts with a simpler arrangement that behaves in a similar way.

These methods rely on engineering judgement to perform the simplifications. The guideline states that special attention must be paid to high and low flow conditions, for the exclusion of pipes could lead to differences in hydrograph timing and system hydraulic performance. Modelling additional pipes to provide sufficient routing is suggested to overcome the potential issue of incorrect timing of flow from large lumped catchments.

Although the Austrian guideline document produced by Muschalla et al. (2016) is not accessible to non-German speaking audiences, it provides a very good overview of conceptual modelling concepts, including different aggregation strategies for various levels of lumping. A summary of the main elements relevant for this study is given below. Firstly, the degree of catchment aggregation is related to the objective of the conceptual model. Second, limiting catchment size is important to avoid errors due to rainfall variability over the area. Areas having mixed system types (separated, combined) cannot be conceptually modelled with one catchment, and therefore need to be separately represented. The importance of knowing the desired temporal scale of the applied rainfall (i.e. rainfall time interval) is also demonstrated in the document.

The dependence of catchment delineation on sewer divisions, and vice versa, is also reviewed in (Muschalla et al., 2016), along with illustrations of specific examples. For example, representing an area by one catchment outletting straight to the outfall is one option, versus another option that would represent the same catchment as outletting to a sewer midway through the catchment prior to outletting to the outfall (See Figure 5). The characterizing catchment parameters for each example would be different because in the first situation all the routing is done by the catchment, whereas in the second, some of the flow routing is covered by the sewer. Similarly, the representative sewers in both examples are also different. In Figure 6, an alternate but similar example of the link between the catchment connection location and sewer delineations is clearly demonstrated.

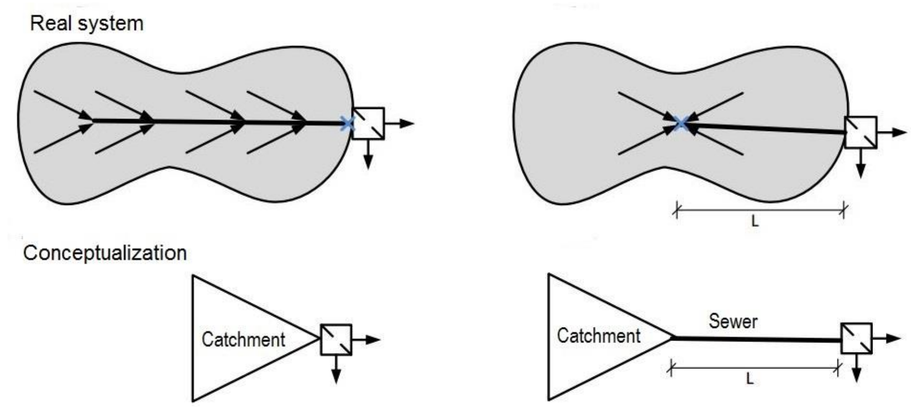

Figure 5: Catchment and sewer aggregation example 1, adapted from Muschalla et al. (2016)

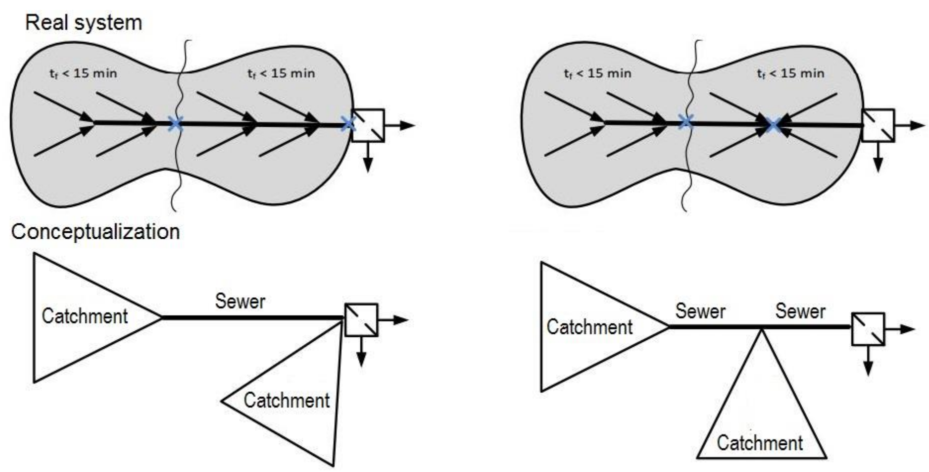

Figure 6: Catchment connection and sewer aggregation example 2, adapted from Muschalla et al. (2016)

The effects of catchment connections on sewer sizing is shown by a set of examples in Figure 7. On the left side, the entire representative sewer diameter is modelled as 400mm, because the catchment F2, which is partly tributary to both the 600 and 800 mm sewers, is connected downstream of the 800mm sewer in the conceptualization. In the example on the right, the modelled sewers are sized differently, because the catchment is connected at a midpoint, thus the routing of the downstream sewer is explicitly accounted for by the modelled sewer.

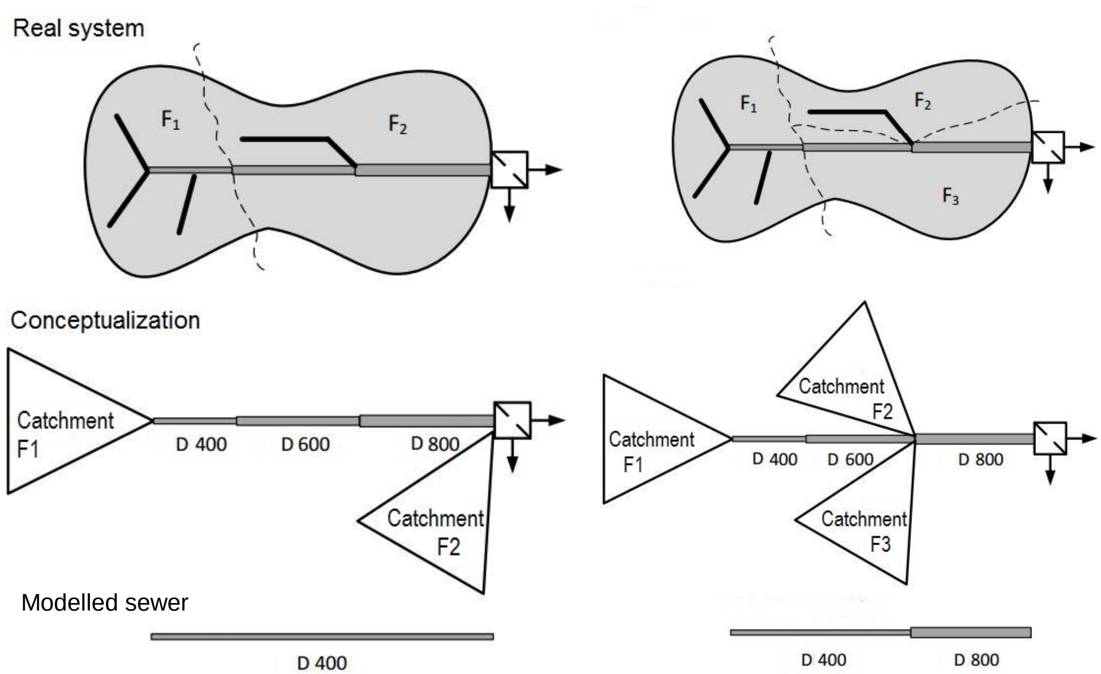

Figure 7: Sewer sizing example, adapted from Muschalla et al. (2016)

2.2.5 Implication of standardizing approaches

Rieger et al. (2013) provide a well-researched generalized approach to develop wastewater treatment models, while outlining both the potential benefits and risks of using a standardized approach.

2.2.5.1 Benefits of standard approaches

As repeated in multiple papers (Rieger et al., 2013, Muschalla et al., 2009, Wolfs et al., 2015), a standardized modelling protocol leads to more efficient and reproducible development of models. Explicitly defining model requirements and limitations at the beginning of the project ensures that models are only used for intended or qualified purposes. Since data collection and analysis consumes a large portion of a project's time, standardizing the data collection step after the project definition clearly saves a lot of effort. In general, standardized protocols should also lead to better quality assurance/quality control of all modelling projects.

The availability of such a procedure would also help guide inexperienced modelers and clients throughout the project. Surprisingly, many model builders and users have never received formal training on the modelling process, therefore following a basic procedure will simplify the learning process of each phase. Furthermore, common obstacles seen in projects may be overcome more easily if approached systematically. Model documentation time is also sped-up through the use of a standardized method.

All end-users of IUWS models, including regulatory bodies, would also benefit from the use of standard procedures, for it would simplify the review process, regardless of the degree of modelling expertise on the part of the regulator. Comparison of simulation results and between different modelling projects would also be facilitated. As a final point, well developed modelling projects increase the reliability of using such models, thus improving their acceptability by users, stakeholders, and regulators.

2.2.5.2 Potential risks of standard approaches

Although a standard approach to modelling projects provides many benefits, it is important to note the potential risks of using such methods (Rieger et al., 2013). A common raised issue with applying standard modelling protocols is the inability to apply innovation to develop cost-effective solutions. Needless complexity may also be added to simpler projects that do not necessarily require all steps. To avoid these types of issues, a continual improvement of the adopted protocol is suggested by adding knowledge gained from additional projects.

2.3 Modelling flows in WEST

This research project used WEST (Wastewater treatment plant Engine for Simulation and Training) as the single-platform modelling tool. WEST is a general modelling and simulation environment, which uses editable model bases, for all biological wastewater treatment plant, catchment, sewer, and river modelling (Vanhooren et al., 2003). In terms of IUWS modelling, WEST has mostly been used for research projects, (e.g. the academic research project conducted by Solvi et al. (2006)); however some projects are attempting to use it for commercial applications (e.g. the industrial-partnered projects conducted by Benedetti et al. (2013) and Prat et al. (2012)).

Before discussing the description of the KOSIM-WEST model included in WEST, the two main flow components of combined sewer systems that are being modelling in this project, namely dry and wet weather flow, are briefly introduced. A review of the basic principles relating to modelling catchments and sewers in KOSIM-WEST is subsequently provided, based on the descriptions provided in Solvi (2007).

2.3.1 Wastewater flow decomposition

When setting up the representation of the catchments in a wastewater model, it is important to understand the components of flow that are being represented. The following sections provide a brief generic overview of each component of wastewater flow.

2.3.1.1 Dry weather flow

The dry weather flow (DWF) includes all flow that enters the system irrespective of rainfall events. This flow can be further decomposed into two components: groundwater flow (also called baseflow or groundwater infiltration in many commercial software) and generated wastewater or sanitary flow (Haestad Methods Water Solutions, 2007, Lai, 2008).

Groundwater Infiltration (GWI), or baseflow, covers all groundwater that infiltrates into the non-pressurized gravity collections system through defective pipes, pipe joints, and leaking manhole walls. Generated wastewater flow is made up of residential, institutional, commercial, and industrial sewage.

2.3.1.2 Wet weather flow

In wastewater collection system models, the rainfall-driven flow that makes its way to the collection systems, also called wet weather flow (WWF), is caused by rainfall-derived inflow and infiltration (RDII). RDII is made up of direct inflow, delayed inflow, and rainfall-induced infiltration (Nasrin et al., 2013, Vallabhaneni et al., 2007b, Lai, 2008).

Direct inflow occurs in all types of systems but is higher in partially separated sewers and highest in combined sewer systems. These inflows allow stormwater runoff to rapidly enter the collection system. The main sources of direct inflow include direct connections to the collection system from catchbasins (combined systems only), roof leaders (combined and partially combined systems) and manhole covers (all systems). Delayed inflow is the portion of inflow that is generated from indirect connections to the collection system or connections which produce inflow after a significant time delay from the beginning of a storm. These inflow sources include: sump pumps, foundation drains, and indirect sewer/drain cross-connections from storm sewers. Rainfall-induced infiltration is a short-term increase in infiltration into the sewer system that results from a rain event. Because rainfall-induced infiltration cannot be fully distinguished from delayed flows, these two sources are often lumped together in many models. Both of these delayed inflow sources have a slow gradual impact on the collections system, in which increased flow gradually decreases after the peak inflow caused by direct connections.

2.3.2 KOSIM-WEST

The hydrological principles from KOSIM (Paulsen, 1987), a modelling tool for the generation and long-term simulations of dry weather flows, rainfall derived-runoff and transport in sewers, were implemented into the WEST modelling environment (Vanhooren et al., 2003) by Solvi et al. (2005). The main challenge in this task was to transform the discrete time-step equations from KOSIM into the underlying ordinary differential equations in WEST so that they could be combined and solved with the models for the other subsystems represented in the modelling tool.

2.3.3 Hydrological equations

The main subsystems and processes that are used in the KOSIM-WEST model to produce or route the wastewater components were explained in detail by Solvi (2007); a brief review is provided below. To begin, this software uses hydrologic modelling for all flow simulations: sewers, catchments, and river reaches. As reviewed in Section 2.1.4, hydrodynamic modelling using the Saint-Venant continuity and momentum equations (Equations 1 and 2, respectively) is normally used to physically define water transport in sewers.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial y}{\partial x} - gA\left(S_o - S_f\right) = 0 \tag{2}$$

y	water depth
t	time
Q	flow rate
x	distance
A	area of flow cross-section
g	gravitational constant
S_o	bed slope
S_f	friction slope

In KOSIM-WEST, a hydrological, or "black box" approach is used, wherein the flow is assumed to be steady in space in each pre-divided section of the sewer, storage tank or river section. This assumption allows for each section to be modelled as a series of cascading linear reservoirs (Figure 8, taken from Solvi (2007)), thus replacing the continuity and momentum equations with the simpler retention and flow-volume relationship equations (Equations 3 and 4), respectively.

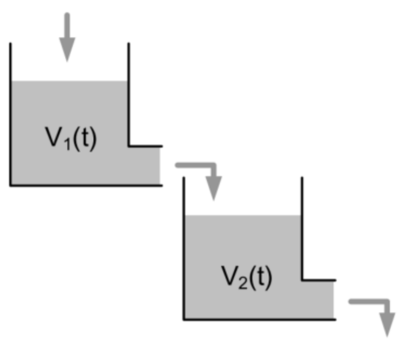

Figure 8 : Cascading linear reservoirs (Solvi, 2007)

$$\frac{\partial V}{\partial t} = Q_{in}(t) - Q_{out}(t) \quad (3)$$

$$Q_{out}(t) = \frac{1}{k}V(t) \quad (4)$$

Q_{in}	inflow
Q_{out}	outflow
V	water volume in tank
n	number of linear reservoirs
k	residence time

A set of linear reservoirs replaces the hydrodynamic routing, however the potential influence of the water level on the outflow of the pipe is not considered (e.g. downstream boundary and hydraulic conditions). Therefore, this approach clearly can not provide accurate results in all flow conditions without modification (e.g. when downstream locations influence the behaviour of upstream locations) (Kamradt, 2008).

As reviewed in previous sections, this hydrological modelling method provides the advantage of faster simulation times, and it is also easier to perform calibrations due to the reduced number of parameters. With limited geometric data available, this simplified model structure should require less resources and effort to construct the model. Furthermore, many IUWS modelling projects do not require the details provided by complex hydrodynamic models. On the contrary, if a detailed model is already available, the latter could be used to generate the data to calibrate the simpler hydrological model. As such, this hydrological approach is often considered appropriate for IUWS modelling projects (Rauch et al., 2002).

2.3.4 The submodels

The main subsystems found in urban drainage are the atmosphere, the drained surface and the sewer network, as shown in Table 1 taken from Solvi (2007). The main processes that occur in each of these systems during dry and wet weather are also listed in this table.

Table 1: Overview of urban drainage processes in a combined sewer network (Solvi, 2007)

Subsystem	Water	Pollutants
DW (Dry Weather)		
Atmosphere	Evaporation	Accumulation* Deposition*
Surface		Accumulation
Sewer network	DW flow	DW pollution pollutant transport sedimentation resuspension biochemical processes*
WW (Wet Weather)		
Atmosphere	Rain Evaporation*	Washout*
Surface	Runoff generation	Washoff
Sewer network	DW flow	DW pollution generation
	mixing DW and WW flow and pollution	
	storage	
	combination and splitting	
		sedimentation resuspension biochemical processes*

*: not represented within the KOSIM-WEST model

2.3.5 Catchment model

The processes that are represented the KOSIM-WEST catchment model are shown in Figure 9 below.

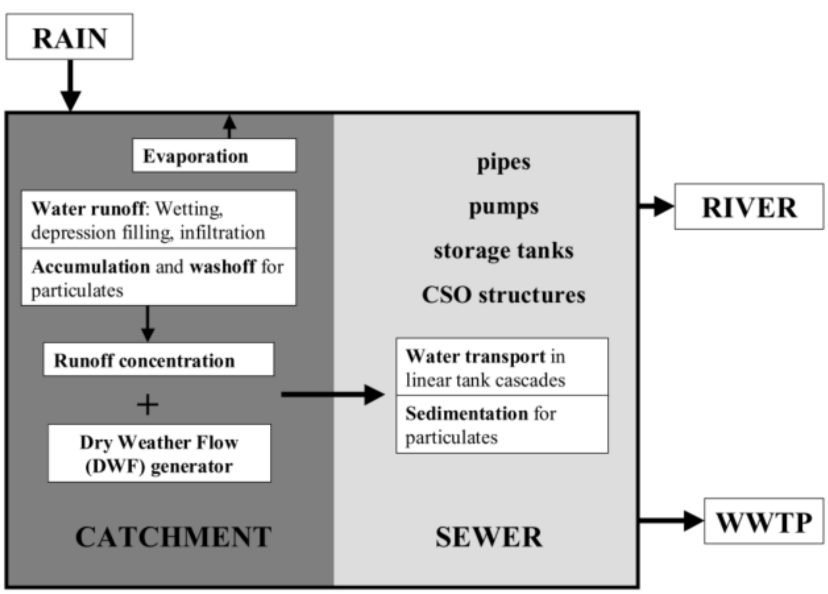

Figure 9: Elements and processes within the KOSIM-WEST model (Solvi, 2007)

The catchment submodel is composed of the dry and wet weather contributions, as well as the evaporation losses. This model is a coupled model of predefined submodels: a potential evaporation model, a runoff submodel that takes into account surface losses, a submodel for the routing of the flow through a set of 3-cascading linear reservoirs, and a DWF generator that is added to the resultant hydrograph.

The evaporation model considers both the daily variation throughout the year and the hourly distribution of the mean potential evaporation. The runoff submodel is set-up as a stormwater model, and considers losses over both impervious and pervious surfaces: wetting, depression filling and infiltration (over pervious surfaces only). The infiltration process is defined using the time-dependent Horton's equations. Due to evaporation, the maximum capacity of these losses regenerate during DWF periods. The amount of effective rain (or runoff) entering the collection system is determined by these losses and a runoff coefficient, which varies as depression losses are filled. In terms of water quality, first-flush concentration effects are also taken into account by conceptual accumulation and wash-off routines.

The third routing submodel accounts for the combined flow of water over the surface and through local sewers. This submodel provides a time translation and retention of peaks by passing the effective runoff through a set of 3 linear reservoirs. The sum of the residence times (k) of the three linear reservoirs is analogous to the concentration time (t_c) used in hydrology (the time it takes for runoff to travel from the most remote location in the catchment to the outlet of the local sewer system). A suggestion for the value of k is given as $t_c = n \cdot k$, with n=3.

The final submodel included in the catchment block is the dry weather flow generator. This submodel uses populations, per-capita flow rates, unit area, and industrial flows, along with predefined diurnal patterns, to produce the generated flow, and a constant groundwater infiltration flow (or baseflow) with a monthly pattern varying over the year. Figure 10 shows how the described submodel blocks are linked.

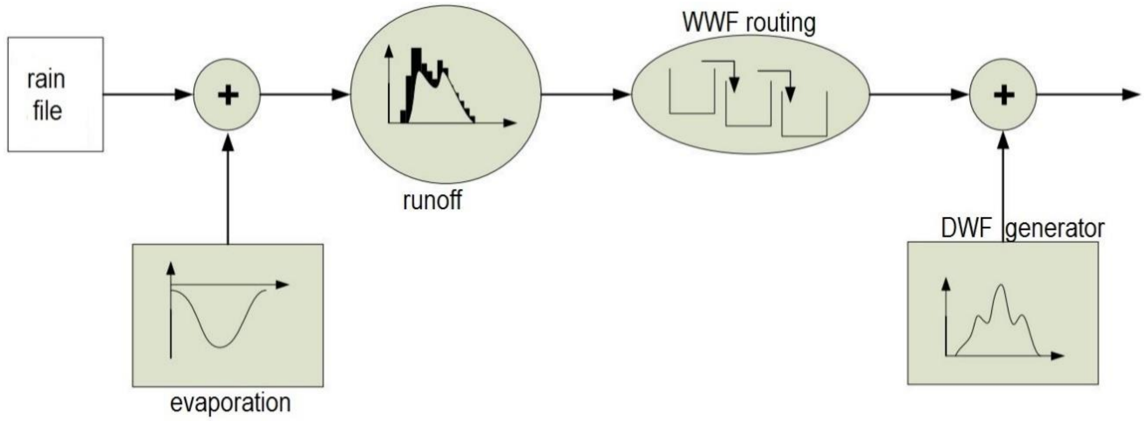

Figure 10: Submodels within the KOSIM-WEST catchment model (Solvi, 2007)

2.3.6 Sewer model

2.3.6.1 Linear reservoirs

In KOSIM-West, sewers are modelled as a series of cascading linear reservoirs. The parameters relevant to representing each reach of sewer (n, k, L*) are determined using the Kalinin-Miljukov method. This method relates pipe or open-channel characteristics with the linear reservoir parameters through the following equations (Equations 5 – 9), solved in the presented order.

$$L_c = 0.4\frac{d}{s} \tag{5}$$

$$n = integer\left(\frac{L}{L_c}\right) \tag{6}$$

$$L^* = \frac{L}{n} \tag{7}$$

$$Q_{max} = a\left[-2 \cdot \log\left(\frac{2.51 \cdot v}{d\sqrt{2gds}} + \frac{k_s}{3.71d}\right) \cdot \sqrt{2gds}\right] \tag{8}$$

$$k = 0.64 \cdot L^*\frac{d^2}{Q_{max}} \tag{9}$$

L	pipe length
L_c	characteristic length of pipe section (intermediary value, not used in model)
L^*	specific length of individual pipe sections in model
d	pipe diameter
s	pipe slope
n	number of linear reservoirs
Q_{max}	maximum discharge of a pipe
a	cross-sectional area of pipe
ν	kinematic viscosity
g	gravity
k_s	pipe roughness

Because the presented cascading linear reservoirs cannot represent backwater effects, a model configuration, as presented below in Figure 11, was developed by Solvi (2007) and implemented in KOSIM-WEST to conceptually represent such phenomena. Once flow is routed through a set of linear reservoirs, a combiner adds that flow to the flow from the downstream backflow. This combined flow is then run through a splitter, that sends excess flow back to the upstream pipe based on a maximum flow through the pipe (Q_{back}). Although this configuration provides relatively accurate results, the increase in the capacity of a pipe with increasing upstream head is not represented. Furthermore, an additional calibration parameter (Q_{back}) is added to the system.

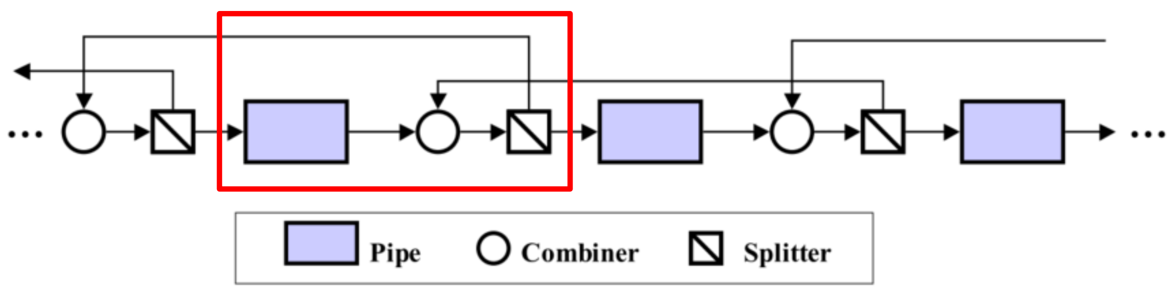

Figure 11: Backflow model implemented in KOSIM-WEST (Solvi, 2007)

2.3.6.2 Non-linear approach

An alternative representation of sewers in KOSIM-WEST is a single tank with a non-linear volume-outflow relationship. This representation stems from the non-linear relationship between the discharge from a circular pipe and the filling degree. Kamradt (2008) described how this non-linear approach was implemented into KOSIM-WEST. Basic pipe characteristics (pipe diameter, length, slope, roughness, and slope in the volume-outflow relationship above Vfull) are used to define this tank's characteristics.

A similar approach to the above-explained backwater model above has been applied to represent the backwater using non-linear pipes (Kamradt, 2008). In this setup, volumes larger than the completely filled pipe are defined, allowing a higher pressurized flow to pass downstream until a maximum ($Q_{max,NL}$, which is analogous to Q_{back} in the linear backwater model) is reached. In this method, two parameters are simultaneously calibrated: the $Q_{max,NL}$ with the outflow-volume relationship gradient (a_{NL}) (See Kamradt (2008) for details).

This non-linear pipe method proved to provide very similar and slightly more realistic results compared to the linear reservoirs method (Vanrolleghem et al., 2003). In addition, the actual pipe characteristics can be used to represent the lumped-model pipes. Furthermore, the replacement of many linear reservoirs with one non-linear reservoir reduces the number of differential equations to be solved, thus increasing simulation efficiency.

2.3.7 Combiners and splitters

Combiners and splitters are models without volume that are meant to add or divide flows. Two kinds of splitters exist in the model: absolute and fractional splitters. Absolute splitters send all flow up to a defined value in one direction and the excess flow to the other, while fractional splitters divide the flow into two depending on a defined fraction. In the model base that Solvi (2007) developed a special kind of splitter was implemented, namely the combined sewer overflow (CSO) model. This model splits flows into two parts Q_{out} and Q_{over} when Q_{in} reaches a critical value Q_{crit}., as shown in the Figure 12 below.

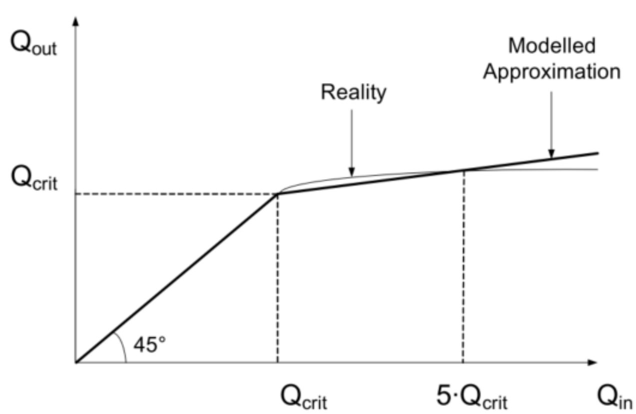

Figure 12: Illustration of modelled vs real flow from CSO (Solvi, 2007)

This model accounts for a constant increase of the outflow with increasing inflow, until the critical flow is reached, at which point the rate of increase of the outflow is fixed to a certain correlation factor δ. This factor is determined by the following equation (10), whereby Q_{out} is determined by Equation 11.

$$\delta = \frac{Q_{out}(Q_{in} = 5 \cdot Q_{crit})}{Q_{crit}} \tag{10}$$

$$Q_{out} = \frac{\delta - 1}{4} \cdot Q_{in} + \frac{5 - \delta}{4} \cdot Q_{crit}, for\ Q_{in} \geq Q_{crit} \tag{11}$$

δ	correlation factor
Q_{out}	outflow
Q_{in}	inflow
Q_{crit}	critical flow at which overflow begins

The current KOSIM-WEST model library no longer includes this CSO model, but similar results can be obtained by combining absolute and fractional splitters to suit the desired structure configuration and hydraulic behaviour.

Chapter 3 Project overview

3.1 Research Objectives

As discussed in the literature review, simplified system representations are absolutely necessary to ensure the efficiency of IUWS modelling. However, oversimplifications may lead to compromises on accuracy that can affect the reliability of the overall model results. It is therefore apparent that the degree and method to simplify models has a large impact on the model outcomes.

To tackle this problem, this research project focused on developing a modelling procedure that translates detailed catchment and sewer models into simplified conceptual models within the context of IUWS modelling. The project concentrated on a procedure related to capturing the water quantity representations, more specifically the hydrology and hydraulics of the catchments and sewers, while working within an IUWS modelling platform, namely WEST, to allow for future water quality analyses. The following objectives were pursued:

- Understand the current approaches used to develop conceptual representations of hydrologic and hydraulic models;
- Establish a methodology and guiding rules for the development of a conceptual IUWS model from a detailed model by adapting existing methods;
- Consider the specific needs of a case study in the application of the developed procedure;
- Describe the level of aggregation obtained in the developed conceptual models; and
- Compare the accuracy and simulation time of the conceptual models to the detailed models.

3.2 Scope of work

The scope of work for this type of broad research objectives could easily expand to include many tasks. It is therefore necessary to understand that the most amount of work was completed within the timeframe of a Master's thesis project, and omissions were not necessarily oversights but instead carefully selected due to lack of time or resources. The following sections provide a brief overview of the selections and assumptions that were made to manage the scope of the project.

3.2.1 WEST software selection

Many times, the selection of a modelling tool is part of a model development procedure, however this research project intended to perform all conceptual modelling using the pre-selected WEST modelling platform, for several reasons. Firstly, as previously discussed, WEST is a powerful biological wastewater treatment plant modelling tool. The additional integrated modelling tools provided in the software allow for IUWS models to be produced using a single modelling platform. WEST is also the chosen software for the model*EAU* research group. Therefore, continuing its use simplifies knowledge transfer between colleagues and potentially improves the group's future capabilities. Although there are technical pros and cons to selecting any software for a project, logistical advantages often play a big part in the selection process. This fact is also absolutely apparent in industry, whereby choice of software is often determined by availability, client needs or in-house expertise. For these reasons, selecting an alternate software for this project was not considered.

3.2.2 Main tasks

To accomplish the above stated objectives, the completed tasks, or methodology, used to achieve the project goals can be grouped into three main categories. Because this research project is focused on methodology development, only a summary of these three main steps is provided in this section, while each task is described in detail in the appropriate Chapters.

First, a thorough literature review was performed to gain an understanding of the current IUWS modelling approaches used to develop conceptual representations of hydrologic and hydraulic models (Chapter 2).

Second, a large portion of the time was devoted to understanding the model code and the functioning of the WEST modelling platform. In doing so, some model code was modified to suit the needs of this project, and suggestions were made to the software developer to increase the user-friendliness of the modelling platform. These findings are important because many of them address the stated obstacles limiting the acceptance of integrated models, as reviewed in Section 2.1.5. A summary is found in Chapter 4.

The third category of work involved building a conceptual model of the selected case study by following and adapting existing researched procedures. First, the formulated procedure is described in Chapter 5, then the application of the procedure to a case study is explained in Chapter 6. Two versions of the lumped model were created: the first (herein referred to as Model V1) was created with a certain level of aggregation, while the second was a further aggregation of the first model (herein referred to as Model V2). Both models were calibrated and compared to the detailed model and to each other. The results are presented and evaluated in Chapter 7. Chapter 8 presents a general discussion about the developed procedure, the levels of aggregation, as well as study results and limitations.

Chapter 4 WEST software development

Significant time was spent understanding the model code, which was developed over 10 years ago, and subsequently modifying it to increase user friendliness or better suit it to the needs of this project. The catchment model block was modified to provide flexibility to represent the dynamics of diverse catchments. The backwater sewer models were corrected, allowing these predefined coupled models to be used directly in the layout. Several other suggestions were made to improve the user-friendliness of the WEST platform, to reduce the required manual labour for data entry, and to allow for simpler data validation. These suggestions aim to improve the structure of the WEST platform and provide a tool that gives a similar workable experience to anyone familiar with mainstream sewer network modelling tools. Most of these suggestions have already been noted by the software developers and will be implemented in some form in the 2017 release of WEST.

4.1 Catchment block

4.1.1 Block structure

The catchment block has been modified to provide more flexibility in the hydrological representations and the dry weather flow (DWF) routing. The previous configuration of the catchment block is displayed in Figure 13, while the modified version is shown in Figure 14. Sample model codes of each are found in Appendix A.

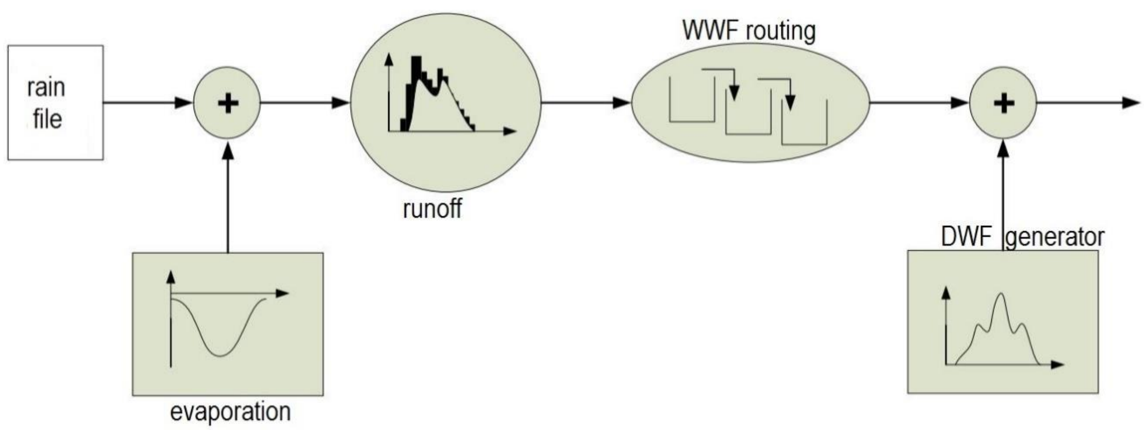

Figure 13: Previous catchment block configuration, from (Solvi, 2007)

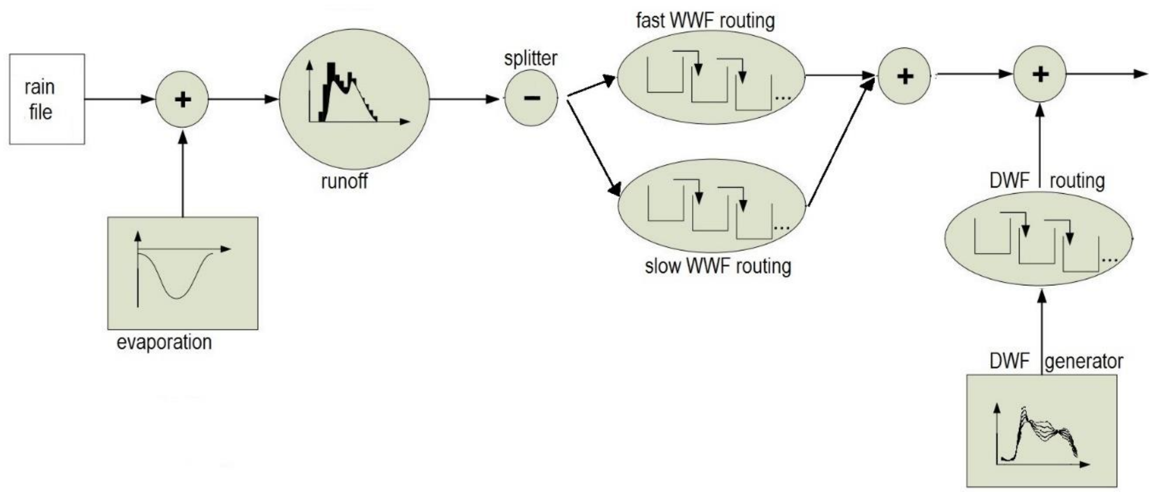

Figure 14: Modified configuration of WEST catchment block

Two main modifications were made. First, a set of linear reservoirs was introduced to provide routing of the DWF component within the catchment. Second, the wet weather response of the catchments, previously represented by 3 linear reservoirs, was replaced by two parallel sets of linear reservoirs. These changes allow the user to capture the varying types of dynamics, which is especially useful for catchments differing in shape and size. Furthermore, the initial structure of the model only considered stormwater (or combined) sewer inflow contributions, while this new set-up introduces flexibility to capture the dynamics of all RDII responses. This is potentially important for separated or partially-separated systems where the dynamics of the various RDII responses have a significant influence on the hydraulic performance of the systems.

4.1.2 DWF

Previously, DWF routing was not explicitly done in catchments. Generic diurnal patterns for pre-defined population-size brackets were assumed to account for the routing of DWF. When dealing with large catchments that may have long or intricate flow paths and multiple types of flow sewage generators, this method to capture flow routing may not be adequate.

A set of linear reservoirs (1, 2, 4 or 8 linear reservoirs) was added after the DWF submodel in the initial coupled catchment model block. This addition allows for the routing to be explicitly represented by a varying number of linear reservoirs. Specific diurnal patterns for different types of generators can then be applied. The standard DWF diurnal patterns account for the types of generator while the linear reservoirs provide the routing.

4.1.3 WWF

Many wastewater collection systems, including the network selected for the case study, have a mix of separated, partially-separated and combined sewers. As a result, the RDII responses vary greatly in shape and magnitude. The current configuration available in WEST, in which WWF is routed by 3 linear reservoirs, was deemed inadequate to capture the varied dynamics from the differing RDII sources. The only editable parameter is the hydraulic retention time, which simultaneously governs the timing and spread of the response but does not give liberty to change the shape.

An alternate scheme was devised, such that the WWF routing is represented by two parallel sets of linear reservoirs, mimicking the slow and fast RDII responses. This flow-splitting concept was also used in SMUSI (Kamradt, 2008), whereby a split-up factor distributed the inflow between two sets of three linear reservoirs. The overall concept is meant to simulate unit hydrographs made up of two distinct responses, such as two RTK triangles. The RTK method is a tri-triangular unit hydrograph method (see Figure 15) that describes fast, medium and slow RDII responses using three sets of R, T, and K parameters. R represents the fraction of rain entering the system, T is the time to peak, and K is ratio of the time of recession to the time to peak (Vallabhaneni et al., 2007b, Haestad Methods Water Solutions, 2007).

Based on the data-derived RTK parameters from the results of the detailed model, the WWF is split between the two sets of linear reservoirs by means of a fraction splitter, which corresponds to the percentage of flow routed by each set of linear reservoirs. Following the typical three-tiered breakdown for RDII discussed in Section 2.3.1.2, the fast linear reservoirs could represent direct inflows while the slow RDII could represent the delayed inflows and rainfall-induced infiltration. Alternatively, these two responses could simply be used to obtain the sought-after atypical hydrograph response.

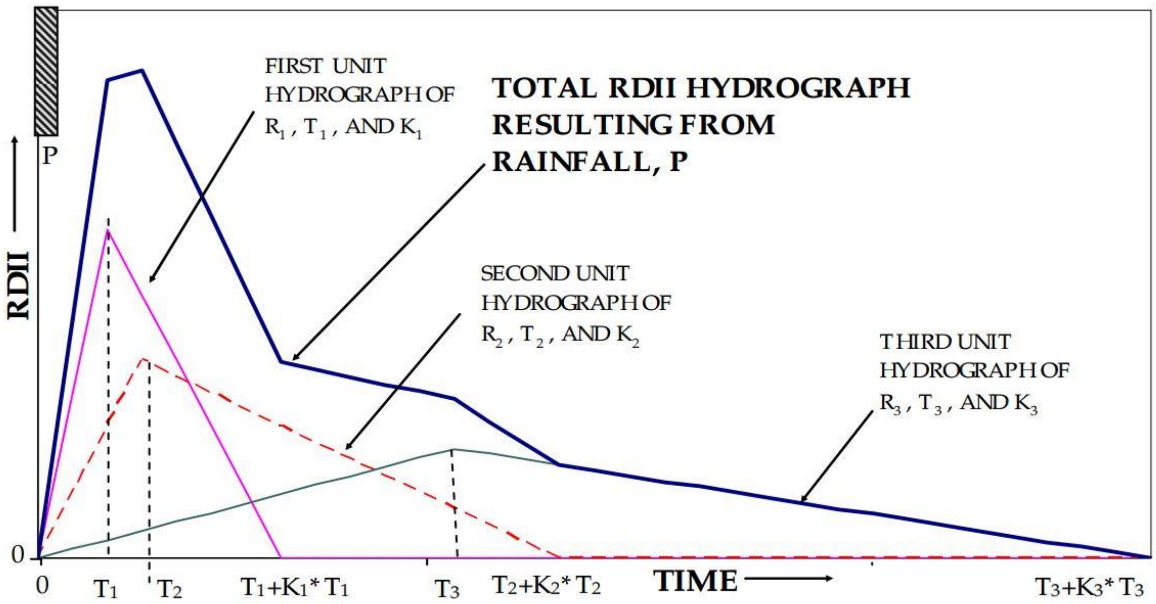

Figure 15: Summation of tri-triangular unit hydrograph (Vallabhaneni et al., 2007a)

Because individual model blocks must be defined for each permutation of the number of DWF and WWF linear reservoirs, both the slow and fast RDII components are made up of a specific number of linear reservoirs. Although this limits the user to specific responses, it also limits the number of individual models required. The fast and slow RDII were represented by a specific selection of 3, 5, 10, or 15 and 1 or 2 linear reservoirs, respectively. The fast component has a larger choice and more linear reservoirs to account for the quicker responses, while the slow RDII, accounting for the delayed inflow, normally produces inflow over a long duration. The split-up factor between slow and fast RDII generally dictates what percentage of the RDII is routed by which set of linear reservoirs.

The above described configuration is made up of two sets of linear reservoirs; however, a similar configuration with 3 sets of linear reservoirs was tested and is described below. This test was done to see whether two or three linear reservoirs were required to mimic the tri-triangle RDII responses.

4.1.3.1 Linear reservoirs test with 2 and 3 sets of reservoirs

In this test, tri-triangular RTK hydrographs (of sample catchments) were graphed in Excel, using one unit of rain. These graphs were compared to similar hydrographs created using 2 and 3 sets of linear reservoir. The linear reservoir parameters (runoff coefficient, n, k) were manually adjusted by visually fitting the 2 and 3 sets of linear reservoirs hydrograph to the RTK hydrograph. Table 2 lists the linear reservoir values for a sample RTK (Riverlane) from the detailed model. The figures below (Figure 16 and Figure 17) show the hydrographs for both the RTK method and the linear reservoir (LR) method.

Table 2: RTK and linear reservoir values for 2- and 3-linear reservoir test; Riverlane RTK

Hydrograph	RTK method			Linear reservoirs			
	R	T	K	Runoff coefficient	k (hrs)	n (# tanks)	% of total runoff ceoff.
				3 linear reservoirs			
Short	0.8%	2.00	2	4.5%	3.5	4	16%
Medium	0.3%	2.2	11	15.0%	12	2	55%
Long	1.5%	2.5	34.6	8.0%	19	2	29%
				2 linear reservoirs			
Short				5.7%	3.6	4	21%
Long				21.8%	16.5	2	79%

The result of this test showed that two sets of linear reservoirs were sufficient to mimic the behavior of RTKs. The addition of the third set of linear reservoirs resulted in additional calibration parameters (split-up factors and linear reservoir parameters) further increasing the complexity of the catchment representation. Calibrating 2 sets of linear reservoirs was much simpler and more intuitive than adjusting the values for 3 sets of linear reservoirs. The use of the third linear reservoirs also increased the run time of the model but did not provide significant improvements to the accuracy of the results. The added third triangle, which represents the medium infiltration (or delayed inflows) in the RTK approach, can therefore be lumped with either the fast or slow responses. In summary, two sets of linear reservoirs were deemed more appropriate. The model could also provide the flexibility to represent the catchment responses as three separate WWF responses, however it would be at the expense of additional simulation time.

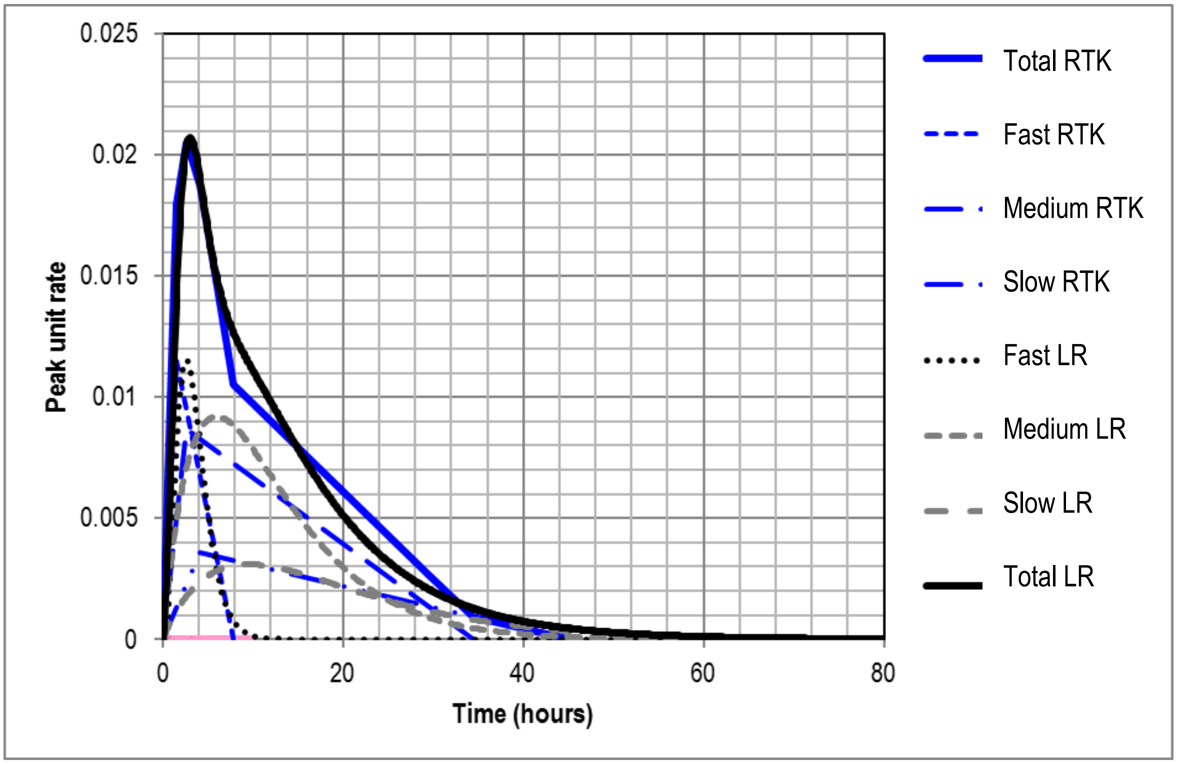

Figure 16: RTK and three sets of linear reservoirs hydrographs in Excel

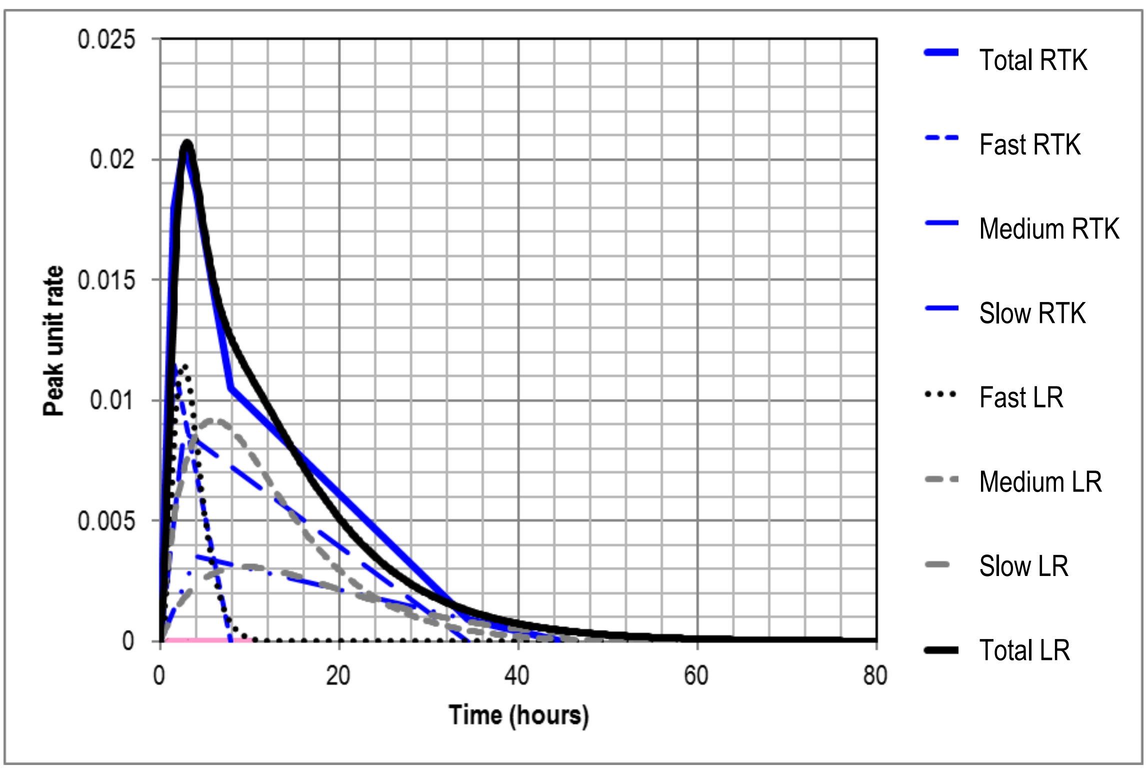

Figure 17: RTK and two sets of linear reservoirs hydrographs in Excel

Although only 2 sets and a limited choice of the number of linear reservoirs were used for this case study, this could easily be changed or extended in the model library for other case studies. The concept however remains the same, that is two (or multiple) sets of linear reservoirs in parallel are used to capture the dynamic RDII responses.

4.2 Corrected backwater models

The backwater tank models in the 2016 release version of WEST were corrected, as none of the predefined coupled models were functioning. The main change was setting the backflow limiter (the Q_back parameter) as a "manipulated variable" instead of a "parameter" in the model code. This change was required because the "parameter" to which Q_back is coupled is in fact a manipulated variable, and coupled parameters must be of the same type in the model-specific-language (MSL). An additional input terminal was also added to the tank block to which the "backflow" input vector of the downstream tank is connected in the model layout. Previously, the "backflow" input vector was assigned to the data input terminal, however the newly corrected Q_back parameter was reassigned to that terminal.

4.3 Increasing user workability of WEST platform

The following suggestions relate to increasing the user workability of the WEST software. Implementing these recommendations would significantly reduce the manual labour required to build and validate a model, thus potentially resulting in an increased use of this platform for IUWS modelling projects.

4.3.1 Editable variables in coupled models

The main editable parameters of coupled model blocks appear in the Block details window when selected. However, many important parameters that are often used to characterize catchments or sewers did not previously appear in the main block's details window. Some parameters were simply hidden and others only appeared in the sub-models' block details. This issue makes it difficult to find parameters required for characterization and calibration, but also poses a more significant issue: some parameters apparent in submodels were not actually connected to the main coupled model. Although these parameters would have been editable in the submodel, they would have been over written by the value in the main block once the model is run. This had the potential to have many values overwritten without the modeller being aware.

A solution to this issue was simply connecting all relevant parameters from the submodels to the coupled model and explicitly displaying them on the main block's detailed window. Then a governing good-modelling practice rule could be introduced to avoid confusion: only parameters in the main block window should be edited.

The locations and connections of the parameters displayed and connected in all tank and catchment blocks relevant to the case study were edited to facilitate setting up the model and avoiding the potential issue with values being unknowingly overwritten.

4.3.2 Table editor

In IUWS modelling, it frequently occurs that many blocks of the same class are included in a layout. Making sure that all parameter values and/or initial conditions of these blocks are correctly and consistently configured is cumbersome, since each block needs to be separately selected to view and/or modify its settings. For larger models, the manual labour required to enter all parameter values adds significant time to the model building process and poses a greater risk of inadvertently entering or overlooking typographical errors.

It is therefore suggested to add a new tabular editor to WEST that would allow viewing and editing the parameter values of multiple blocks at the same time. Viewing the data in tabular format would also facilitate importing and exporting data, and would provide an efficient means to validate values. This suggestion is being implemented in the 2017 version of WEST.

4.3.3 Block selection based on Class or Icon

The ability to multi-select all blocks of a certain type (i.e. of a certain class or with a certain icon) would be very useful as it would allow to easily configure coupled parameters and certain types of outputs (e.g. file, plot, etc.). This type of feature would go hand-in-hand with the suggested table editor above, and is also being implemented in the 2017 version of WEST.

4.3.4 Patterns

Being able to define case study specific recurring patterns is crucial in IUWS modelling. In WEST, these patterns are currently specified as vectors in MSL and are not visually represented. Creating and updating such vector declarations is rather cumbersome, because each vector value must be manually updated in the model code.

To be consistent with conventional sewer modelling software, a tabular approach to vector editing (and by extension: matrix editing) would be very useful. Furthermore, displaying the patterns could also serve as an important visual validation tool. The suggestions related to the patterns are being considered for the 2017 version of WEST.

Chapter 5 Developed generic procedure

This section reviews the generalized procedure that was developed in the process of creating the two conceptual models of the selected case study. The main goal involved determining how to translate a detailed hydrologic and hydraulic model into a simplified conceptual model, using WEST as the platform, in a structured, systematic and repeatable way. Given the absence of a clear procedure to lump catchments and sewers, the project work focused mainly on developing and using the devised procedure.

Although generalizations have been made, it should be noted that this procedure was developed using a specific case study, therefore not all methods may apply to alternate case studies. The application of this procedure to the case study is discussed in the following chapter, Chapter 6.

5.1 General methodology overview

The proposed generic procedure was developed by adapting, modifying, and building off existing procedures. Some of the more influential procedures were reviewed in Section 2.2 in the literature review. The considerations for delineating and aggregating catchments and sewers drew from the study findings described in Section 2.2.4.

The proposed procedure is broken down into four main stages: project definition, model development, calibration and validation. The flow chart of Figure 18 illustrates the four phases and individual tasks of the formulated procedure, all of which are described in detail in the following sections. While the individual tasks are written in a generalized sense and applicable to a wide range of applications, they were tailored to this case study.

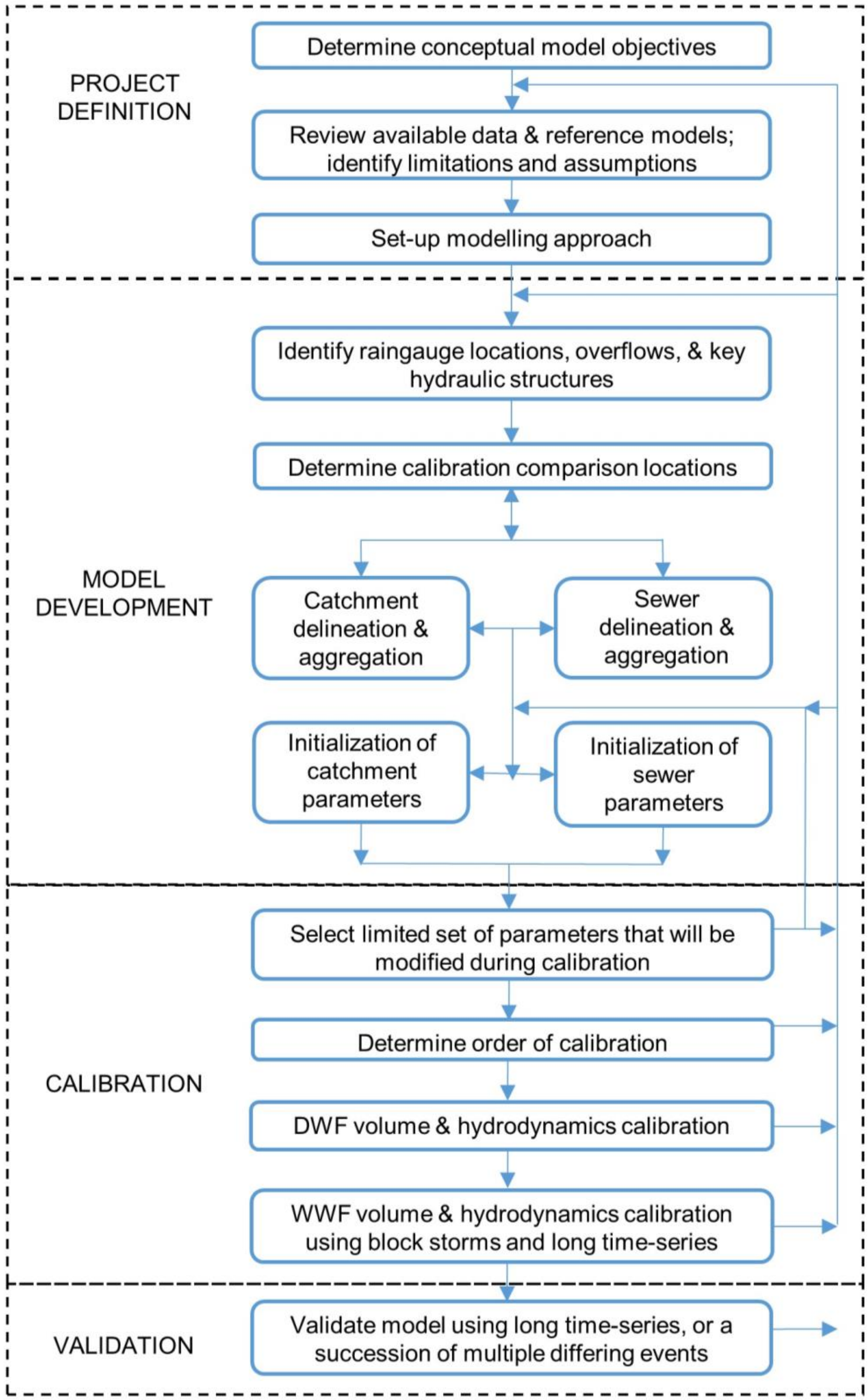

Figure 18: Flow chart of the proposed procedure for developing a conceptual model

5.2 Project definition

5.2.1 Model objectives

The objective of a modelling project is normally defined by the motivation to complete a project. Objectives often aim at determining the source of a problem and/or finding solution(s) for it. Determining this objective is the first important step in setting up a project. Examples of such objectives for an IUWS modelling project could include: reduction of overflow volumes or pollution loads; or maintain receiving water quality below stipulated limits. Once this objective and all its necessary details are determined, all subsequent steps aim at fulfilling this goal.

5.2.2 Understanding the system

Gaining a general understanding of the system, available data, and reference models is crucial for determining the modelling approach.

5.2.2.1 Available data and reference models

Data requirements vary depending on the objectives of the project and the model selected for reaching them; however, typical sets of data are often required. Firstly, determining the availability of a calibrated detailed reference model is required to decide whether the conceptual model should be built from a reference model or from raw data. If this model is used as the basis for the conceptual model, the model structure, set-up and assumptions should be well understood. Great importance should be paid to identifying the mechanisms used to represent both DWF and WWF in the reference detailed model. Note that although this project provides a procedure that assumes a detailed reference model is available, some considerations are provided for the situation where one would not be available.

Representative and reliable rainfall data is one of the most important data sets because it drives the creation of flow in the models. Rainfall records from raingauges that are well distributed over the study area are required at an acceptable time interval (5 minute intervals are often used). Long rainfall time series are required to calibrate certain parameters and ensure a proper validation; information on synthetic design storms and individual events is most often not enough.

If reference models are not available, detailed information and data about the contributing areas and sewers (the study area) is necessary to determine catchment and sewer characteristics. Identifying the type(s) of sewers in the system is vital: separated, partially-separated, and combined. Not only do these different types of systems respond with varying amounts of RDII, but the pollutant loads (for future quality modelling) also vary greatly. Other important characterizing information includes additional sewer information, ground elevation and drainage directions, soil data, imperviousness, population figures, landuse types, water usage records, flooding records, etc. (WaPUG, 2002). Information about tributary areas and water courses is also required if they affect the study area. Information on special hydraulic structures, including overflows is required. For systems that include any operated automated and/or dynamically hydraulic structures, operational records and control procedures are also needed for these can have a significant impact on the sewer system performance. Much of this information can be extracted from detailed GIS layers, watershed reports, and Supervisory Control and Data Acquisition (SCADA) systems.

Flow monitoring information is a crucial data set that will either supplement results from reference models or will be used as the basis of calibration. If existing flow data exists, determining its validity is an important step. For projects where budgets permit performing flow monitoring campaigns, careful planning should be done to ensure a successful campaign. Some considerations for water quantity flow monitoring projects include coupling the campaign with water quality monitoring, determining installation locations and procedures, maintenance and removal logistics, placing monitors at outlets of discrete catchments, and ensuring that at least 3 larger storms of varying size are captured over the monitoring period.

Once an inventory of available data is made, data gaps can be identified and either solutions for obtaining that information can be devised or calculated assumptions can be made.

5.2.2.2 Limitations and assumptions

All project and modelling limitations should be tracked throughout the project. Identifying these limitations is a broad subject that could cover any shortcomings related to software capabilities, mathematical descriptions, boundary conditions, etc. As limitations and data gaps are identified, assumptions are made to make up for the lack of information. These assumptions should be made with the model objective in mind. For example, if boundary conditions at an outlet need to be assumed, knowing the intentions of the model will affect if static or dynamic conditions are chosen. Other relevant assumptions should be tracked throughout the process.

5.2.3 Setting up modelling approach

A specific modelling approach can be structured once modelling objectives are defined, knowledge about the system is gained, and the available data are reviewed. This step involves planning the model development and calibration phases, starting with a high-level schematic of the conceptual model layout. The data sets and information that will be retained to build the model are also selected. Basic model structures for specific submodel blocks are determined, and consequently the suitability of the available modelling process is assessed.

General temporal and spatial aggregation scales should be determined at this point, as it dictates the level of detail to include in the submodel blocks and how to delineate the catchments and sewers. Also, parameters that are consistent, or similar, in both the detailed and conceptual models should be highlighted.

If an interfacing modelling approach, which couples multiple modelling platforms, is selected, these interfaces would be initially described in this stage. Because this project deals with a built-in transformation function, no additional insight about interfacing is incorporated in this thesis.

In this final step of the project definition, the conceptual model's objectives have been considered to guide the model development and calibration phases. The reviewed available data has also defined how the information from the detailed model is translated to the conceptual model.

5.3 Model development

The model development phase begins with the identification of key hydraulic structures that, based on the stated objectives, impact the distribution of flows in the system at key points of interest and subsequently inform the delineation of catchments and sewers. Determining the desired calibration locations, either from monitoring data or by selecting strategic locations, follows. Delineating and aggregating the catchments and sewers must be done concurrently because the boundaries of the former affect the boundaries of the latter. In addition, initialization of parameter values and subsequent calibration of each item depends on these thoughtful divisions.

5.3.1 Identifying key structures and raingauges

Identifying overflows and critical hydraulic structures is a crucial step in being able to adequately represent the distribution of flows and dynamics at the key points of interest in a lumped conceptual model. The list of overflows that would have been made in the project definition phase should be carefully reviewed. Often IUWS modelling projects aim to accurately reproduce the overall overflows and not necessarily at particular locations, hence properly defining them is essential. Key hydraulic structures that could impact the distributions of representations of flows in the important collectors or at key overflow locations should be identified and reviewed, for these structures will most likely need to be explicitly defined in the conceptual model. A review of all regular and extreme-weather operation processes, including those operated in real-time control and equipped with all manner of flow control devices such as flow-diversion chambers, storage tanks, bifurcation gates, weirs, orifices, vortexes, and pumps, should be performed. If simplifications are required to implement these rules into the conceptual model, these should be defined. Bifurcations, defined as locations where flow can branch in two directions, should also be identified and assessed, for if these locations lie between major drainage areas they may affect catchment and sewer delineations.

One of the most overlooked consideration in delineating catchments is the locations of the raingauges. Locating these raingauges is vital to ensuring that the effects of spatial and temporal variability of rainfall are not ignored. The most influential variable on the accuracy of the simulated flows from catchments is the rainfall. Due to the high spatial and temporal variability in rainfall distributions (Bach and Ostrowski, 2013, Coutu et al., 2012, Fletcher et al., 2013, Khu et al., 2006), catchments should also be divided with the raingauge locations in mind.

5.3.2 Determining calibration comparison locations

Delineating catchments and sewers not only depends on the location of raingauges and key structures, but is also affected by the locations that will be used for calibration. These locations are selected with multiple goals in mind. Firstly, if good monitoring data is available, the location of the monitoring sites may be used to compare modelled results to the flow monitoring data. Regardless of whether flow monitoring data is or is not available, selection of comparison sites should take into consideration the ease to isolate a catchment or sewer for calibration. Overflows are also good comparison locations. However, locations along a main collection or just upstream of main sewer confluences are just as important to ensure that the flows in major branches are being well represented. This fact is even more true if backwater conditions exist, for if no sewer block is used to hold back the water, flows will be misrepresented.

Determining the catchment and sewer delineations, should be done concurrently with the selection of comparison locations. As the process is carried out, poorly selected comparison locations will become apparent. It will either not be possible to parameterize catchments or sewers, or calibration of these blocks will not be possible. These comparison locations will thus be updated as the catchment and sewer blocks are defined.

5.3.3 Catchment delineation and aggregation

Delineating catchments for conceptual models is not as straightforward as it is for detailed models because the conceptual catchments must represent both the area and the routing impact of local sewers. As reviewed in Section 2.2.4, there are many methods that exist for delineating detailed catchments based on detailed GIS data. For high-level conceptual models, catchments in effect represent drainage areas. Insightful considerations for this process have been reviewed, and used to create guiding principles to delineate the catchments. It should be noted that because IUWS models are often developed using calibrated detailed models as the reference, many of these guidelines are in fact related to lumping or aggregating detailed catchments into larger so-called drainage areas. Some studies (e.g. Maruéjouls et al. (2015)) have lumped spatially-not-adjacent detailed catchments based on average travel times; however this method is not suggested, for the ability to capture the spatial variability in rainfall will be lost.

As mentioned in previous sections, using the overflow locations, the selected key hydraulic structures and the main trunk sewer as the starting point for catchment delineation is recommended. Identifying these locations will naturally subdivide the areas into tributary regions to each item. Furthermore, highlighting the raingauge locations, and creating Theisen polygons around each, will define the zone of influence for each raingauge.

These divisions will give a good indication of boundaries for catchments, and may shed light on upper level limits for maximum catchment sizes. Catchments in the conceptual model should never span across multiple raingauges. Using confluence locations or a selection of all detailed catchment locations upstream from a main collector will provide additional organic divisions. Grouping detailed catchments based on similar land uses or drainage characteristics is also a tool that can help identify natural divisions. Reducing the heterogeneity in delineated catchments will simplify the calibration process. Sewer system type is another useful division attribute. As such, separated and combined areas should each have their own catchment. Finally, the shape of the catchment may need to be considered. For example, the outflow from a long thin catchment includes flows that travelled short distances near the mouth of the catchment and long distances from the upper ends of the catchment. Representing these flows with one catchment may be difficult, for a large distribution of flows must be captured. Therefore, the catchment would be divided along the long axis into multiple catchments. This phenomenon may be more critical for specific rainfall characteristics or specific sewers system types (i.e. combined sewers have quick large inflows compared to infiltration-dominated separated systems).

5.3.4 Sewer delineation and aggregation

Delineating the individual sewer blocks to be represented in a conceptual model is closely tied to the catchment delineation process. In addition, the ease of calibration of each block must be considered. As with the catchments' delineation process, the sewers will be naturally divided between key structures and collector confluences. Any hydraulic configuration (major sewer size changes, drops, etc.) that would cause a drastic change in flows should be considered as a division point if it would affect the result at the desired locations (e.g. overflows). To reduce complexity, only major sewer segments should be considered to include in the conceptual model. As such, highlighting main sewer sections of the system will help determine a skeletal structure. These considerations draw from the pruning, merging or equivalence methods described in Section 2.2.4, wherein smaller pipes are excluded, similar consecutive pipes are merged, and complex layouts are replaced with simpler arrangements.

Calibrating a catchment through which a conceptual sewer runs (see Section 2.2.4.2) is often difficult, as its outlet is the same as that of the sewer. For example, a collector sewer may have many small flow-receiving local branches. Most likely a catchment would be delineated to represent these inflows along the main sewer, however calibrating this catchment separately from the sewer would not be possible. The outlet from the sewer would then be used to calibrate both the catchment and sewer flows, therefore the way in which the sewer is divided should allow for this calibration. To do so, only one sewer should cut through this type of a catchment, otherwise calibrating the catchment would not be possible.

5.3.5 Initialization of catchment parameters

Assigning initial values to the catchment parameters is closely tied to the delineation and aggregation step, for the way in which they are divided affects their defining characteristics. In this step, the initial DWF and WWF parameter values are assigned to the best knowledge of the modeller. Parameters for which the value is less certain will either be calibrated in a later step, or the assumed parameter will then be considered as a potential limitation of the model.

5.3.5.1 Dry weather flow

As reviewed in Section 2.3.1.1, the main DWF components are the generated wastewater flows and the GWI. Each flow may also have an attributed time-varying pattern. If an existing detailed model exists, these flow values and temporal patterns are most likely available. Their source and validity should, however, be confirmed.

5.3.5.1.1 Generated wastewater flow

The generated flow is made up of residential, institutional, commercial, and industrial sewage. In a wastewater model, these flows are often lumped into an average flow, or a value is added for each generator. Generation rates may be derived from flow-monitoring data or they can be estimated using water meter records in normal conditions, during which water usage can be assumed to return to the collection system. For instance, water records should not be used during summer months, because a large portion of water may be used to water lawns or for season-specific uses and therefore does not return to the collection system. Special attention should also be given to areas of manufacturing or processing where water is used up in the process. Alternatively, generated flows may be calculated using populations and average generation rates noted in local guideline documents or past studies.

Generic diurnal patterns exist for all types of landuses, and could be extracted from the same sources as the flows. A diurnal pattern is often applied to each or the sum of the generated flows. Alternatively, convoluted patterns (a mix between certain types of landuses, i.e. residential and commercial) may be applied.

Aggregating DWF generation flows and patterns can most often be done by summing or averaging the values from detailed catchments. Values for which there is less confidence will be calibrated during the calibration phase.

5.3.5.1.2 Baseflow

Baseflow, or GWI, covers all groundwater that infiltrates into the non-pressurized gravity collection system through defective pipes, pipe joints, and leaking maintenance hole (MH) access structures. Because this value depends on surface, soil and pipe conditions, accurate standard values cannot exist; therefore, this parameter is often calibrated. An average of the GWI values should represent a decent value for the lumped catchments. A monthly baseflow pattern is often applied to account for the seasonal variations in baseflows.

5.3.5.2 Wet weather flow

The WWF is defined by multiple parameters, as reviewed in Sections 2.3.1.2 and 2.3.5. As with the DWF parameters, some of the WWF parameters can be summed or averaged for the aggregated catchments, however others are not comparable and therefore must be determined differently. One exception may be the evaporation, surface loss and infiltration parameters. These parameters commonly use guideline values from the detailed model since they are often standard between models.

Surface imperviousness, or the equivalent runoff coefficient, is the most influential parameter governing the surface runoff volume because it governs the amount of flow entering the system (Haestad Methods Water Solutions, 2007). Imperviousness is normally calculated using detailed GIS layers, or estimated using standard values for certain land types. Alternatively, these values would have been calibrated in a detailed model. It is important to determine whether the impervious value relates to the total imperviousness or the effective imperviousness (the impervious area in a catchment that is directly connected to an inlet). Although imperviousness is not a parameter that can be simply averaged over the lumped catchments, there is no defining formula that describes how to vary the parameter based on catchment size. Too many variables could affect the imperviousness on a detailed level to allow for simple averaging in a lumped model. Furthermore, the use of imperviousness in a lumped catchment may, and often would, be used to define both stormwater and all RDII contributions.

The WWF routing leads to the second set of parameters that need to be defined in an aggregated model. As reviewed previously, the hydrologic response of large urban catchments is inherently linked to the configuration of the sewer network conveying flow in the catchment. Hence, the defining catchment parameters must represent both the sewer hydraulic and hydrologic responses simultaneously. The aggregation of the concentration time or catchment width and slope parameters that often govern the routing dynamics over detailed catchments are not sufficient to describe the responses over lumped catchments. The variability in the dendritic nature of the sewers, the shape of the catchment, and connectivity of the local sewers makes it impossible to translate routing information from detailed to lumped catchments. Furthermore, as reviewed in Section 2.3.1.2, the direct and delayed inflows have varying dynamics, that further change as these flows are routed through local sewers. As such, an estimation of routing parameters is often done, and these values are adjusted during calibration.

5.3.6 Initialization of sewer parameters

Sewer characteristics depend on the approach that was used to delineate and aggregate the catchments and sewers. The diagrams provided in Section 2.2.4 demonstrate different potential ways to characterize sewers. The first step involves determining which main section of the collector sewer is being represented by the conceptual sewer block, and which sewers are considered to be incorporated in the catchments' representation.

As with the delineation step, using a map of the labelled main sewer sections of the system could help in this process.

One option for determining specific lumped sewer characteristics, such as diameter, slope, and roughness, could be calculating length-weighted averages. However, as reviewed in Cantone and Schmidt (2009), skeletonizing and aggregating sewer systems may lead to lost conduit storage. The authors state that errors due to aggregated parameterization could therefore be accounted for by calibrating certain parameter values. If representative sewers are well selected for the conceptual model, this effect can be reduced. Furthermore, because the hydrologic responses from catchments are meant to include the local sewer response, some of the lost storage is inherently accounted for by these routing dynamics.

Translating the detailed parameter characteristics to the lumped model parameters may be done using proven methods. For the linear reservoirs sewer configuration in WEST, the Kalinin-Miljukov method has been proven to be an acceptable method to determine the parameter values of these linear reservoirs, as discussed in Section 2.3.6. Alternatively, as reviewed in the literature review, a single non-linear pipe would be characterized using pipe characteristics and estimated maximum flows and volume-outflow gradients, as described in Section 2.3.6.2. Regardless of the chosen method, all characteristics and assumptions in assigning conceptual sewer values should be stated and documented.

5.3.7 Representing special structures

The identified special structures are defined and modelled on a case-by-case basis. Simple diversion chambers would be represented differently compared to dynamically controlled flow-regulation structures or pumping stations. Using the gained knowledge from the system assessment stage, structure characteristic, operation and process control rules could be simplified, as necessary. These structures will be tested in the calibration phase, where significant misrepresentations will become apparent.

5.4 Calibration

Most studies reviewed in Chapter 2 expressed the importance of calibration to ensure that the conceptual model acts as expected. As summarized in Rieger et al. (2013), calibration is the process of modifying parameters to match simulation results to observed data or a reference model. This process is normally carried out by manual manipulation of parameter values. Automatic algorithms to estimate and calibrate model parameters do exist, however they are prone to convergence problems and providing “correct” responses for wrong reasons in complex models (Dochain and Vanrolleghem, 2001), thus they were not used in this project.

The following sections review the formulated calibration approach, followed by a summary of the specifics related to calibrating DWF and WWF parameters.

5.4.1 Calibration approach

Selecting a structured calibration approach is a vital step in ensuring that appropriate parameters are modified in a logical order, until a desired goodness-of-fit is achieved. Following such an approach should result in more accurate and efficiently-determined results. Proper concurrent documentation of the tracked adjustments and the entire calibration process is suggested (Rieger et al., 2013).

5.4.1.1 Calibration runs and modifiable parameters

Normally a calibration strategy is defined such that multiple calibration runs are performed, each with specific goals in mind. For example, the DWF parameters are often first calibrated in dry conditions, followed by a calibration of the WWF parameters, and iterating back until convergence is achieved. To break it down further, beginning with a calibration of the volume of flow during DWF is first suggested. A calibration of the hydrodynamics follows. Once the DWF is calibrated, the WWF calibration follows the same strategy: the volume response is first calibrated, followed by a calibration of the hydrodynamics. Multiple and successive events should be used to calibrate the WWF response, because as shown by Cantone and Schmidt (2009), the calibration of parameters to fit a particular storm event may result in non-representative responses for storms of different duration, temporal distribution and magnitude.

Following a structured calibration method, as described above, reduces the possibility of randomly modifying all parameters at once. In following this logic, it is suggested to pre-select a limited set of parameters that will be modified in each calibration sequence. These parameters should include those for which the assigned value is uncertain, not measured and most sensitively influences the results. These parameters could be selected using sensitivity analysis (Dochain and Vanrolleghem, 2001). The parameters for which values were assumed to be correct will not be calibrated. If this initial assumption is incorrect, an adjustment to the calibration parameters may have to be made.

5.4.1.2 Calibration order

To further structure the calibration approach, each block or item (e.g. catchment, sewer, storage tank, hydraulic structure, etc.) should be assigned a calibration order. Starting with the most upstream catchments (i.e. those that are unaffected by the calibration of others) are assigned an order value of 1. The next step is to sequentially number all items that can be simultaneously calibrated such that their result depends on the previous calibration order component. In doing so, each block or item will be numbered, and a calibration order will be defined. Each calibration run defined in the previous sections (Section 5.4.1.1) should then follow this calibration order. This step will help ensure that upstream parameters that affect downstream results are modified first. However, it means that downstream calibrations are conditional on upstream calibrated values, thus iteration may help to find the overall best parameter values.

5.4.1.3 Calibration criteria

The calibration process is completed once a pre-defined set of calibration criteria is met. During the calibration process, simulated and reference hydrographs are normally visually compared first. Criteria indicators are then calculated to ensure a suitable fit has been reached.

Many performance criteria exist, however the following criteria, selected from Hauduc et al. (2015), are most often used for hydrological and wastewater modelling projects. A comparison of the total DWF and WWF volumes is generally performed and qualitatively assessed using percent volume error (PVE). The Nash-Sutcliffe coefficient (NSE) is used to asses the predictive power of a hydrological model, by comparing the modelled and reference flows to the mean flow. Peak values attained during each event are also commonly compared in terms of flow and timing. Percent error in peaks (PEP) will characterize the difference between the observed and the modelled peak flows. The equations (Equations 12 – 14) for these criteria are presented in Table 3. Other appropriate criteria could be chosen based on the objective of the project.

Table 3: Performance criteria equations

Percent Volume Error (PVE)	$PVE = 100 \times \frac{(O-P)}{O}$	**(12)**
Nash-Sutcliffe coefficient (NSE)	$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$	**(13)**
Percent error in peaks (PEP)	$PEP = 100 \times \frac{(O-P)}{O}$	**(14)**

Note: O for observed data (or reference data); P for predicted data (or modelled); n is the number of data points

5.4.2 Dry weather flow

As previously stated, the DWF volume should first be calibrated, followed by the shape of the DWF pattern. This calibration focuses on the catchment parameters, because it is assumed that the basic pipe characteristics (either the n and k parameters from the linear tanks in-series equations determined using the Kalinin-Miljukov method, or the parameters for the non-linear pipes) are representative.

5.4.2.1 DWF Volume

By following the calibration order, all pre-selected DWF calibration parameters that affect the volume will be adjusted in this run. Generally, these parameters include sewage generation rates and GWI. Depending on the trustworthiness of each initially assigned value, most likely one or the other will be modified.

5.4.2.2 DWF Dynamics

The DWF dynamics are defined by time-varying patterns, namely the diurnal generation patterns and monthly baseflow patterns, and the routing of flow. Because lumped catchments combine the catchment characteristics and the effect of the local sewer hydraulics, the model should account for both phenomena. For the modified catchment block defined in Section 4.1.2, generic diurnal patterns are assigned to a catchment and the routing of the flow is accounted for by the number of linear reservoirs (n) and their hydraulic retention time (k). Simultaneously adjusting these two values, along with the diurnal pattern, permits representing variations in DWF dynamics.

If the flow propagation in sewer blocks is not representative, the initial n and k parameter values are to be manipulated during calibration on the basis of detailed model simulations of the considered sewer section.

5.4.3 Wet weather flow

The basic strategy for WWF calibration involves systemizing the calibration runs and parameter adjustments based on a specific goal. Besides following a volume-dynamics calibration sequence and an internal calibration order, particular storms, or sets of storms, are good options to use for the first calibration runs, to test the system under non-stressed conditions (i.e. no backwater). Larger and successive storms can then be used to re-adjust parameter values and check backwater conditions. It is suggested to first simplify hydraulic structure process controls (i.e. RTC) in both the detailed and conceptual models to reduce the complexity of calibrating the basic catchment and sewer blocks. Once the basic conceptual items have been calibrated, RTC rules can be sequentially re-introduced in both models, and calibrated accordingly.

To get a good starting point for the calibration parameters without having to iteratively change parameters and run the model excessively, the outflow curves from the detailed catchments could be compared to calculated linear reservoir curves in a spreadsheet. Conceptual model parameter values are adjusted until the curves match in shape. This strategy may result in a better estimation of initial parameter values.

5.4.3.1 WWF Volume

As reviewed in Section 5.3.5.2, the parameter that most affects the WWF response is the runoff coefficient or the imperviousness. This parameter is calibrated to match detailed and lumped model resultant volumes. The evaporation, surface loss and infiltration parameters are not generally calibrated as these values are often represented by the same parameters in both the detailed and conceptual models. If this were not the case, the loss parameters would become additional calibration parameters.

5.4.3.2 WWF Dynamics

The dynamic hydrologic response of different types of large catchments (i.e. shape, local sewer network, sewer type, etc) varies greatly in volume and in shape. The shape of the response is governed by the routing of flow over the surface and through the local sewers. In lumped conceptual models that use cascading linear reservoirs, this routing is represented by the number of linear reservoirs (n) and their hydraulic retention time (k).

In the modified catchment block described in Section 4.1, the fast and slow routing components essentially represent the varying dynamics of direct and delayed responses, along with routing through the local sewers. For this configuration, the number of linear reservoirs (n), their hydraulic retention time (k) and the split between the two sets of linear reservoirs should be calibrated. For conceptual models with alternate configurations of model structures, the identified routing parameters will be calibrated.

Similar to the DWF calibration step, if the flow propagation in sewer blocks for WWF is not representative, the n and k parameter values are to be adjusted during calibration. However, the pipe parameters that often require special attention during calibration are associated with backwater conditions. These parameters (either Q_{back} for linear reservoirs, or Q_{max} and 'a' for the non-linear reservoir) are modified sequentially using larger and successive storms that produce backflow in the detailed model.

5.5 Validation

The calibrated parameters are validated using a pre-selected independent data set that reflects the goal of the model. This stage ensures that the complex dynamics of the systems are still representative under different conditions. As such, the validation data set should include different types of events (i.e. varying intensity, duration, and succession of events) compared to the ones used for calibration. The resultant flow hydrographs should closely follow both in timing, shape and magnitude. An objective evaluation of the quality of the validation compared to the calibration could be determined using the Janus coefficient (Sin et al., 2008) (Equation 15).

$$J^2 = \frac{\frac{1}{n\_val}\sum_{i=1}^{n\_val}(y_{ref,k,i} - y_k(t_i,\theta))^2}{\frac{1}{n\_cal}\sum_{i=1}^{n\_cal}(y_{ref,k,i} - y_k(t_i,\theta))^2} \tag{15}$$

Discrepancies in results will indicate potential issues that should be investigated, and further verification subsequently can take place. In summary, the validation stage will verify the model's ability to perform under new conditions. If successful, the model can be used for its purposes; however, if the validation is unsuccessful, a return to one of the previous steps in the procedure is required.

Chapter 6 Case study application

The following sections explain how the formulated generic procedure was applied to the selected case study. Each section follows the same format and refers to the above procedure. Only the application of the procedure is described in this section; the results of the calibration and validation efforts are provided and discussed in Chapter 7.

6.1 Selected case study overview

The case study selected for this research project is located in Ottawa, Ontario. A detailed trunk-level PCSWMM model of the entire City of Ottawa wastewater and combined sewer system was built by Stantec Consulting in 2013. The model covers over 38,000 ha, including all sewers larger than 600 mm in diameter. The model consists of 850 catchments and almost 6,000 sewer segments, including separated, partially-separated and combined sewers. The combined sewers are the oldest and are found in the central area of the city. The sanitary sewers within partially separated areas, which receive stormwater drainage flows primarily from foundation drains and in some cases from directly connected roof and driveway drains, surround the central core. Much of the newer parts of the City are serviced by fully separated sanitary sewers, which receive smaller amounts of extraneous flows. An intricate collection of static and dynamically operated (RTC) flow-regulation gates are found in the inner parts of the City.

This detailed model was created as a planning level tool to help identify sewer system capacity constraints in larger collector sewers under severe storms (i.e. 100-year return period). Flow monitoring data from locations through the City and at pump stations was used to calibrate the model. The DWF generation rates were extracted from the flow monitoring data, and two large storms were used as the basis for the WWF calibration.

This case study was selected due to the availability of the model and the existing extensive background knowledge available about the model. The central urban portion (6,400ha) of the calibrated detailed model was used as the reference model in this case study. This portion contained sanitary areas, all the partially-separated and combined areas in the City, and all overflows, making it a diverse study area. Furthermore, the central area can be easily extracted from the rest of the model for there are minimal connections to the remainder of the sewer system. Figure 19 shows the areas of the detailed model that were converted into the conceptual model.

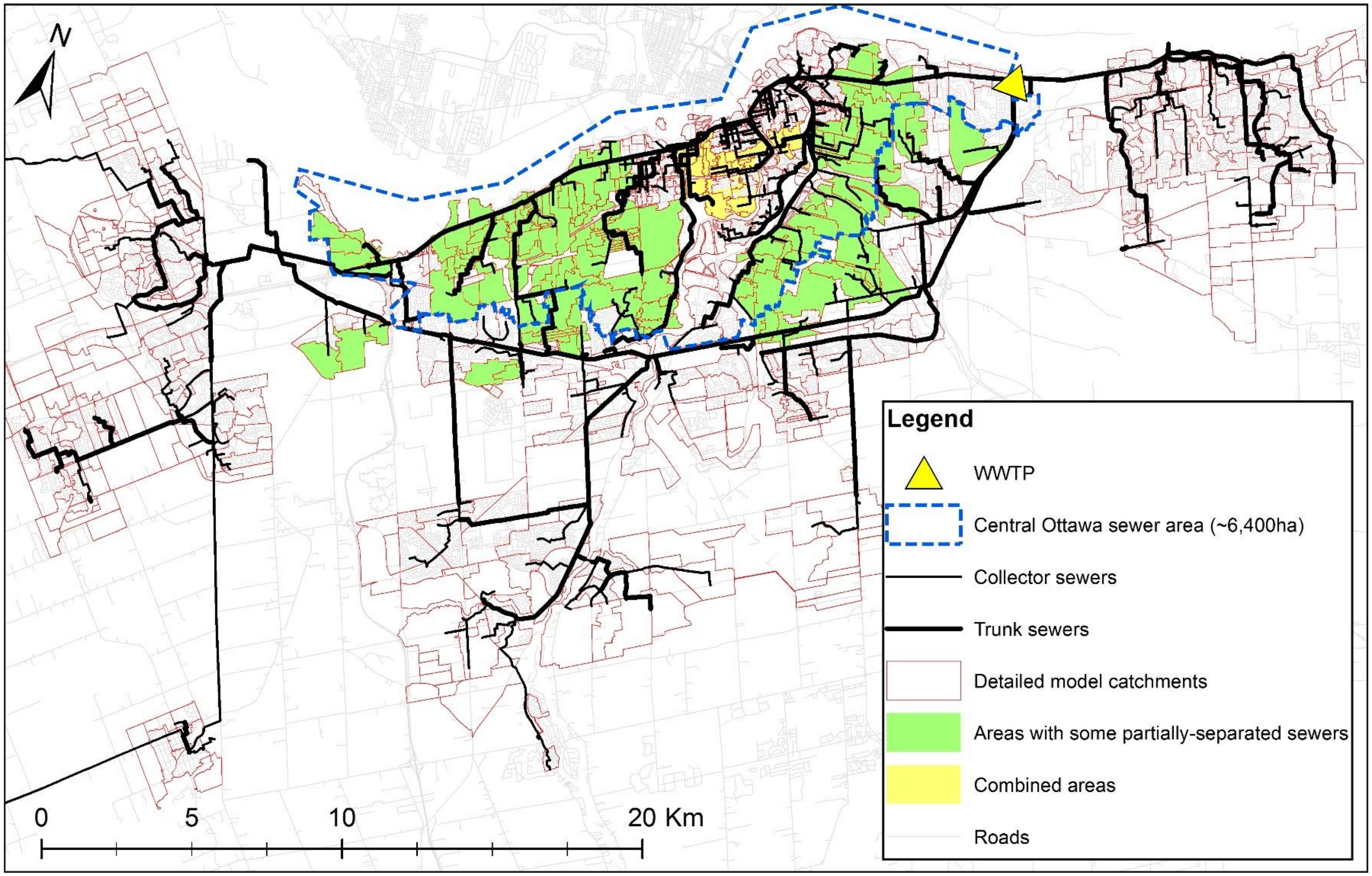

Figure 19: City of Ottawa case study area in relation to detailed model

6.2 Project definition

6.2.1 Model objectives

For the purpose of developing and testing the procedure to aggregate and calibrate catchments and sewers, it was assumed that the objective of the conceptual model was to accurately represent the flows from the detailed model, both peaks and volume, at specific locations: along the main trunk sewers; at the system's outlet which discharges to the wastewater treatment plant, and at the overflows.

This objective is measured by certain criteria. Although guideline criteria for IUWS models do not exist, planning-level models often aim to meet specific criteria. The Code of Practice for Hydraulic Modelling of Sewer Systems (WaPUG, 2002) suggests the following guide for modelled flow verification against reference flows.

DWF:

- The shape should closely match and the timing of the peak should be within 1 hour;
- The modelled peak flow rate should be within ± 10%; and
- The modelled volume of flow (or average flow) should be ± 10%.

WWF:

- The shape should closely match and the timing of the peaks and trough should be similar;
- Each modelled peak flow rate during an event should be within +25% to -15%;
- The modelled volume of flow during an event should be within +20% to -10%.

Generally, less error is expected for DWF comparisons. Higher errors are permitted in WWF simulations because of larger variabilities present. Because these guidelines are for planning-type models, erring on the conservative side (i.e. higher flows) is more acceptable.

These guideline values cannot be blindly applied for verifying the accuracy of conceptual IUWS models for two reasons. First, conceptual models are expected to have poorer fits than detailed model. Second, these guidelines are for comparisons between model simulation results and observed flow. However, because no rules exist to define the verification criteria for translating a detailed model into a conceptual model, the above guidelines are loosely used to determine whether the conceptual models' objectives are met.

6.2.2 Understanding the system

The City of Ottawa and Stantec generously collaborated with the researchers on this project to provide the necessary background information.

6.2.2.1 Available data and reference models

The detailed model mentioned above, along with GIS layers, were provided by the City for review. As introduced in Section 6.1, this model was created for extreme weather assessments. DWF of the detailed model was generated using populations and commercial/institutional areas, and extracting generation rates and diurnal patterns from flow monitoring data. DWF generation rates and diurnal patterns were slightly adjusted during calibration, and baseflow rates were calibrated. The WWF in the detailed model was represented by RTKs for the partially separated and separated areas and by hydrologic catchments that use SWMM rainfall-runoff routing in the combined areas.

Historical flow monitoring and rainfall data (from 2005-2015) was provided for various locations throughout the City. However, because of the significant amount of work required to validate this data and adjust the model to reflect the conditions at those specific dates, the time frame for this thesis project did not allow this data to be used to calibrate the model. The one set of rainfall data that was retained for use in this project was from the year 1980, which was considered an “average year” in terms of rainfall events. This data set was used to validate the conceptual model. Raingauge locations were provided and mapped, as these were to be considered in the catchment delineation phase.

Some generic area and sewer characteristics have already been introduced in Section 6.1. All this information is available as GIS layers and was considered in the initial development of the detailed PCSWMM model. The core of the City is generally made up of residential, institutional and commercial areas. All important special hydraulic structures were already included in the detailed model, including their operational rules.

No significant data gaps were identified, however in reviewing the available information, assumptions required before setting up the conceptual model were noted.

6.2.2.2 Assumptions

Below is the list of assumptions made to simplify the application of the developed procedure. Other more specialized modelling assumptions are tracked within the appropriate sections.

- Because only the core of the City was used as the reference model, any outflow connections between this region and the other parts of the sewer system were assumed to act as additional overflows.
- The wastewater treatment plant operations were completely simplified and it was represented as a free outfall.
- The RTC regulated structures were simplified to non-regulating structures in the detailed model prior to translating them into the conceptual model. This was done because the focus of this project was on the representation of catchments and sewers and not complex RTC rules.

- There are known issues with the institutional and commercial sewage generation rates loaded in the detailed model. However, the model was calibrated to account for these.

- It was assumed that the way in which the detailed model functions represents reality in both DWF and WWF conditions. Although the detailed model was calibrated to larger storms, the generic procedure of translating this information to a conceptual model could still be developed and tested.

6.2.3 Setting up the modelling approach

Setting up the modelling approach mostly involved assessing the model structure and code in WEST, as reviewed in Chapter 4. The model structure of the catchments and sewers were modified to better suit the needs of this project. However, even though the advantages of using non-linear reservoirs have been reviewed in Section 2.3.6, these models were only used for sewer segments that have no backwater. The mentioned issues with the modelling code presented in Section 4.2 were only corrected for the linear models; the non-linear backwater models have not yet been adjusted. Suggestions for using these non-linear pipe models instead of the linear reservoirs for both catchment and sewer modelling, once properly modified for this purpose, are discussed in Section 8.3. Although this method will in fact increase the calculation efficiency, the generic model development strategy discussed in this thesis remains the same.

A 5-minute interval was selected as the temporal scale for rainfall input and output results from the detailed model. The consistent parameters between WEST and PCSWMM were summarized, and used to parametrize the conceptual model parameters. Because WEST allows all modelling to be done in the same platform, interfacing was not required.

6.3 Model development

6.3.1 Identifying key structures

All key structures, overflows and critical hydraulic structures, were identified and are highlighted in Figure 20. As stated in the assumptions, all highlighted RTC structures were simplified in the detailed model. All active and permanent raingauges were also identified.

6.3.2 Determining calibration comparison locations

The comparison locations were concurrently selected with the delineation of catchments and sewers. Because flow monitoring data was not used, this was not a factor in selecting locations. In general, all overflow locations were selected. Locations along the main West-East running trunks (the West Nepean Collector and the Interceptor Outfall Sewer (IOS), as indicated in Figure 21) were selected based on catchment and sewer divisions. Throughout the calibration process, model adjustments to catchment and sewer delineations resulted in modified comparison locations along the main trunk.

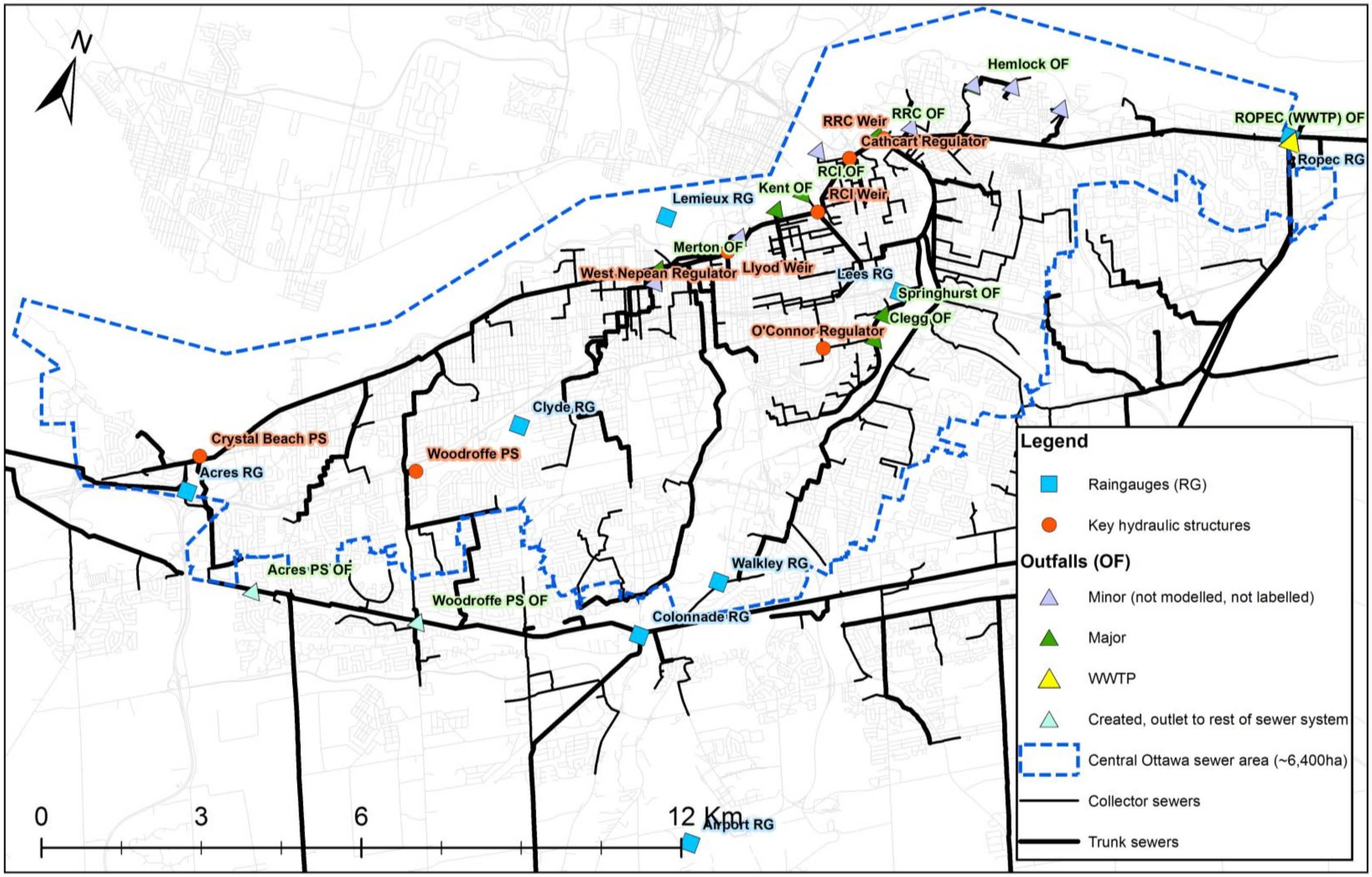

Figure 20: Key hydraulic structures, overflows and raingauges of Ottawa case study area

Abbreviations on Figure: RG: raingauge; OF: outfall or overflow; PS: pump station; RCI: Rideau Canal Interceptor; RRC: Rideau River Collector; WWTP: Wastewater Treatment Plant

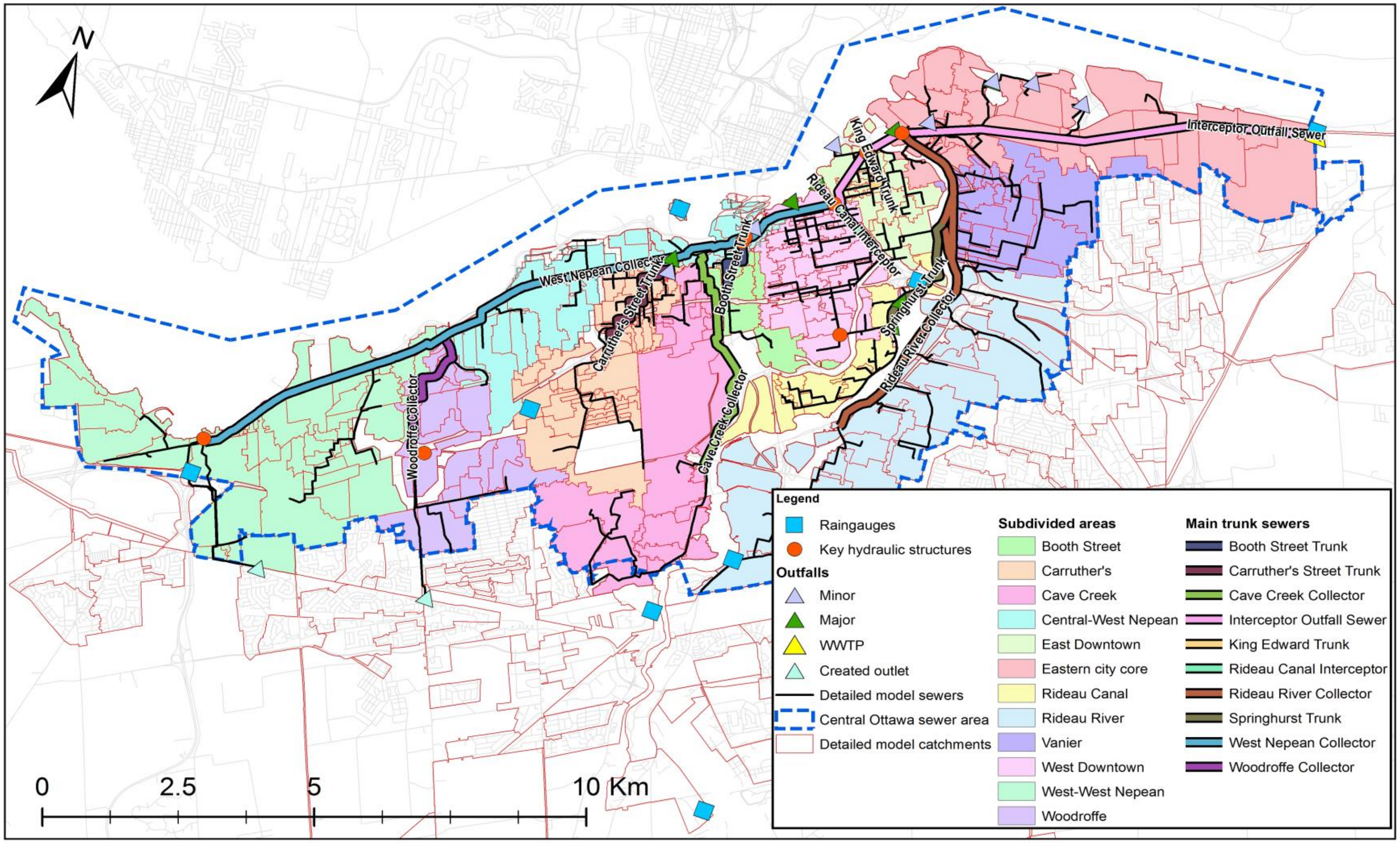

Figure 21: Main collector sewers and subdivided tributary areas of Ottawa case study area

6.3.3 Catchment delineation and aggregation – Models V1 and V2

Two conceptual models were created with increasing levels of aggregation; V1 was first created and calibrated, and subsequently V2 was built by further aggregating the V1 model.

The first step in delineating the catchments and sewers for the V1 model involved highlighting the main sewer trunks and grouping tributary areas that outlet to the same location or trunk sewer. With these sewers highlighted, and the overflow locations, key hydraulic structures and raingauges selected, natural divisions in the sewer system and catchments appeared (see Figure 21). Raingauge influence zones were determined by grouping areas around each raingauge, to ensure that catchment divisions consider the spatial variability of rainfall. Large grouped areas that either spanned across multiple raingauges or a long stretch of sewer were further subdivided. Major collector sewer confluences were also used as division points. Examples of these divisions are provided in Figure 22. Combined areas were always treated separately from the other types of sewer system areas, and were therefore represented with their own storm catchment blocks in the model. Because there was no clear distinction between separated and partially separated sewers in the detailed model, these two types of areas were considered and modelled together.

The final grouping of areas led to the aggregation of the detailed catchments, which then defined the new lumped catchments for model V1 (Figure 23).

The second iteration of the model (Model V2), was created once the entire model V1 was built and calibrated. For Model V2, the lumped catchments from Model V1 were further aggregated, where possible. The goal was to reduce the model complexity as much as possible, while still representing the flow accurately. Areas where the sewer network was in a simpler dendritic pattern were aggregated further than those that had complex configurations or nearby special hydraulic structures. For example, catchments upstream from major special structures were combined into larger areas, while catchments with special structures directly downstream remained as small catchments. This method led to a greater variation in catchment sizes for the V2 model. Figure 24 shows the aggregated catchments of model V2 in relation to those of model V1.

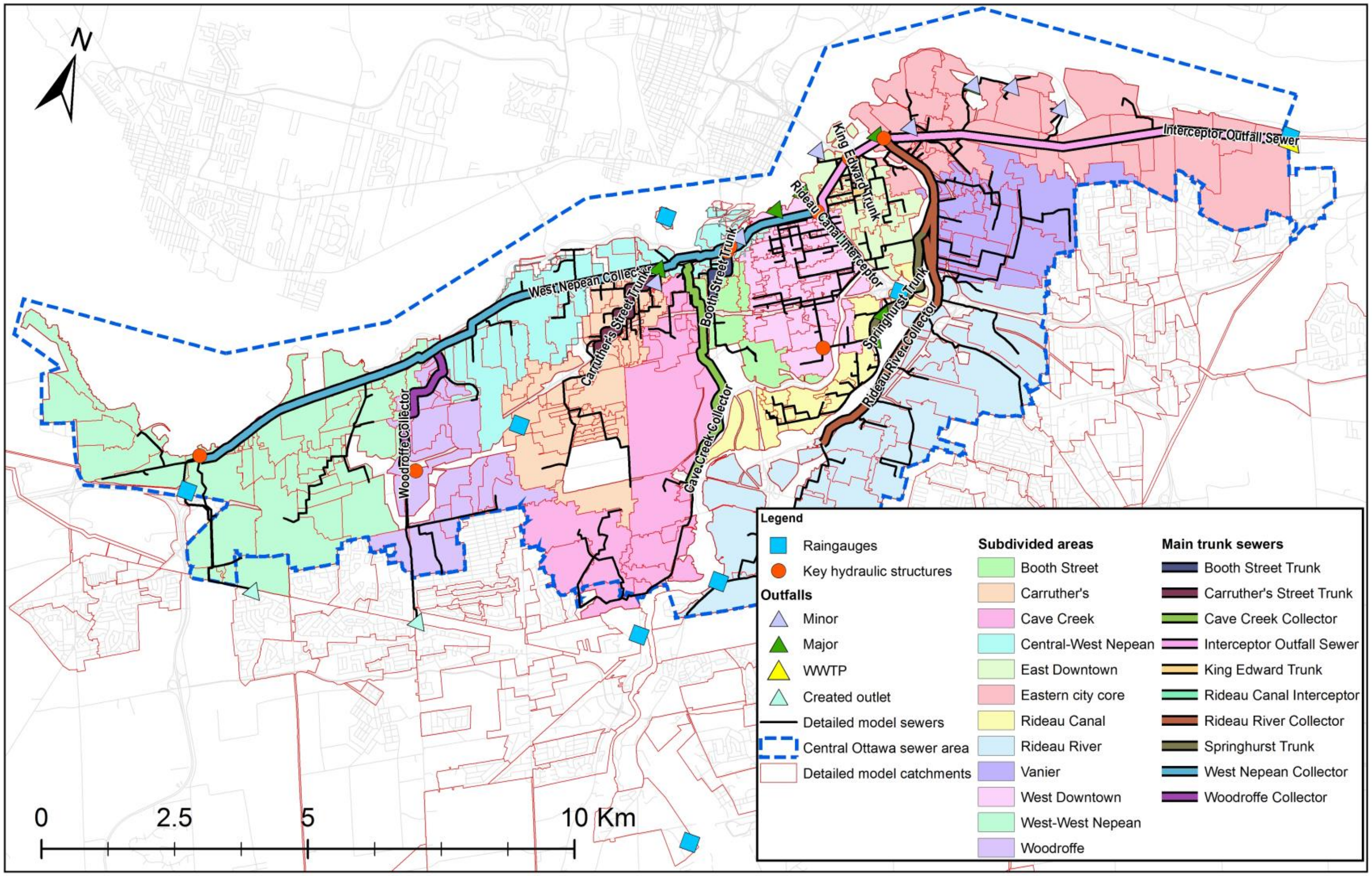

Figure 22: Catchment delineation examples, with main collectors and raingauge regions, of Ottawa case study area

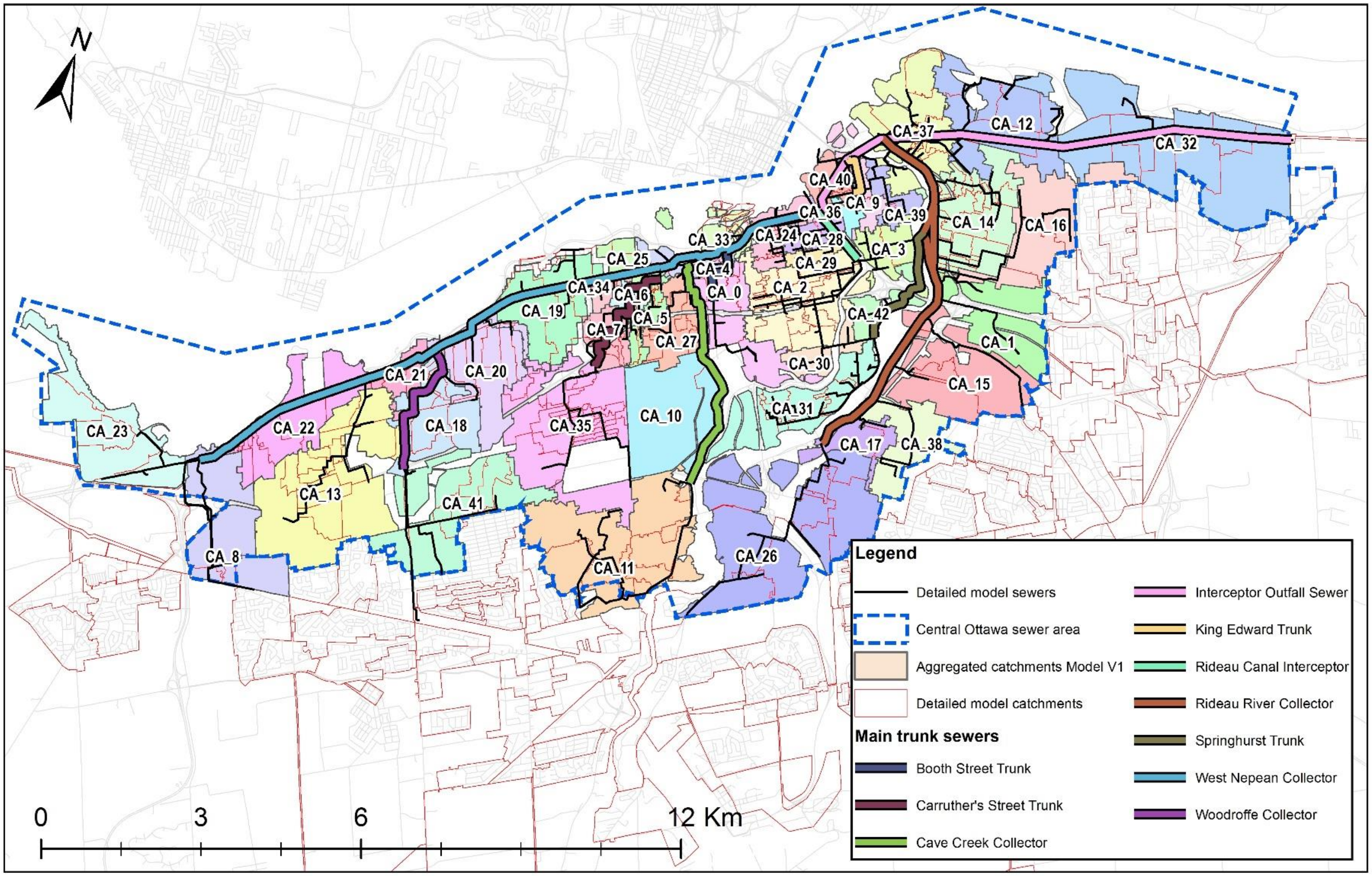

Figure 23: Aggregated catchments for model V1 of Ottawa case study area, with main collectors

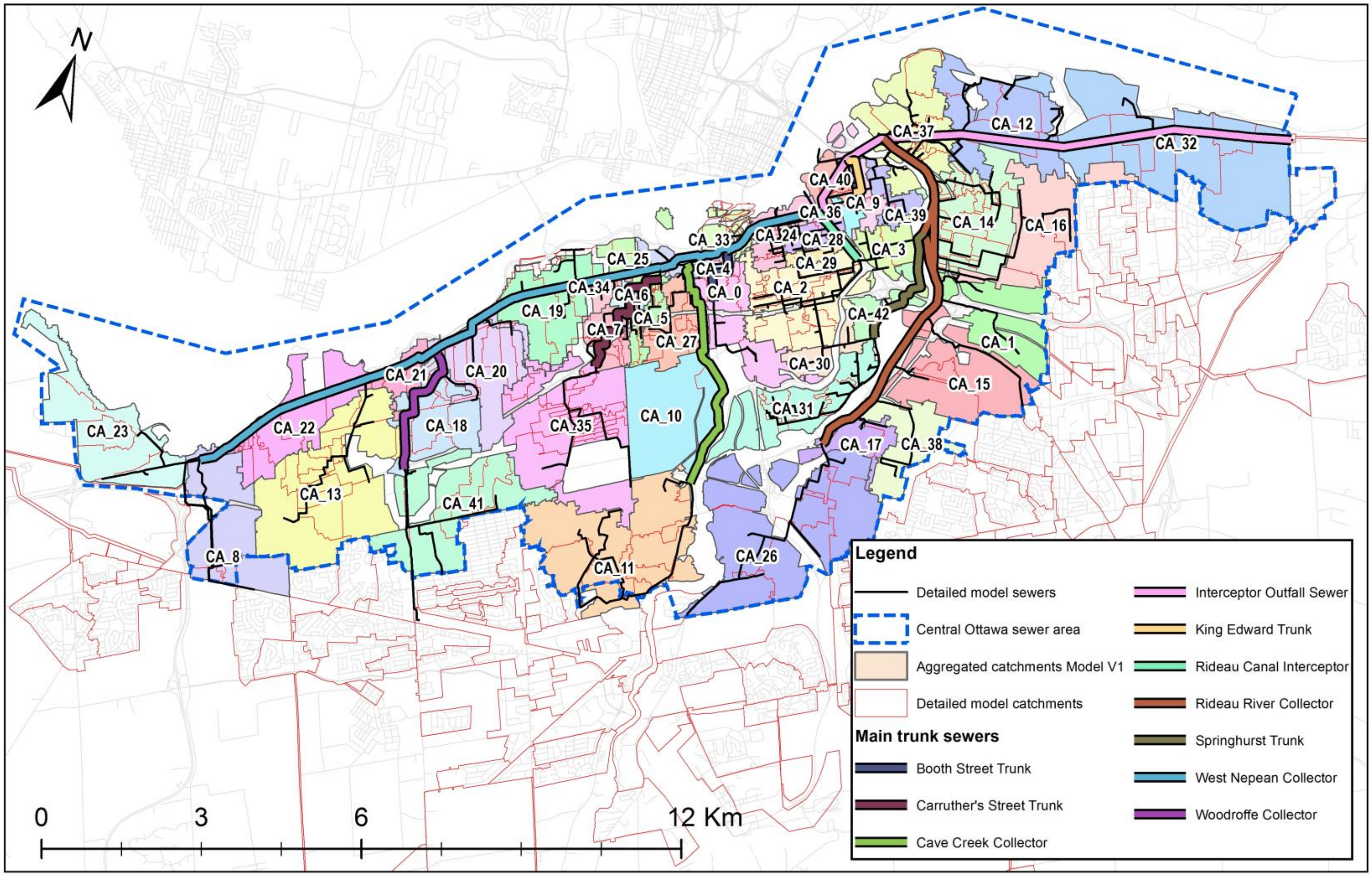

Figure 24: Aggregated catchments of model V2 of Ottawa case study area, with main collectors

Note: thin blue lines within the V2 catchments demonstrate the delineations of the V1 catchments

6.3.4 Sewer delineation and aggregation

The highlighted collector sewers were delineated into sections in parallel with the delineation process for the catchments. Locations of sewer divisions were adjusted in the calibration phase, to simplify the calibration, as reviewed in Section 2.2.4.2. In general, sewer sections were delineated between catchment boundaries or up to the nearest hydraulic structure. Examples of such division are shown in Figure 25.

Figure 26 and Figure 27 show the sewers from the detailed model that were explicitly modelled in the conceptual models V1 and V2, respectively. Figure 28 and Figure 29 show the final conceptual model configurations for V1 and V2, respectively. (Note that the conceptual models' layout was re-arranged compared to the detailed model layout: the Western section of the model is represented on top, while the Eastern section of the model is represented below. This layout adjustment was simply made to allow the entire conceptual model to be seen on one screen.) Appendix B contains the same figure with the raingauge assignment lines included. Figure 30 shows how the sewer segments from the V1 model were aggregated for the V2 model.

6.3.5 Conceptual models V1 and V2

The difference in aggregation between the two models can be examined by comparing the number of sewer and catchment blocks in each. Table 4 summarizes these differences. The number of catchments in the more aggregated model (V2) is less than half of the V1 model, and the number of sewers in the V2 model is also 50% less. Some catchments and sewers from the V1 model remained the same in the V2 model, therefore the size range of these components is greater in the more aggregated model.

Table 4: Attributes of conceptual models V1 and V1

Block	Attribute	Model V1	Model V2
Catchments	Number of blocks	52	22
	Average / median size	146 ha / 102 ha	289 ha / 192 ha
	Size range	26 – 435 ha	26 – 732 ha
Sewers	Number of blocks	33	17
	Average / median length	1480 / 1280 m	2580 / 1490 m
	Length range	100 – 3000 m	770 – 7720 m

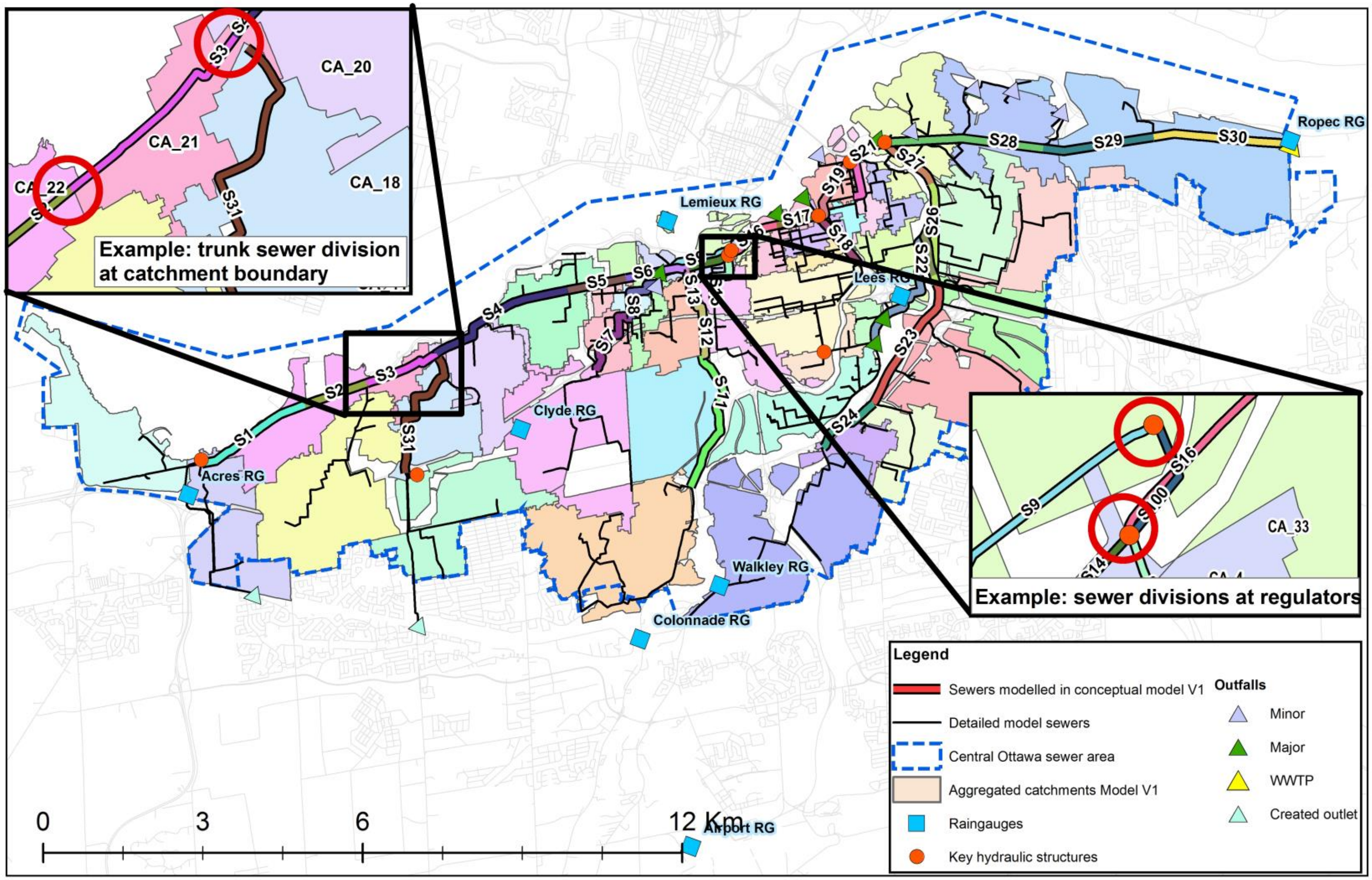

Figure 25: Sewer division examples of V1 model at catchment boundary and regulators of Ottawa case study area

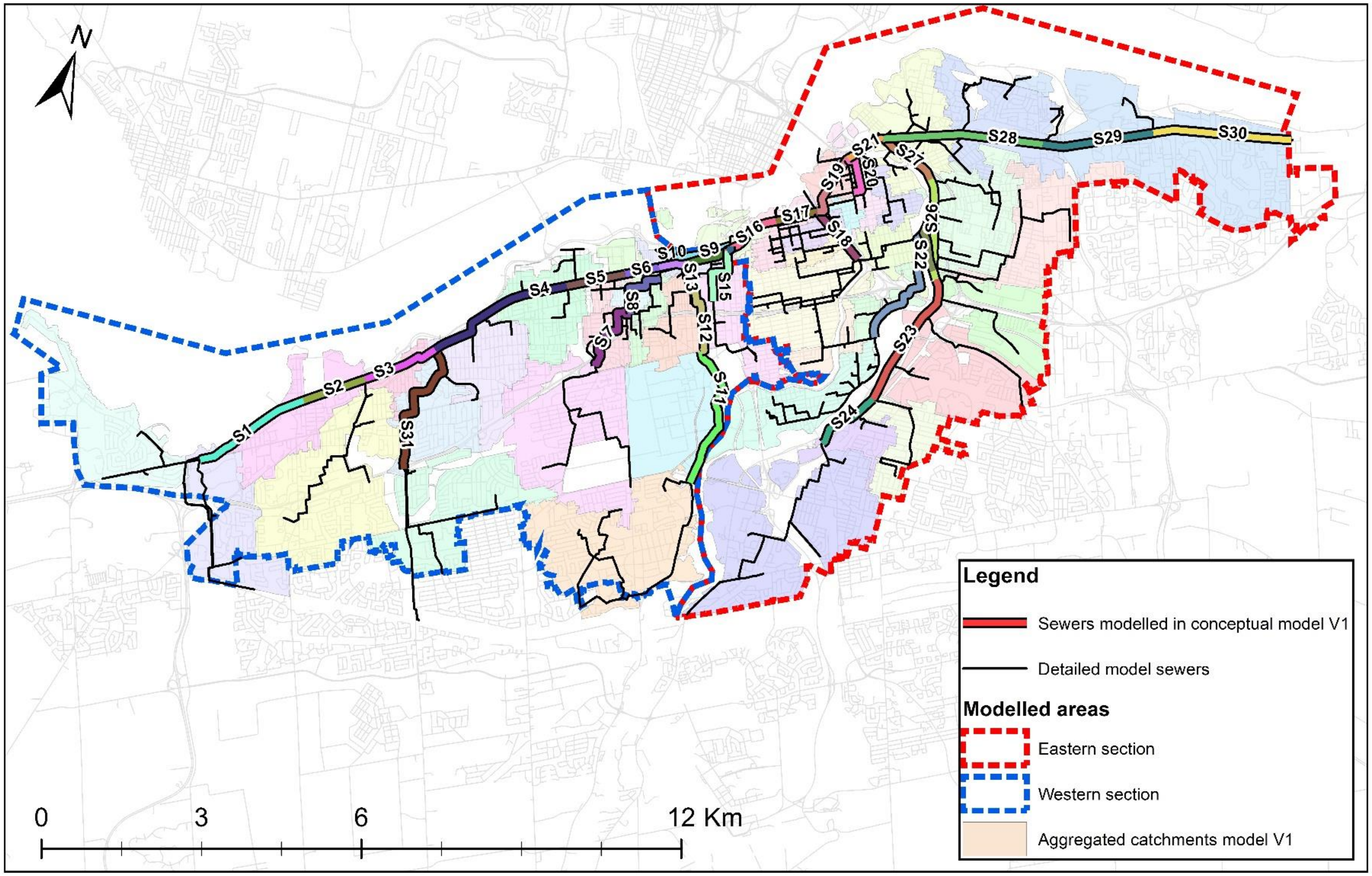

Figure 26: Modelled sewers in conceptual model V1 of Ottawa case study area

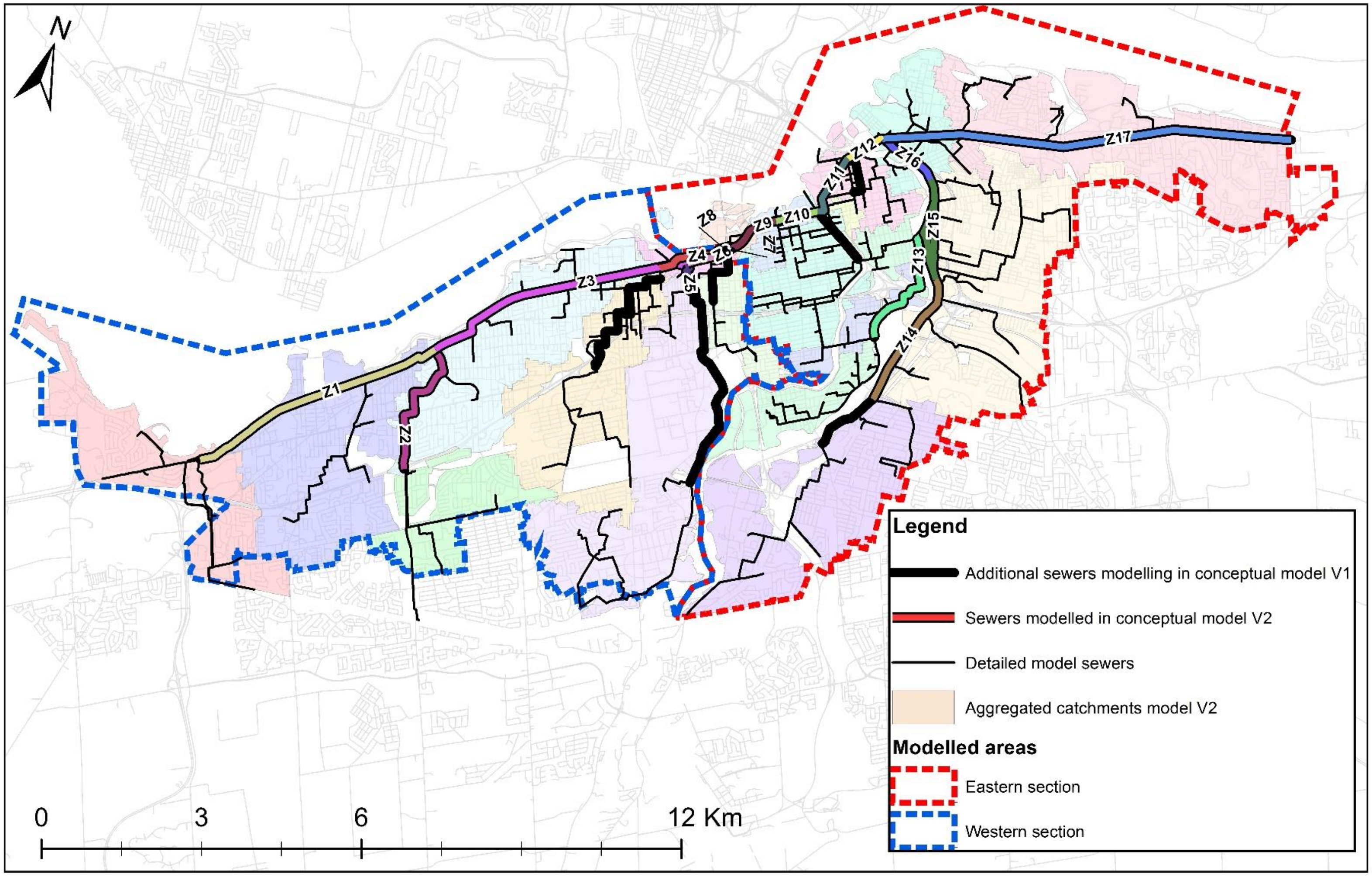

Figure 27: Modelled sewers in conceptual model V2 of Ottawa case study area

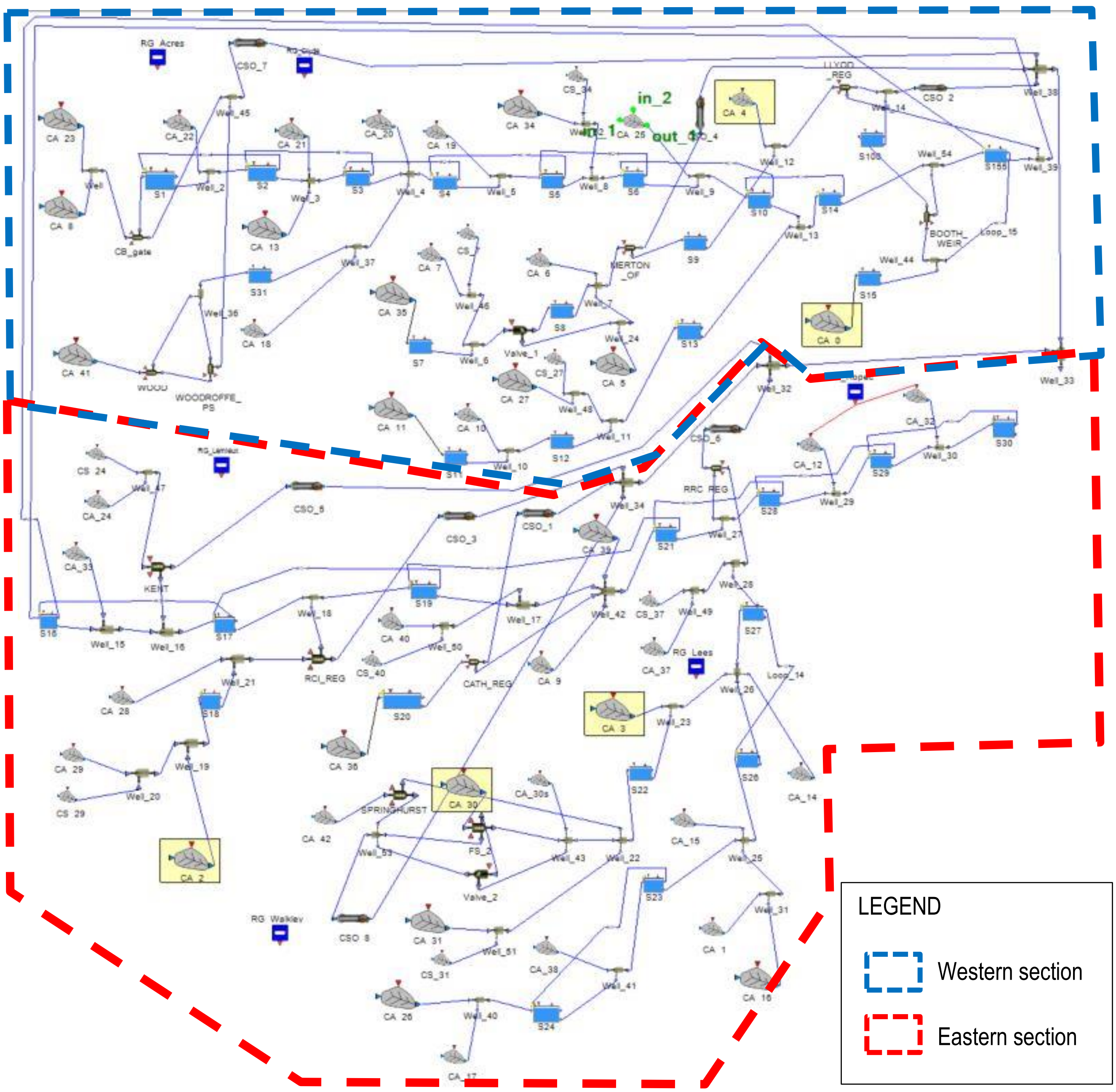

Figure 28: WEST Model V1 configuration, excluding associated raingauges

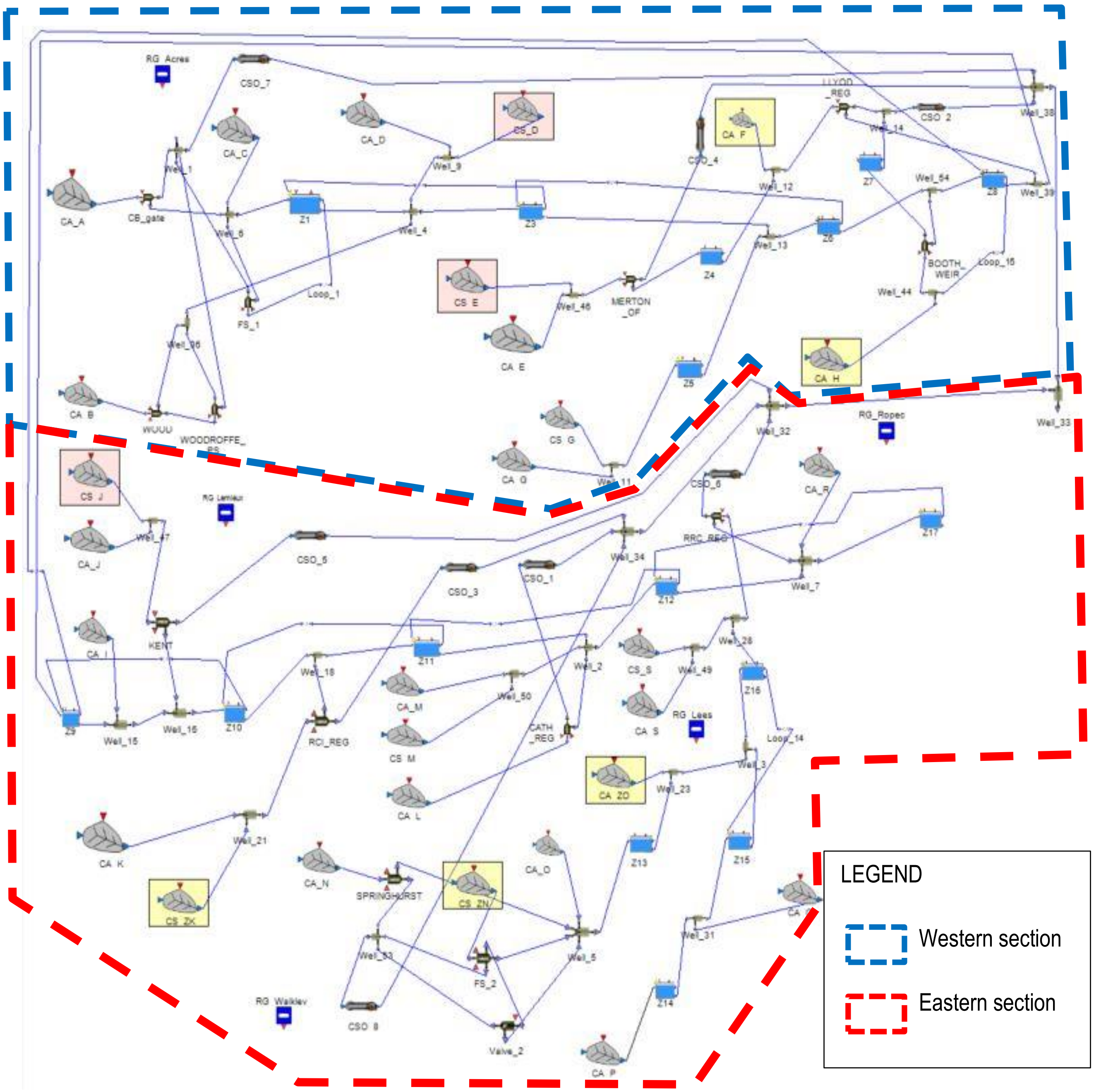

Figure 29: Model V2 configuration, excluding associated raingauges

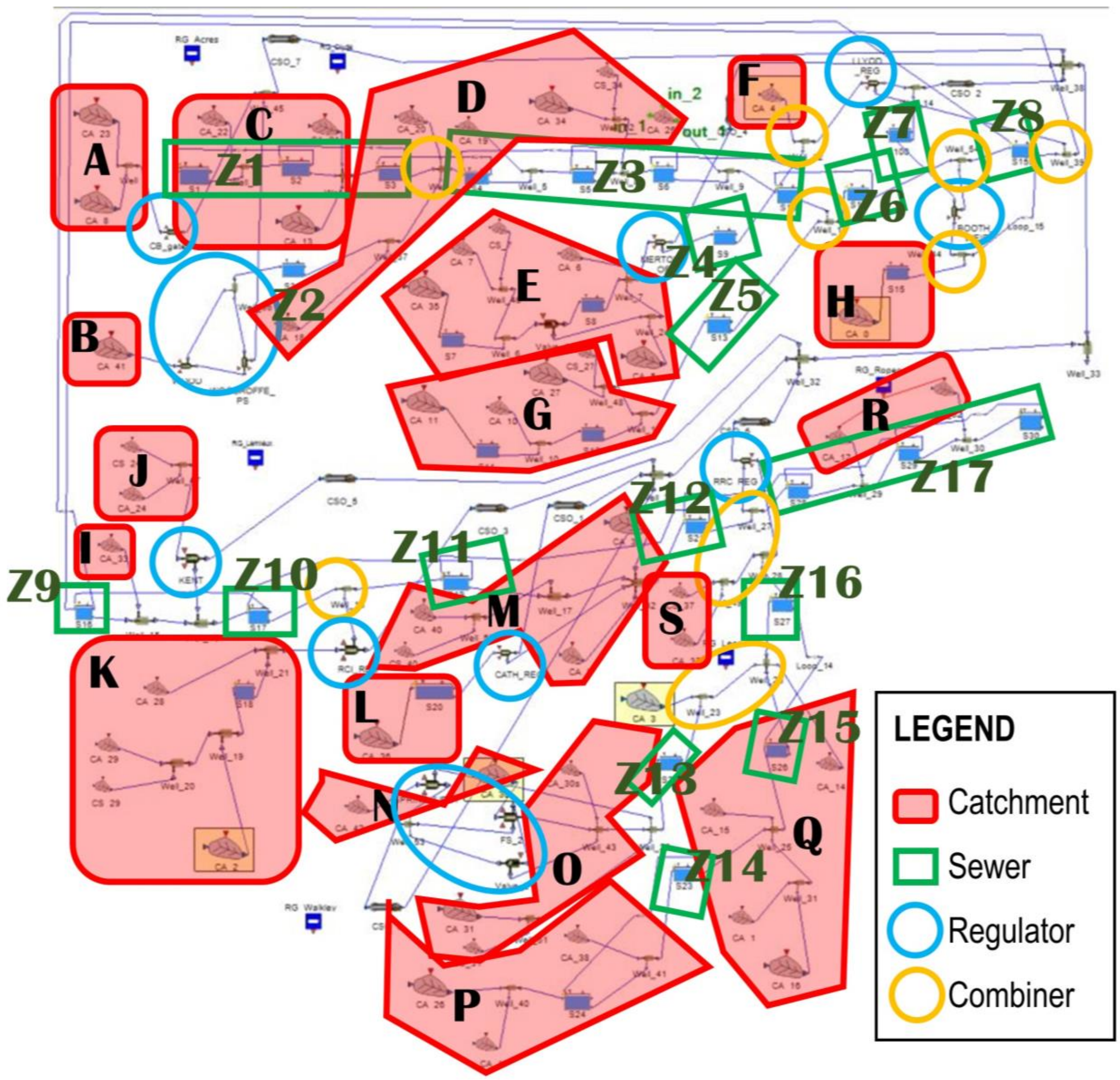

Figure 30: Aggregation planning for development of conceptual Model V2

6.3.6 Initialization of catchment parameters

The catchments were initially parameterized by aggregating the detailed model parameters or applying default values. All catchment parameter values were tracked in tabular format (see Appendix C). Many of the pre-selected parameter values were later modified in the calibration phase.

6.3.6.1 Dry weather flow

The following detailed model parameters were summed or averaged over the aggregated catchments to determine their value:

- Area, summed
- Effective area (defined as the flow-generating area), summed; applied to TotalArea in lumped model
- Population and employees, summed; applied to Inhabitant Equivalents (IE) in lumped model
- Residential and Institutional/Commercial flows, summed; averaged generation rates applied to WastewaterPerIE in lumped model
- Baseflow, averaged over effective area; applied to Infiltration in lumped model

Two basic DWF diurnal patterns were created for the lumped model: one for residential (RES) users and the other for institutional and commercial (IC) users. (Note that in this case study, there are no major industrial users in central Ottawa, therefore this type of generator was ignored.) These two basic patterns were combined based on specific percentages of each type of flow. Five patterns were created by a weighted-sum of the two basic patterns with the specific weights defined below:

- 15% RES, 85% IC; applied to 0-30% RES
- 40% RES, 60% IC; applied to 30-50% RES
- 60% RES, 40% IC; applied to 50-70% RES
- 78% RES, 22% IC; applied to 70-85% RES
- 97% RES, 3% IC; applied to 85-100% RES*

*Note: Because many catchments had a RES makeup close to 100%, this pattern is made up of 97% RES.

The ratio of the RES and IC flow in the aggregated detailed catchments determined which specific convoluted DWF pattern was applied in the lumped models (Figure 31) (note that these patterns are the final calibrated diurnal patterns). The diurnal pattern with the closest makeup of flows was selected as the initial pattern, and the selection of pattern was later modified in the calibration phase.

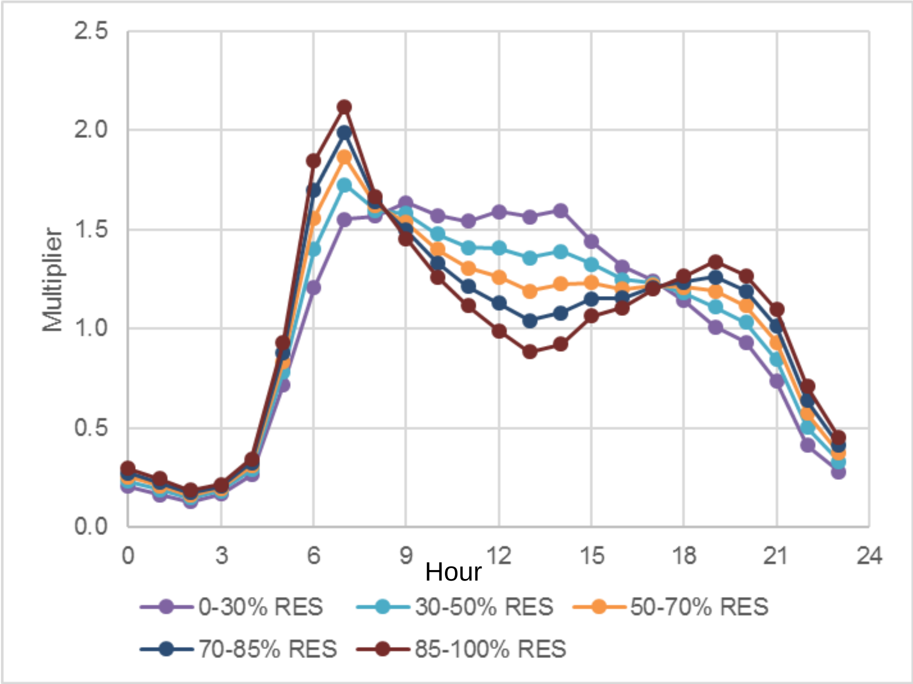

Figure 31: DWF patterns applied in conceptual models

A monthly baseflow pattern was not applied to the conceptual model, because none was applied in the detailed model. Applying a pattern to both models would not change the overall comparative performance of either model.

6.3.6.2 Wet weather flow

As described in the proposed procedure, there is no defining formula to translate the imperviousness, represented by the R value in PCSWMM, from detailed catchments to lumped catchments. This value was therefore first estimated by taking a weighted-area average of the sum of the R values from the RTKs, and later calibrated.

The standard default values that were assigned in the PCSWMM model for the following parameters were also assigned to the conceptual model:

- Max depression storage, City of Ottawa default value
- Max wetting losses, City of Ottawa default value
- Yearly evaporation, WEST default value (this parameter is non-existent in PCSWMM model)

The WWF routing parameters in the conceptual model are defined by the number of linear reservoirs (n) and their hydraulic retention times (k), as well the f_fast parameter that defines the fraction of the total flow routed by the “fast” series of linear reservoirs, as described in Section 4.1. Because the three triangles from the RTK method from the detailed model could be represented by two hydrographs in WEST, as described in Section 4.1.3, the medium triangle component was either added to the fast or slow component or divided between the two, depending on which triangle it most resembled. As such, the initial f_fast parameter was calculated using either the R_{fast} value or adding all or part of the R_{medium} value to the R_{fast} value, depending on the above decision.

6.3.7 Initialization of sewer parameters

Based on his extensive experience using KOSIM-WEST, Lorenzo Benedetti (personal communication) suggested representing pipes that saw backwater conditions in the detailed model by linear reservoirs, and the other pipes with non-linear model. This method resulted in the representation of the main collector sewer segments along the West Nepean Collector and IOS with linear reservoirs, while the smaller collectors were modelled using non-linear reservoirs.

The main sewer sections in the detailed model were labelled and extracted to a spreadsheet to determine their defining characteristics. Length-weighted averages were calculated for the sewer segment diameter, slope and roughness. The flow capacity of the resultant pipe was estimated using the calculated characteristics. Although Section 2.2.4 showed various ways to consider the appropriate sewer characteristics, the catchments and sewers were delineated in such a way that the entire sewer segment could be considered for representation in the model. The Kalinin-Miljukov method was then used to calculate the required parameters for the linear reservoirs (n, k) using the average pipe values, while these average pipe characteristics were used for the non-linear reservoirs. The backflow limiter parameter (Q_{back}) was initially estimated using the pipe capacity. All sewer parameter values, including the type of conceptual model applied, were tracked in tabular format (see Appendix C).

6.3.8 Representing the special structures

In this case study, all special structures represented in the model could be modelled by simple flow splitters, or a combination of several splitters. The identified structures, and their assigned characteristics, were tracked in a table (Appendix C). As the calibration proceeded, several structures were modified to better reflect the detailed model results. This method resulted in oversimplified representations of the special structures; however, because these structures were also somewhat simplified in the detailed model, this method was assumed to represent the flows sufficiently well. For a project that required a greater emphasis on RTC structures, a more detailed or specific representation of such structures would be warranted. However, these structures and their process control rules were not the focus of the project, hence their oversimplified representation was deemed appropriate.

6.4 Calibration

A manual manipulation of parameter values was used to calibrate the conceptual model. The following sections review the calibration of the case study's models. All calibration efforts were tracked in appropriate tables, available in Appendix D, and are described below. The calibration results are found in Chapter 7.

6.4.1 Calibration approach

6.4.1.1 Calibration runs and modifiable parameters

The calibration strategy for the case study involved using multiple runs, each designed to sequentially calibrate specific parameters. First, the models were run under DWF conditions, in which volume parameters, followed by dynamic parameters, were calibrated. Second, a small 2-hour block storm (10 mm/hr), which did not cause any backflow conditions in the detailed model, was applied to all raingauges and used to first calibrate the RDII volume produced from the catchments and calibrate the dynamics of the flow. Naturally, because the dynamics of the RDII hydrographs affect the RDII volumes themselves, the volume parameters were slightly tweaked in the second run, as needed. The third set of calibration runs used a larger 2-hour block storm (20 mm/hr) for all raingauges, which caused backwater conditions in a significant part of the detailed model, without causing flooding. Because the conceptual model is focused on typical conditions without overflows and is not specifically intended to model flooding conditions but should represent backwater, this size of storm is perfect for calibrating the model.

Normally a longer time series with varying rainfall is used to calibrate the model as a whole. This includes monthly patterns and parameters that affect flow in the long run (e.g. monthly baseflow pattern, evaporation, maximum and initial infiltration capacities, Horton's regression constants, etc.); however, due to time limitations, these values and patterns were not calibrated. Instead, a longer time series was only used to validate the model and confirm the calibrated values. The model validation is discussed in Section 6.5.

The two above-described synthetic 2hr block storms were used to calibrate the model. Ideally, realistic events would have been used in conjunction with the block storm, and different rainfall patterns would have been assigned to each raingauge to prove the effect of rainfall variability; however, as previously mentioned, time was a limiting factor.

The pre-selected calibration parameters for each run are described in Sections 6.4.2 and 6.4.3. Pre-selecting these parameters simplified and structured the calibration process.

6.4.1.2 Calibration order

All catchments, sewers and special structures were assigned a calibration order. This order was used within each calibration run to ensure that upstream components were first calibrated before any downstream components. Figure 32 shows an example of this calibration numbering scheme for the conceptual model V2.

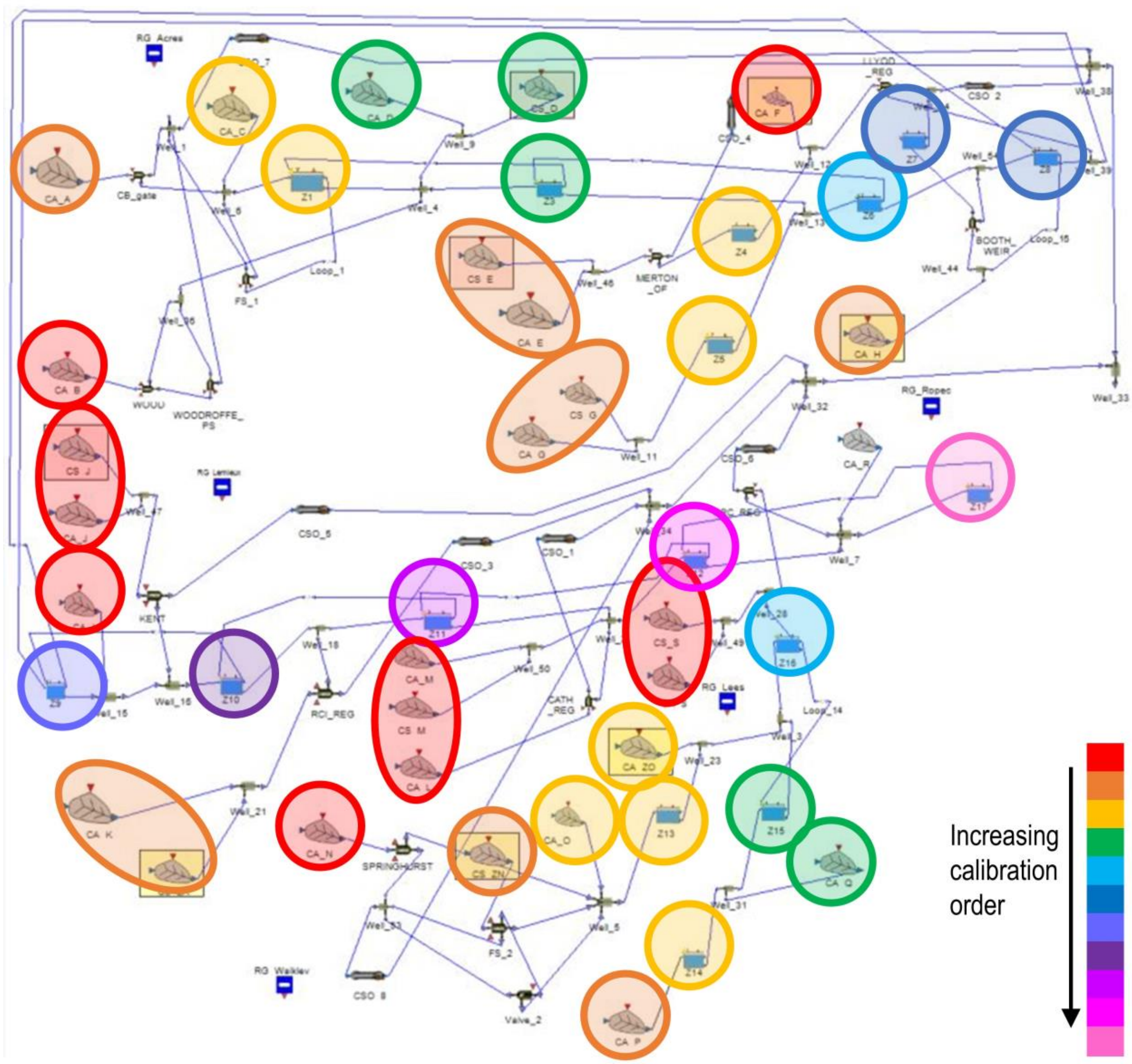

Figure 32: Calibration order numbering scheme example for V2 model

6.4.1.3 Calibration criteria

Simulated and reference hydrographs were visually checked during the manual calibration process. The three main criteria indicators introduced in Section 5.4.1.3 (percent volume error (PVE), Nash-Sutcliffe (NSE) coefficient, percent error in peaks (PEP)) were calculated for the final calibration to ensure a desired fit was achieved.

6.4.2 Dry weather flow

A description of the DWF calibration is provided below, while the actual results of the calibration are found in Chapter 7.

6.4.2.1 DWF Volume

The DWF volume was first calibrated by adjusting the sewage generation rates, and then the baseflow values, where necessary. As explained in Section 6.2.2.2, there were known issues with the loaded IC generation rates in the detailed model, therefore the combined generation parameter (WastewaterPerIE) was the prime candidate for adjustment during calibration. The baseflow value was already calibrated in the detailed model; therefore, because this parameter is the same in both the detailed and conceptual models, this value was kept untouched. The Q_industry parameter, which represents a constant flow from institutional, commercial or industrial sources, was then added and modified if the generic generation rate could not account for the differences between the conceptual and detailed model results. Only in situations where the generation rate and the additional constant inflow rate could not be modified to calibrate hydrographs (e.g. negative values would be required) was the baseflow slightly adjusted (generally reduced).

6.4.2.2 DWF dynamics

Initially, the two base diurnal patterns (RES and IC) were slightly modified to ensure that the convoluted patterns could be successfully applied to the catchments. Calibration of the DWF dynamics was then achieved by simultaneously revising three parameters:

1. The selection of the specific diurnal patterns
2. The number of linear reservoirs (n)
3. The overall hydraulic residence time of the linear reservoirs (k)

In general, the selected diurnal pattern was responsible for the overall shape of the response. The parameters related to the linear reservoirs, namely the number of linear reservoirs and their overall hydraulic residence time, provided a means to shift the timing of the response and spread out the hydrograph. Increasing the residence time spread out the dynamic response and delayed the peak, while more linear reservoirs resulted in a more compact but peakier response. By changing these three parameters, most DWF responses of the detailed model could be accurately represented.

6.4.3 Wet weather flow

As described in the Calibration approach (Section 6.4.1), a small block storm (10 mm/hr for 2 hours) was used to calibrate the catchment RDII volume and dynamic parameters. A larger storm (20 mm/hr for 2 hours) was then applied to calibrate the backwater dynamics.

Before beginning either WWF calibration runs, the conceptual model parameters that were estimated in Section 6.3.6 were first adjusted by comparing the resultant curve from the detailed model RTKs to the summed fast and slow linear reservoirs in an Excel graph (as explained in Section 4.1.3.1). This Excel graph-fitting technique allowed the f_fast, n and k parameters to be adjusted until a visual fit between the two curves was achieved. It should be noted that most catchments in the conceptual model were made up of multiple catchments each with their own RTKs from the detailed model. This curve-fitting method therefore only provided an alternate method to estimate the initial conceptual catchment model parameters.

6.4.3.1 WWF volume

The runoff coefficient parameters in KOSIM-WEST conceptual model were first calibrated using the smaller storm, and then checked using the larger storm. This parameter controls the volume of water that enters the collection system. The internal calibration order was used to adjust the runoff coefficient of catchments in the defined order. These changes were tracked using a table, found in Appendix D.

6.4.3.2 WWF dynamics

The shape of the RDII response from catchments, and hence the routing of flow over the surface and through the local sewers, was calibrated by adjusting the default f_fast, n and k values. As described in Section 4.1, specific permutations of linear reservoirs were made, therefore adjusting the n value for either fast or slow RDII responses was done by selecting one of the pre-made combinations of linear reservoirs. Selecting a higher number of linear reservoirs resulted in a more compact, peakier response, whereas the residence time was responsible for delaying the peak and spreading out the hydrograph.

Catchment responses were verified and adjusted using the larger storm, however regulators and backwater sewer parameters were the focus of this calibration run. The initially estimated backflow limiter parameter (Q_{back}) was adjusted to reflect the maximum flow seen in the detailed model sewer stretches. As such, conceptual modelled resulted are not expected to have the exact same dynamics as the detailed model: the gradual increase to a peak flow seen in detailed models will look like a flow limited to a cut-off value in the conceptual model. If non-linear reservoirs were used to represent sections with backflow, this backflow limiter value would dynamically increase as surcharged pressurized pipes push more flow though (Kamradt, 2008). However, as described in Section 2.3.6.2, non-linear sewer models were only used for sewer sections without backflow in this project.

The regulators were calibrated by adjusting the configuration of combiners and splitters. The flow limiting values were extracted from the detailed model and modified in the conceptual model in the large storm calibration run, as required. To re-iterate, because this project did not focus on representing these regulators, most of them were simplified in the detailed model and further-simplified in the conceptual model. This simplification still allowed the demonstration of the modelling procedure developed in this project.

6.5 Validation

The pre-selected rainfall data set from 1980 introduced in Section 6.2.2 was used to validate the model's ability to perform under new conditions. The 47-day period from June 15th to July 31st (see Figure 33) was chosen because this period included many larger and differing storms. Five larger events were identified in the selected period (Figure 34) and used to evaluate the validation's performance criteria. The properties of these five events are summarized in Table 5, including the periods that were used for comparison for each event. The results of the validation are found in Chapter 7.

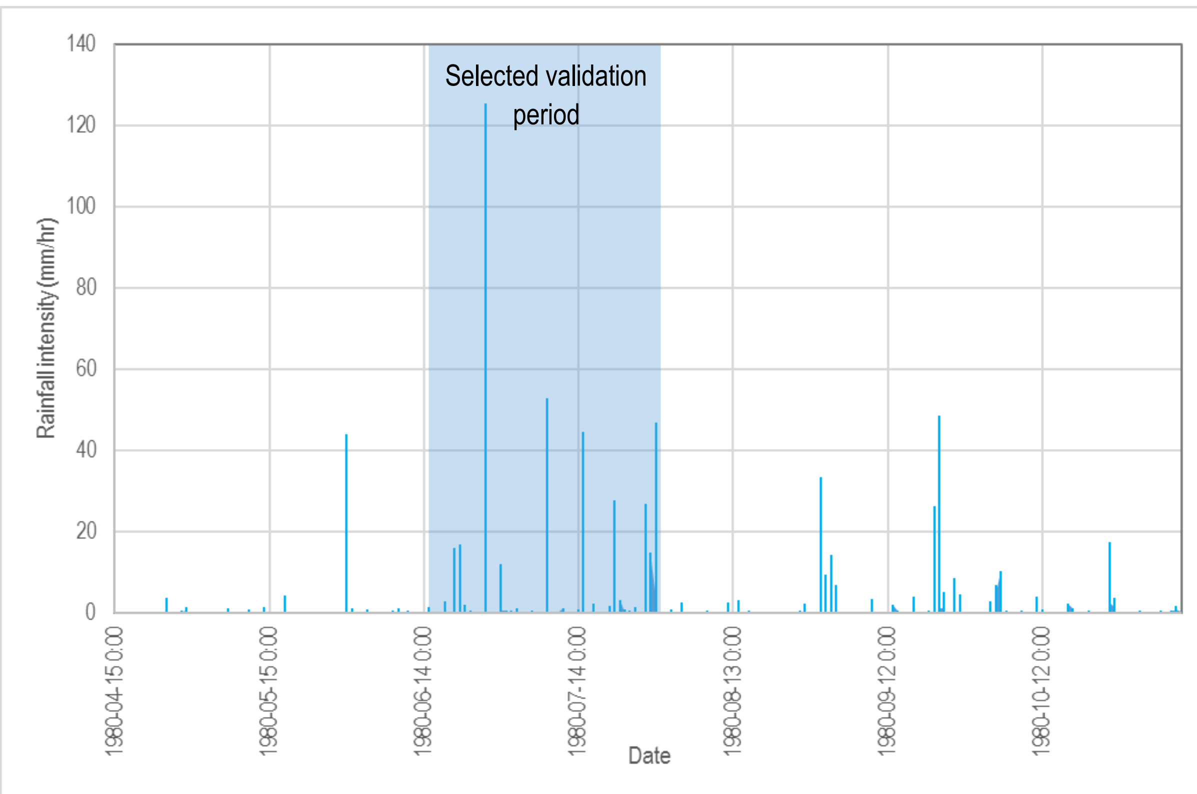

Figure 33: 6-months of 1980 rainfall data, with selected validation period (zoom of period found in Figure 34)

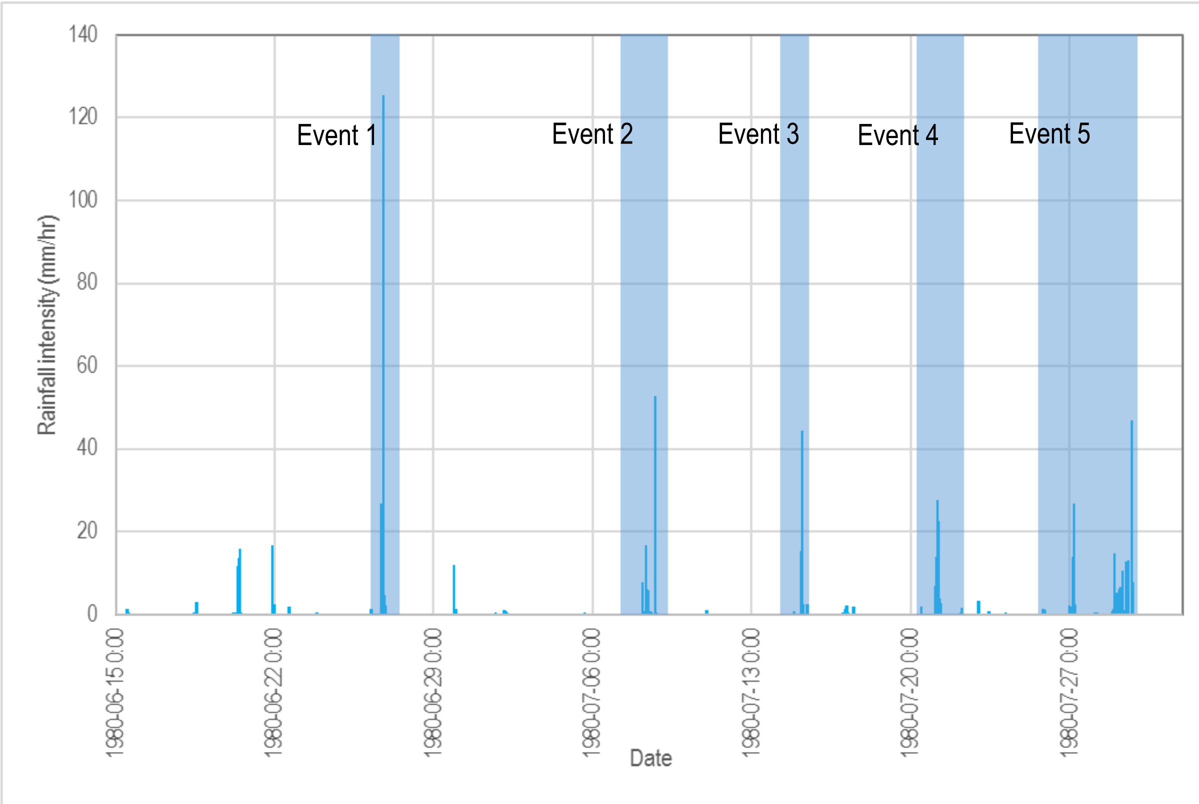

Figure 34: Selected validation period; 1980 rainfall data with highlighted events

Table 5: Selected validation events for comparison

Event	Rainfall period		Duration (hrs)	Total volume (mm)	1hr peak intensity (mm/hr)	Period used for validation comparison	
	Start	End				Start	End
1	1980-06-26 6:00	1980-06-27 7:50	26	27	14	1980-06-26	1980-06-29
2	1980-07-07 8:00	1980-07-09 8:00	48	29	12	1980-07-07	1980-07-11
3	1980-07-14 8:00	1980-07-15 10:55	27	21	13	1980-07-15	1980-07-19
4	1980-07-20 8:00	1980-07-22 7:45	48	21	9	1980-07-20	1980-07-24
5	1980-07-25 20:00	1980-07-30 7:45	108	49	9	1980-07-25	1980-08-01

Chapter 7 Model results & analysis

This chapter presents the results and an analysis of the model calibration and validation efforts. The comparison locations used are first presented followed by both graphical and tabular results of the DWF and WWF calibration, and the validation period. A summary of the impact of the level of aggregation of the V1 and V2 models follows.

7.1 Case study comparison locations

Locations along the trunk sewers that were equivalent in both V1 and V2 models were used to compare the conceptual and detailed model results (see Figure 35 and Figure 36). In the following sections, only results from a midpoint location and the most downstream location are shown as examples that demonstrate the goodness of fit achieved. The results from all equivalent locations are included in Appendix E.

7.2 Comparison graphs and criteria

The quality of the calibration and the validation achieved is determined visually by graphs and quantitatively by comparison against performance criteria.

Flow hydrographs from both conceptual models and the detailed model were compared on a single graph for the DWF and WWF calibration runs, and the validation run. One-to-one scatter plots were also created to visualize the overall differences in flows between the various locations. An error box plot was created for the final validation results to graphically depict the distribution of model differences.

As explained in the calibration approach and the project definition steps (Sections 5.4.1.3 and 6.2.1, respectively), specific performance criteria should be used to determine the acceptability of the calibration and validation to meet the model's objectives. The previously introduced criteria, namely the percent volume error (PVE), the percent error in peaks (PEP) and Nash-Sutcliffe coefficient (NSE), were calculated for all identified locations, and are presented in the following sections.

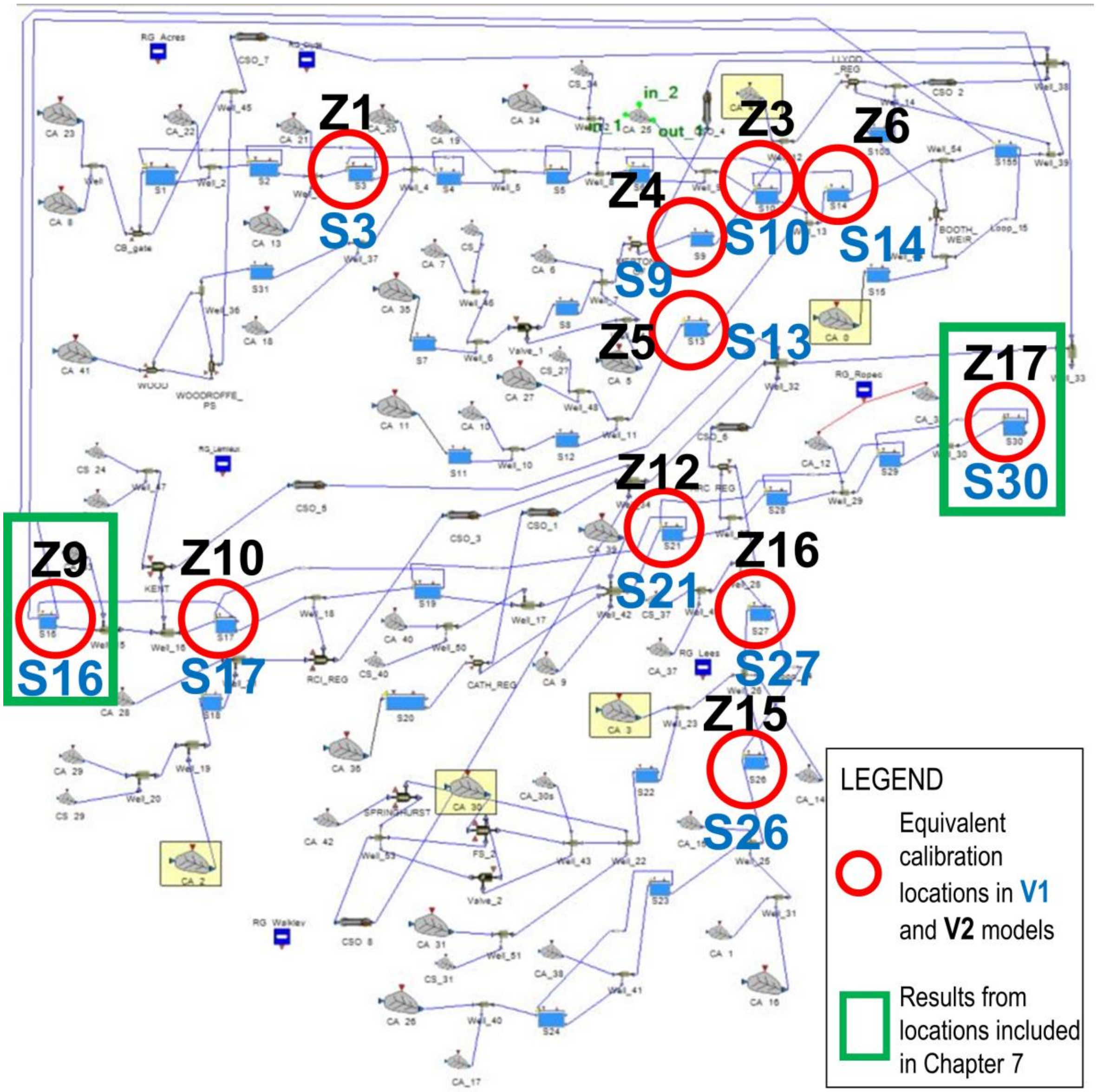

Figure 35: Conceptual Model V1 comparison locations (S), including equivalent link in V2 model (Z)

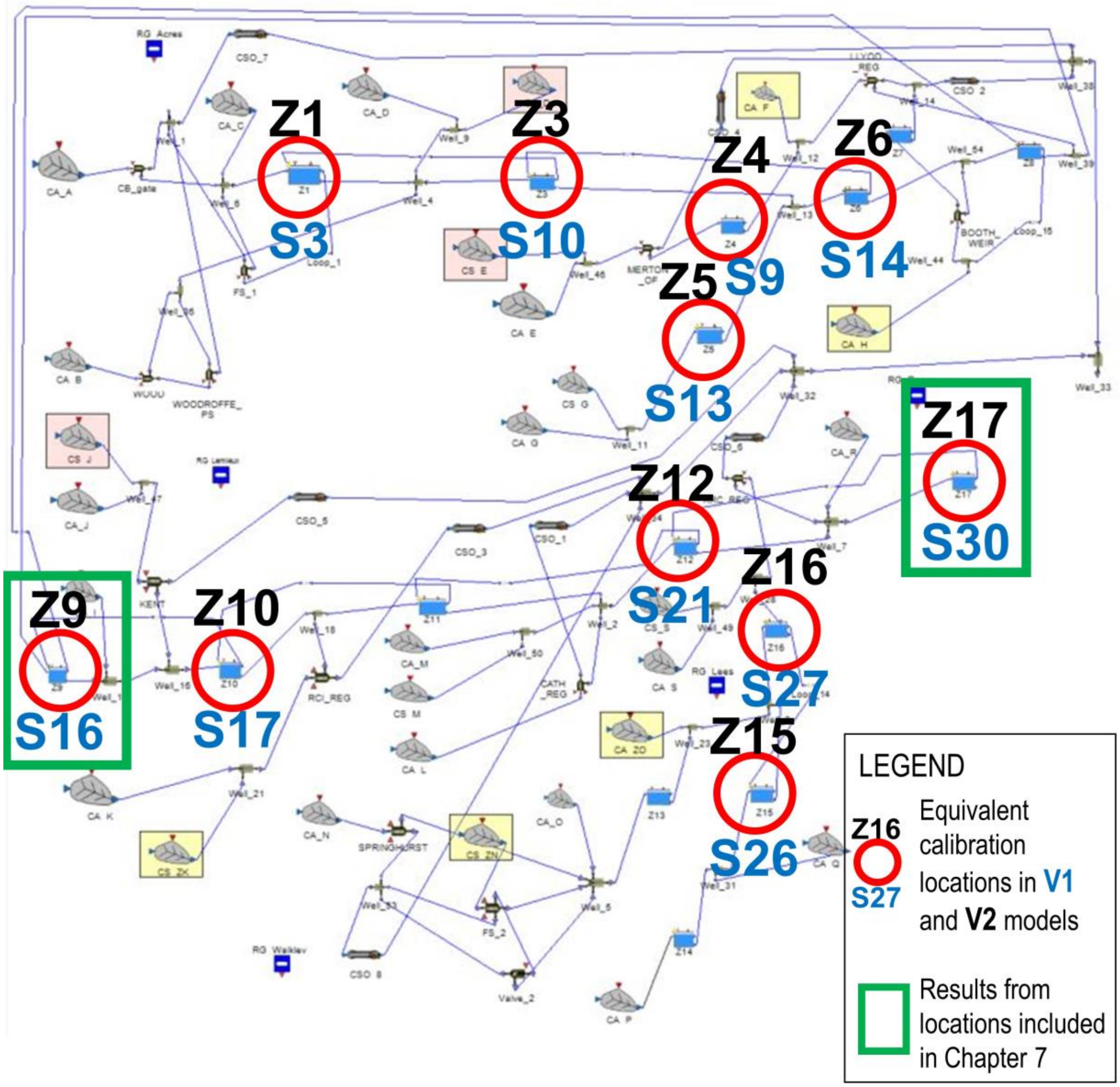

Figure 36: Conceptual Model V2 comparison locations (Z), including equivalent link in V1 model (S)

7.3 DWF results

The average DWF from all identified locations are plotted in the one-to one graph below (Figure 37). The flow from the detailed model is graphed on the x-axis and the conceptual model flows are found on the y-axis. This graph shows that the average DWF stays well within the 10% error lines for all comparison locations, indicating very good calibration results. Likewise, the hydrographs plotted in Figure 38 depict how closely both lumped models replicate the dynamics of the detailed models. Additional hydrographs for all locations are included in Appendix E. The three performance criteria for all locations were calculated and summarized in Table 6. The PEP and PVE values are both below 10%, while the NSE values are nearly 1. These values confirm the visually-determined good fit.

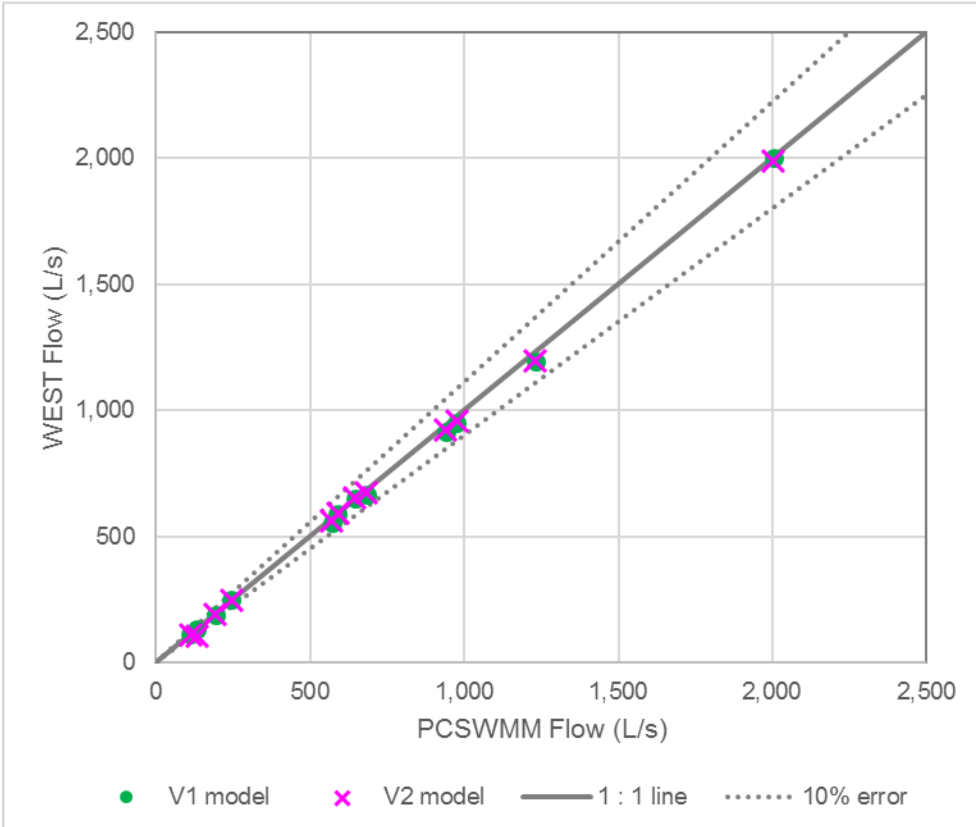

Figure 37: 1:1 average DWF plot: conceptual models vs. detailed model at all comparison locations

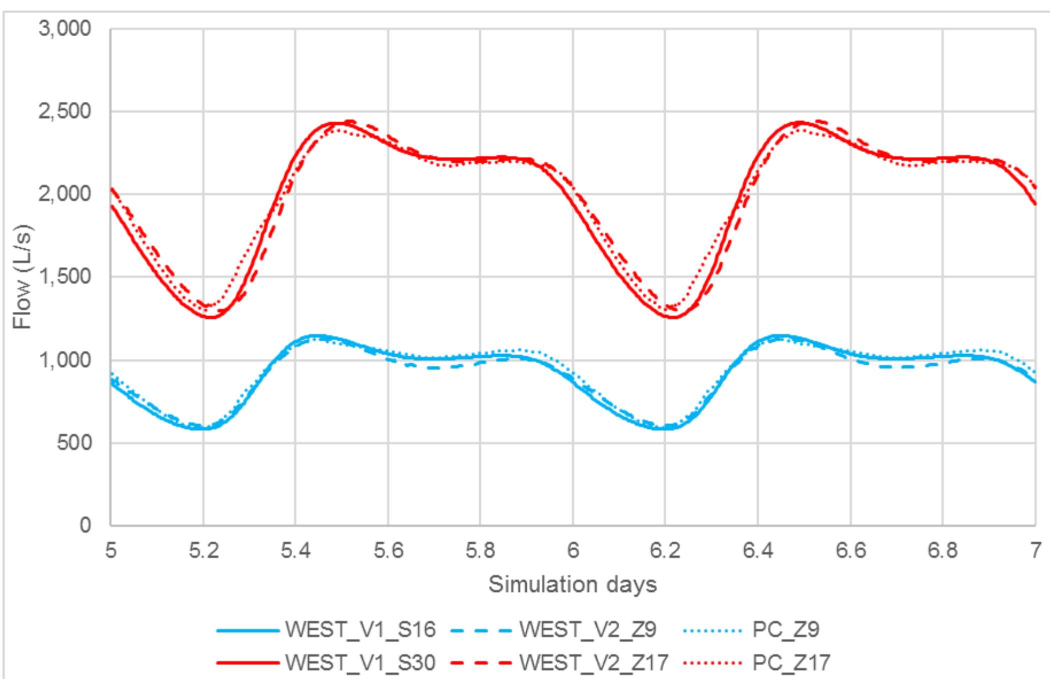

Figure 38: Sample DWF results at two selected locations (S16/Z9 and S30/Z17) for the detailed (PC) and both conceptual models (V1 and V2)

Table 6: DWF Calibration performance criteria (PC detailed model and V1 and V1 conceptual models)

Sewer link	Average flow (L/s)	Min flow (L/s)	Peak flow (L/s)	PVE (%)	PEP (%)	NSE
Z1						
PC	246	144	307			
V1	248	158	323	-1.1%	-5.0%	0.998
V2	248	160	325	-1.1%	-5.8%	0.996
Z3						
PC	570	377	683			
V1	561	372	689	1.7%	-0.9%	0.999
V2	555	379	694	2.6%	-1.7%	0.996
Z4						
PC	192	104	273			
V1	191	109	274	0.5%	-0.6%	0.995
V2	190	109	271	1.4%	0.4%	0.995
Z5						
PC	112	59	146			
V1	111	60	151	0.9%	-3.0%	0.996
V2	111	64	146	0.9%	0.3%	0.997
Z6						
PC	683	438	825			
V1	672	433	837	1.5%	-1.4%	0.999
V2	667	445	831	2.4%	-0.7%	0.997
Z9						
PC	939	591	1,124			
V1	921	581	1,147	2.0%	-2.1%	0.998
V2	913	604	1,127	2.8%	-0.3%	0.997
Z10						
PC	977	615	1,171			
V1	956	596	1,194	2.1%	-1.9%	0.998
V2	949	620	1,178	2.8%	-0.6%	0.997
Z12						
PC	1,230	753	1,499			
V1	1,198	724	1,504	2.6%	-0.3%	0.996
V2	1,194	749	1,495	2.9%	0.3%	0.996
Z15						
PC	590	395	741			
V1	594	386	723	-0.5%	2.5%	0.998
V2	591	382	725	-0.1%	2.2%	0.999
Z16						
PC	645	434	808			
V1	654	421	801	-1.4%	0.8%	0.998
V2	652	419	803	-1.0%	0.6%	0.999
Z17						
PC	2,004	1,301	2,388			
V1	1,988	1,257	2,434	0.8%	-2.0%	0.998
V2	2,003	1,298	2,444	0.1%	-2.4%	0.998

The slight differences in volume between the conceptual models and the detailed model could be attributed to imperfect calibration. The mostly positive PVE values in Table 6 confirm that the conceptual models slightly underestimate the flow. Although the DWF volumes could be better matched through additional calibration efforts, the low error in simulation results fell well within the sought goodness-of-fit. Similarly, the differences in DWF dynamics are minimal and therefore acceptable; however, if required, it could be slightly improved through additional calibration. The mostly negative PEP values in Table 6 are due to the slightly higher peaks in the conceptual model results compared to those of the detailed model. Nevertheless, it should be noted, that due to the structure of the catchment's DWF model code, in which a specific number of linear reservoirs and pre-defined diurnal patterns are established, only incremental changes to the dynamics can be achieved. Nonetheless, due to the varied and stochastic dynamics that are generally seen in actual sewer systems, a perfect match in flows or dynamics is not warranted.

The results of both the V1 and V2 models are of similar quality. Slight differences in hydrographs are simply attributed to manual calibrations of parameter values. In addition, because the V2 model was created based on the calibrated V1 model, it is possible that some parameters were essentially further and better calibrated compared to the V1 model. As such, the marginally better or worse fit of the V2 model cannot be attributed to the further aggregation of the catchments and sewers.

7.4 WWF results

The WWF results from the larger block storm are assessed in this section. The 3-day WWF volumes at all locations are compared in Figure 39. The simulation results from both conceptual models show that the overall error is less than 10% for all locations. Figure 40 depicts sample hydrographs, which shows an overall good fit for both volume and dynamics. The plateau that occurs in the conceptual model graphs around day 5.1 is a result of the upstream overflow control structures, represented by absolute splitters that send flow above a certain limit directly to the overflow. Appendix E contains additional flow hydrographs for the sewer locations, a few sample catchments, the regulators, and the overflow locations. The performance criteria for all sewer locations are tabulated in Table 7. The PEP and PVE values are below 10%, and most of the NSE values are again very close to 1.

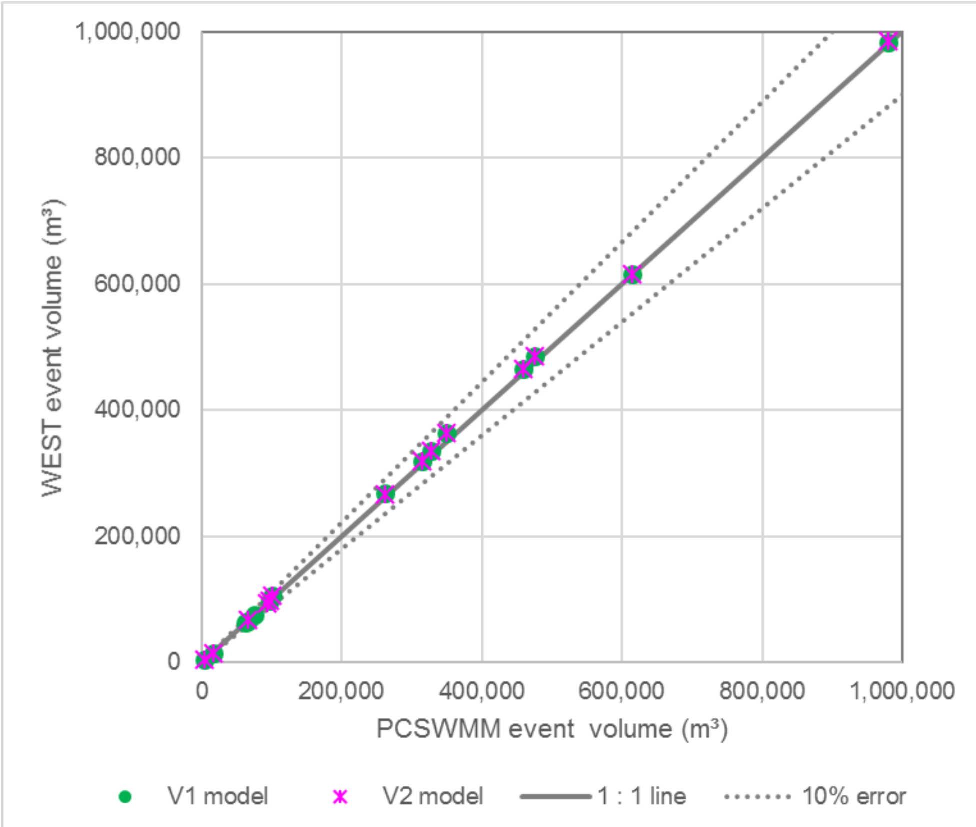

Figure 39: 1:1 total WWF 3-day volume plot: conceptual models vs detailed model at all comparison locations

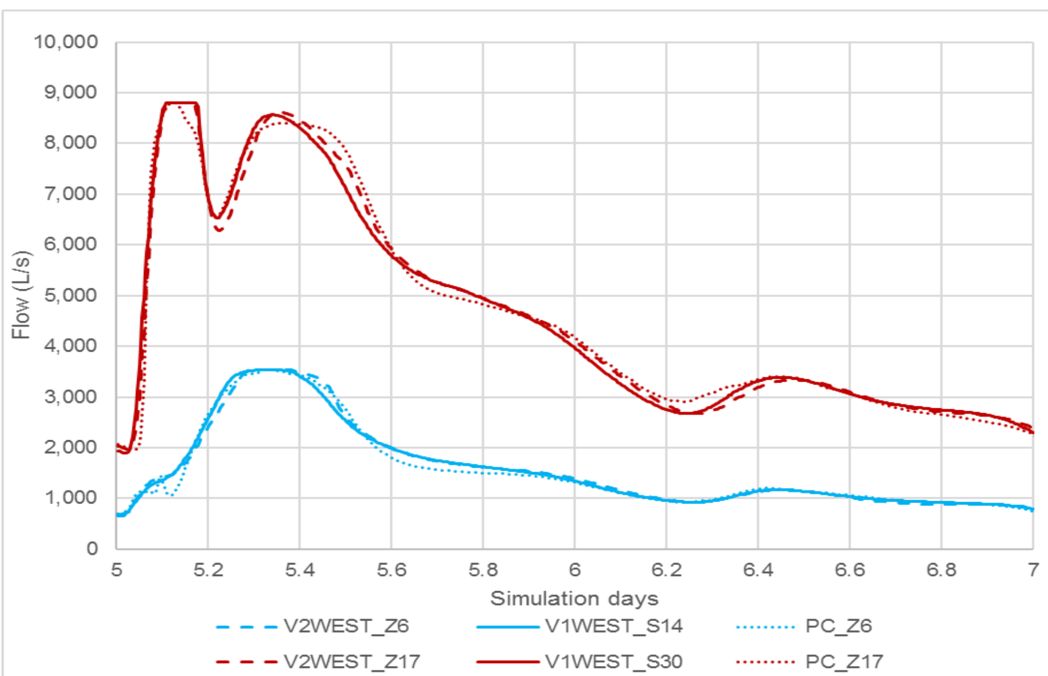

Figure 40: WWF sample flow results at two selected locations (S16/Z9 and S30/Z17) for the detailed (PC) and both conceptual models (V1 and V2)

Table 7: WWF Calibration performance criteria (PC detailed model, and V1 and V1 conceptual models)

Sewer link	3-day volume (10^3 m3)	Min flow (L/s)	Peak flow (L/s)	PVE (%)	PEP (%)	NSE
Z1						
PC	101	145	1,080			
V1	107	177	1,080	-5.6%	0.0%	0.97
V2	106	168	1,080	-4.3%	0.0%	0.97
Z3						
PC	261	390	2,738			
V1	268	442	2,738	-2.8%	0.0%	0.99
V2	268	440	2,738	-2.4%	0.0%	0.99
Z4						
PC	98	104	1,239			
V1	98	130	1,167	0.6%	5.8%	0.96
V2	99	131	1,231	-0.8%	0.6%	0.97
Z5						
PC	67	59	805			
V1	66	78	808	0.4%	-0.3%	0.97
V2	68	83	852	-2.4%	-5.8%	0.98
Z6						
PC	328	450	3,539			
V1	335	521	3,539	-2.1%	0.0%	0.99
V2	335	523	3,539	-2.3%	0.0%	0.99
Z9						
PC	459	603	4,708			
V1	466	701	4,729	-1.6%	-0.4%	0.91
V2	467	710	4,643	-1.7%	1.4%	0.95
Z10						
PC	475	628	4,880			
V1	486	722	4,880	-2.4%	0.0%	0.89
V2	486	731	4,880	-2.4%	0.0%	0.92
Z12						
PC	615	769	6,910			
V1	615	873	6,936	-0.1%	-0.4%	0.96
V2	615	873	6,936	-0.1%	-0.4%	0.98
Z15						
PC	314	395	3,684			
V1	320	432	3,779	-1.8%	-2.6%	0.99
V2	319	429	3,711	-1.3%	-0.7%	0.99
Z16						
PC	349	434	4,104			
V1	365	490	4,404	-4.6%	-7.3%	0.98
V2	363	489	4,272	-4.2%	-4.1%	0.99
Z17						
PC	979	1,345	8,801			
V1	984	1,502	8,801	-0.5%	0.0%	0.99
V2	986	1,513	8,801	-0.7%	0.0%	0.99

Calibrating the WWF parameters is more difficult than the DWF parameters because more complex phenomena are being represented and it involves more parameters. In addition, the regulators, overflows and backwater effects are engaged under high-flow conditions, adding an additional level of calibration complexity. Additionally, the more simplified representation of the regulators and the overflows in the conceptual model introduce known errors at these and at subsequent downstream locations. As such, the quality of the results is expected to be inferior to that of the DWF calibration.

The differences in the flow hydrographs found in Appendix E, which are still within the selected criteria, are highest at locations downstream of regulators and overflows (e.g. Z7, which is downstream of the Booth regulator). Otherwise, differences in WWF can be attributed to the calibration of the catchments' RDII response (imperviousness, and fast and slow linear reservoir characteristics). As described in the DWF results section, a lengthier calibration could have improved results slightly. However, because the number of WWF linear reservoirs are also only defined in specific increments, a perfect match in dynamics is not necessarily achievable. In addition, an exact match in results for one specific storm is not desired, for the dynamics of the system change with varied and subsequent storm events. As described above, many of the differences are also attributed to the further simplifiedrepresentation of the regulators and overflows. This results in flow diversions that are both off-timed and different in volume compared to the detailed model. However, given the reduction in complexity in the conceptual model, the conceptual models' overall ability to reproduce representative flow dynamics is very good.

As explained in the DWF results section, no clear conclusions could be drawn about the differences in results between the V1 and V2 models.

7.5 Validation results

The results from the validation run using the 47-day time series were assessed to determine the conceptual models' ability to perform over a long-time period and under new conditions. The first 5 days were used to initialize the model, while the remaining 42 days were used to evaluate the validation. As previously mentioned, a longer time series was not used in the calibration; it was only used to validate the model and verify the calibrated values. Poorer results are expected compared to those achieved in the DWF and WWF calibration because the conceptual models were not calibrated using longer time series.

The 42-day total volume at all locations are compared in the one-to-one graph in Figure 41. The simulation results from both conceptual models show that the overall error is less than 10% for all locations, however on average, the conceptual models produced higher flows and provide for a slightly more conservative result.

Note that the simulation days in WEST (day 0 – 47) begin at the start of the validation period (June 15th, 1980), and the selected validation events' simulation days used in WEST (and on the hydrographs) are summarized in Table 8.

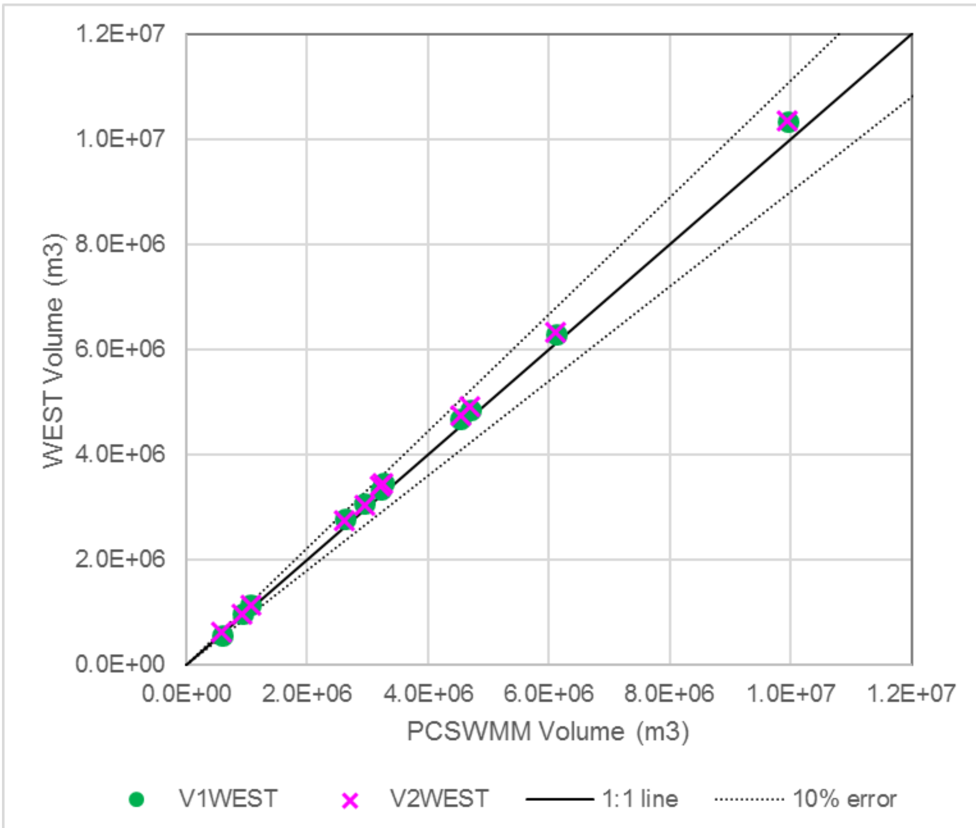

Figure 41: 1:1 total WWF 42-day volume plot: conceptual model vs detailed model at all comparison locations

Table 8: Validation events; periods expressed as days

Event	Period used to verify validation in WEST		Period (in days) used to verify validation in WEST, as displayed on graphs	
	Start	End	Start	End
1	1980-06-26	1980-06-29	11	14
2	1980-07-07	1980-07-11	22	26
3	1980-07-15	1980-07-19	30	34
4	1980-07-20	1980-07-24	35	39
5	1980-07-25	1980-08-01	40	47

Sample hydrographs for the two selected locations are shown in Figure 42. This figure demonstrates the ability of the conceptual model to behave similarly to the detailed model. Appendix E contains similar hydrographs for all sewer and overflow locations. The overall performance criteria for these locations are tabulated in Table 9, and Table 10 contains the criteria for Event 1. Appendix F contains similar tables for the remaining four events. The overall performance criteria give an indication of the model's ability to mimic both dry and wet weather conditions, and the performance criteria for the events assess the models' performance under wet weather conditions.

Box plots of the differences between detailed and conceptual lumped models at each time step (using 5% and 95% percentiles for the boxes) were created for both conceptual models (Figure 44 and Figure 45). These graphs demonstrate that most (90%) of the simulation differences are below 20%.

For the performance criteria, the PVE values are below 10%, and most of the NSE values are above 0.8, and close to 0.9. The box plots reveal that, in general, both conceptual model results show larger negative errors, meaning that the detailed model simulation results are less than the conceptual models'. Some of the box plot whiskers, and the PEP values, may appear to be rather large, however many of these are due to slightly mistimed peaks or instabilities in the detailed model (some examples are circled on Figure 42).

The general trend in the differences can be explained by multiple factors. Firstly, the calibration efforts focused on matching the imperviousness and catchment routing dynamics, without editing the evaporation and loss values. The detailed model specifies initial abstractions associated with the RTK unit hydrographs. Because these parameters are not directly related to those found in the detailed model, the estimated losses and evaporation values are potentiallynot representative. Secondly, because the conceptual model results are being compared to those of the detailed model, the latter's limitations also effect the comparison results. More specifically, the detailed model RDII is represented using the tri-triangular RTK method. In this method, the tail of the unit hydrographs end abruptly at the end of the triangle unlike the gradually decreasing tails in the linear-reservoir method, or as expected in reality (see Figure 46). Over a longer storm or time-period, the linear-reservoir method would thus produce more RDII than the RTK method. Another explanation is simply that calibrating the conceptual models using only block storms is inadequate, and hence the calibrated parameters would have had to be modified during a long-time series calibration. Finally, the simplified special structures could also account for the other errors seen during the validation period.

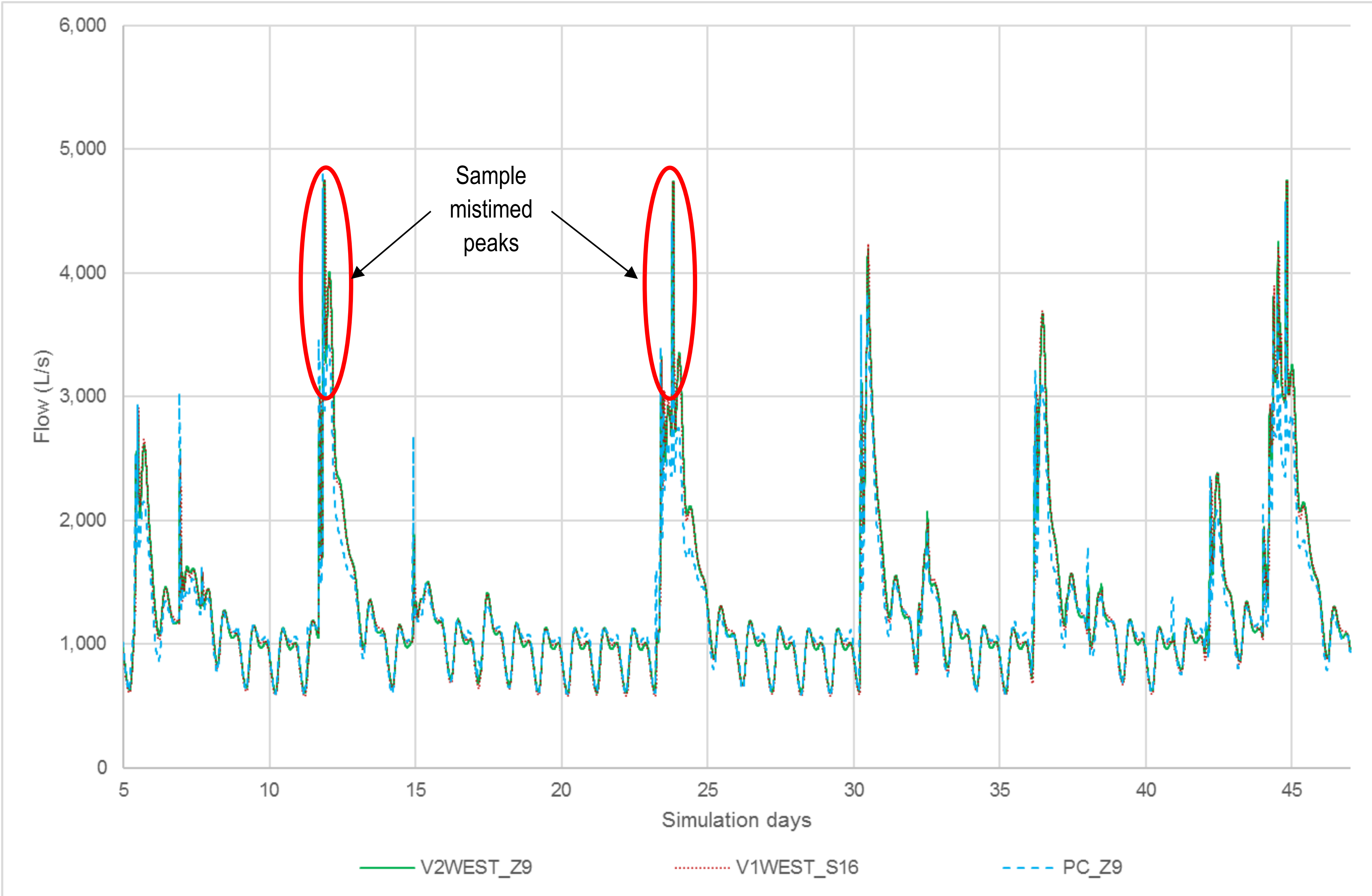

Figure 42: 42-day WWF sample flow results at select location (S16/Z9) for the detailed (PC) and both conceptual models (V1 and V2), with sample mistimed peaks

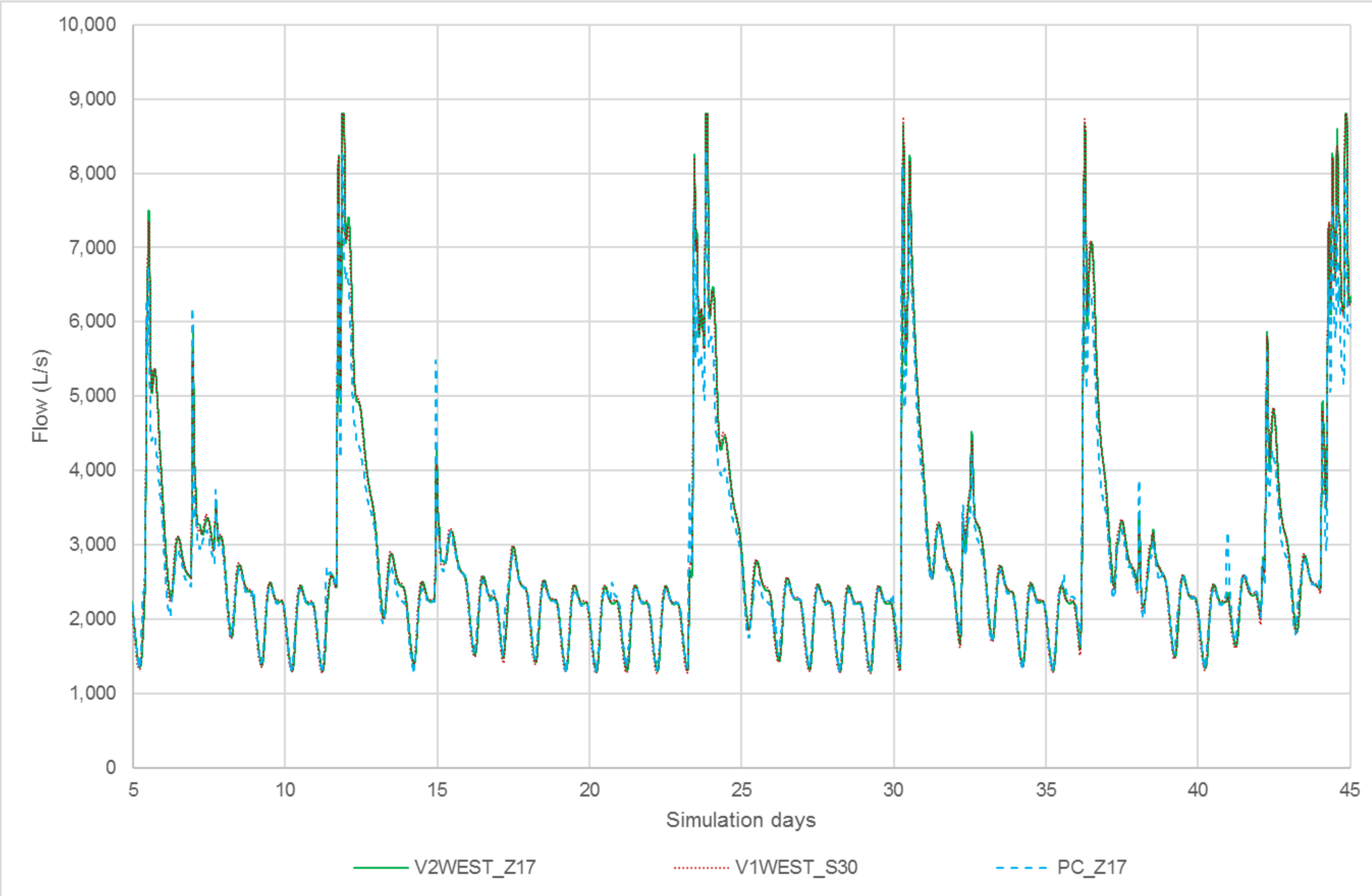

Figure 43: 42-day WWF sample flow results at select location (S30/Z17) for the detailed (PC) and both conceptual models (V1 and V2)

Table 9: Validation - overall performance criteria (PC detailed model, and V1 and V2 conceptual models)

Sewer link	Total 42-day volume (10^3 m^3)	Min flow (L/s)	Peak flow (L/s)	PVE (%)	PEP (%)	NSE
Z1						
PC	1,070	160	880			
V1	1,150	159	979	-7.0%	-11.3%	0.88
V2	1,130	160	1,002	-5.6%	-13.9%	0.89
Z3						
PC	2,630	433	2,106			
V1	2,790	374	2,474	-6.2%	-17.5%	0.89
V2	2,760	382	2,433	-5.0%	-15.5%	0.89
Z4						
PC	929	126	1,735			
V1	981	110	1,011	-5.5%	41.7%	0.83
V2	978	110	1,029	-5.3%	40.7%	0.83
Z5						
PC	588	77	1,161			
V1	562	60	613	4.4%	47.2%	0.92
V2	636	65	657	-8.0%	43.4%	0.85
Z6						
PC	3,220	513	2,628			
V1	3,350	435	3,016	-4.2%	-14.8%	0.92
V2	3,400	448	3,080	-5.6%	-17.2%	0.89
Z9						
PC	4,540	689	4,833			
V1	4,700	585	4,753	-3.6%	1.7%	0.79
V2	4,740	607	4,751	-4.6%	1.7%	0.84
Z10						
PC	4,700	716	4,662			
V1	4,870	601	4,880	-3.6%	-4.7%	0.79
V2	4,910	624	4,880	-4.5%	-4.7%	0.84
Z12						
PC	6,120	889	7,026			
V1	6,300	735	6,936	-2.8%	1.3%	0.79
V2	6,340	753	6,936	-3.5%	1.3%	0.84
Z15						
PC	2,950	490	3,919			
V1	3,080	386	3,530	-4.4%	9.9%	0.90
V2	3,050	384	3,555	-3.4%	9.3%	0.92
Z16						
PC	3,260	542	4,202			
V1	3,480	423	4,037	-6.7%	3.9%	0.89
V2	3,450	421	3,974	-5.8%	5.4%	0.89
Z17						
PC	9,950	1,301	8,315			
V1	10,300	1,279	8,801	-3.9%	-5.8%	0.93
V2	10,400	1,306	8,801	-4.1%	-5.8%	0.93

Table 10: Validation – performance criteria for Event 1 (PC detailed model, and V1 and V2 conceptual models)

Sewer link	Event volume (10^3 m^3)	Peak flow (L/s)	PVE (%)	PEP (%)	NSE
Z1					
PC	90	880			
V1	100	979	-10.9%	-11.3%	0.95
V2	98	1,002	-9.1%	-13.9%	0.87
Z3					
PC	229	2,106			
V1	253	2,474	-10.7%	-17.5%	0.97
V2	251	2,433	-9.8%	-15.5%	0.87
Z4					
PC	83	1,735			
V1	91	1,011	-9.5%	41.7%	0.84
V2	91	1,029	-9.6%	40.7%	0.68
Z5					
PC	55	1,161			
V1	55	604	0.3%	48.0%	1.00
V2	62	650	-12.9%	44.0%	0.77
Z6					
PC	284	2,628			
V1	308	3,016	-8.5%	-14.8%	0.98
V2	313	3,080	-10.4%	-17.2%	0.86
Z9					
PC	401	4,833			
V1	436	4,753	-8.7%	1.7%	0.88
V2	442	4,751	-10.2%	1.7%	0.74
Z10					
PC	415	4,662			
V1	452	4,880	-8.7%	-4.7%	0.94
V2	458	4,880	-10.2%	-4.7%	0.74
Z12					
PC	543	7,026			
V1	586	6,936	-8.0%	1.3%	0.92
V2	591	6,936	-8.9%	1.3%	0.80
Z15					
PC	267	3,919			
V1	289	3,530	-8.2%	9.9%	0.95
V2	286	3,555	-7.0%	9.3%	0.87
Z16					
PC	295	4,202			
V1	329	4,037	-11.3%	3.9%	0.99
V2	326	3,974	-10.2%	5.4%	0.83
Z17					
PC	879	8,251			
V1	944	8,801	-7.4%	-6.7%	0.99
V2	947	8,801	-7.7%	-6.7%	0.91

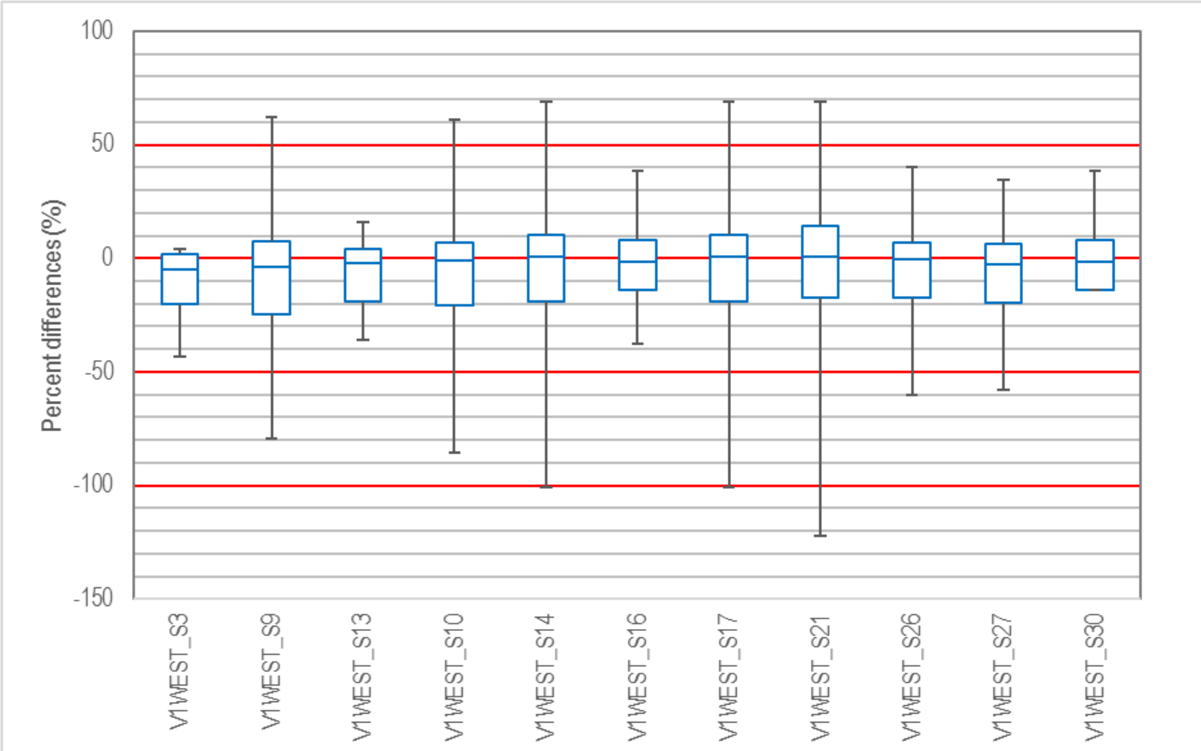

Figure 44: Difference in models, error box plot: V1 conceptual model vs detailed model, with 5% & 95% boxes

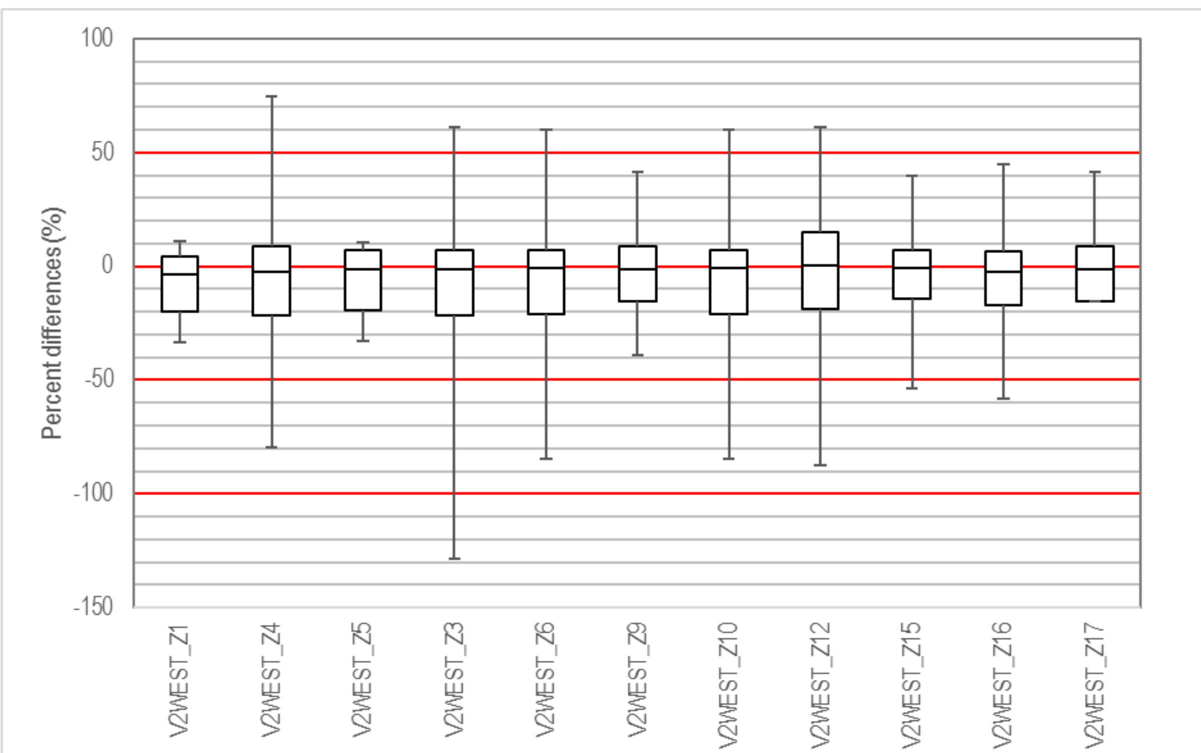

Figure 45: Difference in models, error box plot: V2 conceptual model vs detailed model, with 5% & 95% boxes

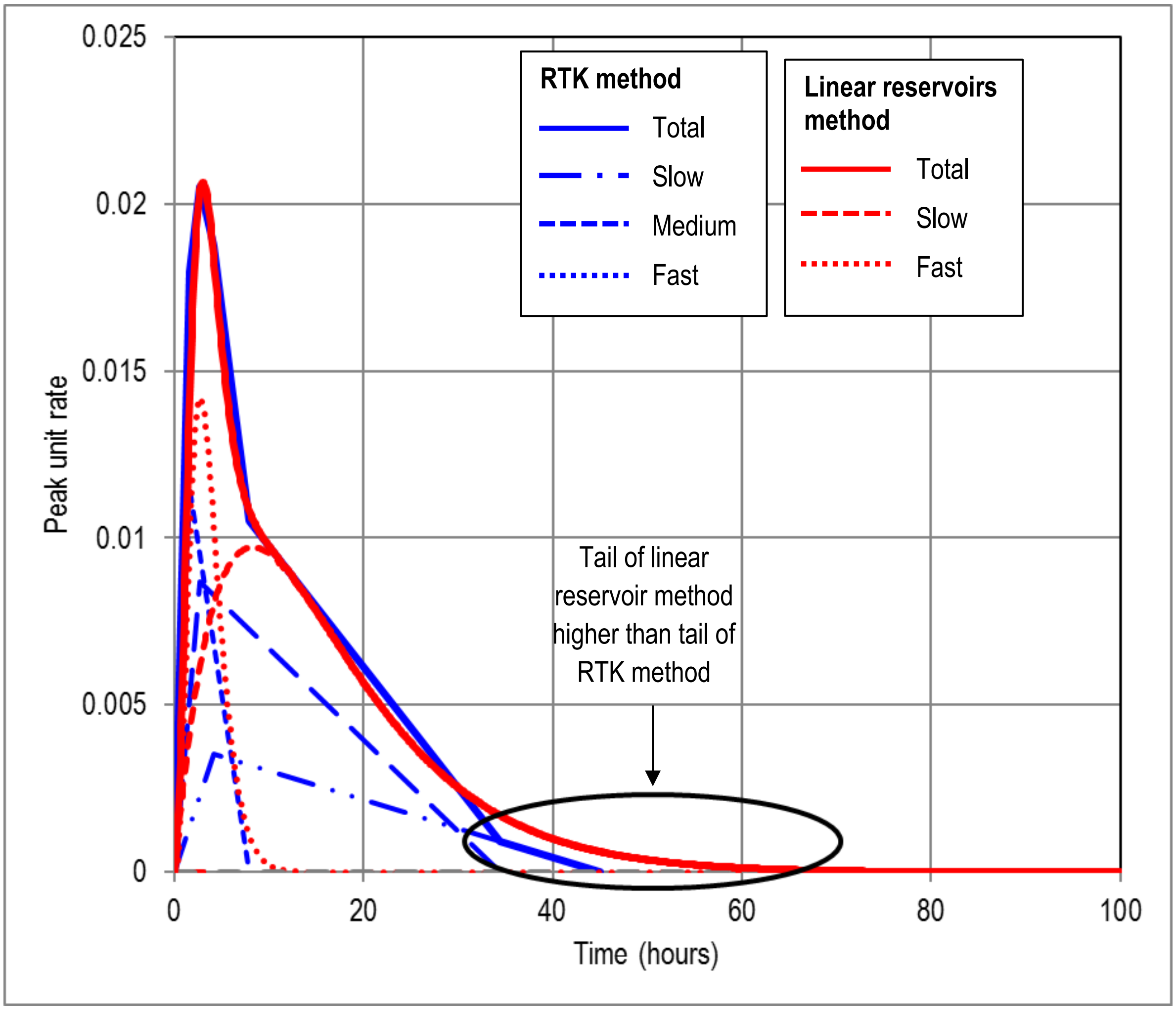

Figure 46: Unit hydrographs of RTK and linear reservoir methods, demonstrating differences in the tails

As a final test, the previously -defined Janus coefficient (J^2) was calculated to evaluate the goodness of fit of the models during the validation period compared to the calibration period. The flow in the last sewer segment (Z17) during the validation period was used to calculate the J^2 values. The V1 and V2 resultant values were 3.0 and 1.7, respectively. A value close to 1 indicates comparable results, while a value greater than 1 indicates that the accuracy of the validation period was less good than that of the calibration period, which is to be expected. Generally, a value below 2 signifies that the model passes the validation test, while higher values suggest model inadequacies. This result confirms the findings from above, in which explanations for these discrepancies during the validation period are provided.

7.6 Aggregation level

This section provides a summary of the impact of the level of aggregation of the V1 model compared to the V2 model on the simulation performance. Table 11 summarizes the attributes of each model, specifically the number of blocks and reservoirs used to represent sewers and catchments in the model. The simulation time for each of these models, as well as that of the detailed model, are also provided for the DWF, WWF and validation periods.

These results indicate that the more aggregated V2 model has approximately half the number of blocks and reservoirs than the V1 model. The catchments are responsible for this trend because they account for a large portion of the number of reservoirs, for each catchment contains three sets of linear reservoirs. As seen in the table, sewers do not follow this trend: the number of linear reservoirs for the sewers in the V2 model is very close to the number of sewers in the V1 model. This tendency is explained by the fact that the V2 model re-uses many of the same sewer segments that are found in the V1 model. Only three new sewer sections are created in V2, which was done by merging sewer sections from the V1 models. These merges resulted in longer sewer stretches, which were then represented with multiple linear reservoirs-in-series, hence the low reduction in number of reservoirs. In contrast, the number of non-linear reservoirs in the V2 model is drastically reduced compared to the V1 model. The simplifications that were made to obtain the V2 model explain this fact, which mostly involved pruning the V1 model by removing the smaller trunk sewers tributary to the main collector that were represented by non-linear reservoirs.

Table 11: Aggregation attributes of V1 and V2 model compared to detailed model and simulation performance improvement for the simulation scenario

Block	**Attribute**	**Detailed PCSWMM model**	**Model V1**	**Model V2**
Catchments	Number of blocks/sewers	NA	52	22
	Number of linear reservoirs (DWF / WWF)	NA	130 / 405	60 / 168
Sewers	Number of blocks	2,600	33	17
	Total reservoirs	NA	43	30
	Number of linear reservoirs	*NA*	*30*	*26*
	Number of non-linear reservoirs	*NA*	*13*	*4*
Model	Total reservoirs	NA	578	258
Simulation scenario				
DWF (2 days)	Run time (mins) [speedup factor*]	8.03	0.53 [15.2]	0.33 [24.3]
WWF block (3 days)	Run time (mins) [speedup factor*]	30.65	0.63 [48.7]	0.38 [80.7]
Long time series	Run time (mins) [speedup factor*]	191.72	16.60 [11.5]	10.53 [18.2]

*speed up factor = Detailed model run-time / conceptual model run-time

The simulation time of the two conceptual models for the DWF, WWF and long-time series events show that both conceptual models provide a significant reduction in computational time compared to the detailed model. As expected, the further aggregated V2 model runs significantly faster than the V1 model (37-40% reduction in computational time).

Chapter 8 General discussion

This section discusses the general findings, considerations and issues raised throughout the research project. First, a reflection on the developed modelling protocol is provided. The level of aggregation is subsequently discussed, followed by an evaluation of the modelling' simulation times. This Chapter concludes with a discussion about the limitations associated with the modelling software and the study itself.

8.1 Model development protocol

The development of this protocol confirmed the findings of the interviews with European research groups conducted in November 2015: it is not possible to create a defining list or set of equations that simply describe how to translate a detailed model into a conceptual model. However, creating a set of guidelines to help with this process would help modellers structure the process. This research project provided the base framework with these guiding rules.

The developed procedure draws from many of the protocols and aggregation method considerations discussed in Section 2.2 and the main phases in the protocols are consistent with those found in the literature review.

A review of the main generalized findings for each of the four phases is summarized in Table 12. These findings will help future users efficiently apply the procedure for building the catchments and sewers in IUWS modelling projects, while focusing on particular elements of each of the modelling steps. Each phase is described in further detail in the following sections.

Table 12: Key findings about the developed generic procedure, organized per modelling phase

Phase	Key findings
Project definition	• The conceptual model's objectives guide the method of model development and calibration. • The available data and the reference models' structure dictate the conversion mechanisms of individual components.
Model development	• Identifying overflows and critical hydraulic structures is a crucial step in being able to properly represent the flow distributions and hydrodynamics at key locations in the lumped model. • Splitting larger drainage areas that span across multiple rain gauge influence zone helps reduce errors related to rainfall variability. • Delineating catchments and sewers must be done concurrently because the boundaries of the former may affect the latter. In addition, simple parameterization and calibration depends on thoughtful divisions.
Calibration	• Determining which parameters are assumed correct and which parameters should be modified during calibration is an important step before beginning calibration. • Setting-up a calibration order not only simplifies the calibration process, but also serves as a useful tool to verify model interconnections. • Breaking down the calibration process into ordered specific runs, each intended to allow calibration of only a few parameters, helps isolate the calibration of individual parameters in a systematic manner, and thereby prevents randomly changing all parameter values. • Calibrated values depend highly on the scale of aggregation in the lumped conceptual model.
Validation	• A well devised validation pinpoints deficiencies in the initial assumptions and calibrated values.

8.1.1 Project definition

The project definition phase in the described protocol follows a similar approach to the other reviewed generic protocols. This phase acts as a screening process to answer the following preliminary questions about the model:

- Why is the model being built?
- What is the intended use of the model?
- What information is available about the system?
- What information is missing and required?
- How will the model be built?

The case study highlighted the fact that the reference model's objectives should align with the conceptual model's objectives. In this project, this was not necessarily the case, and the model validation suffered because of it. The importance of assessing the available data was also proven in this phase. Because GIS data was available, this case study utilized this data to aid in the delineation and aggregation phases. Analyzing the specific hydrologic and hydraulic methodologies applied in the detailed model (e.g. RTKs used for RDII generation) allowed for the consideration of these specific aspects of the case study in the model development phase. Lastly, explicitly stating the assumptions used in each model proved helpful in consequent phases, as they guided the method of certain steps, such as initializing the catchment parameters.

8.1.2 Model development

The main findings from the model development phase relate to the delineation and aggregation of the catchments and sewers. While delineating the catchments and sewers, the boundaries of each were constantly revisited to ensure that each block (catchment or sewer) could either be properly calibrated individually or together. There were some circumstances in which the divisions that were chosen resulted in some catchments that could not be compared to the detailed model. This included catchments that were along a main collector with many small tributary sewers, or catchments that were split at special structures. The conclusion from these findings is that the catchments and sewers must be delineated concurrently, while considering the locations of the raingauges and all key structures.

For the catchment parameterization step, it was found that understanding exactly how the detailed catchment was parameterized is important to properly translate equivalent parameters into the conceptual model. As discussed in Chapter 7, some of the discrepancies found in the validation of the WWF simulations could have been related to improperly transferring initial abstraction and loss parameters into the conceptual model.

The selection of the sewer model, linear versus non-linear reservoirs, was based on whether the detailed model sewer section saw backwater or capacity constraint conditions. This choice affected the aggregation results by skewing the number of reservoirs for the sewers. To further explain, most sewers that saw backwater conditions had low slopes, while the tributary sewers that did not see backwater conditions had higher slopes. Using the Kalinin-Miljukov method to calculate the number of reservoirs in series for sewer sections results in few reservoirs for stretches with low slopes and many more reservoirs for high-sloped pipes. Because non-linear reservoirs were used to represent the sewer sections that saw no backwater, this method only added one reservoir per sewer section. This described method to select which models are used for sewers (i.e. linear vs. non-linear models) leads to much fewer reservoirs in the conceptual model compared to a selection method that would use a series of linear reservoirs to represent all sewer sections.

8.1.3 Calibration

The calibration process that was described in Chapters 5 and 6 was developed based on the reviewed literature and the calibration of the case study. Some findings from this phase relate to the calibration process itself, whereas the others relate to the actual task of calibrating the models.

Due to the complexity of integrated models, simplifying the calibration process by structuring its steps was crucial. Reducing and properly selecting the number of calibration parameters in each identified run helped add structure to the calibration sequence of individual parameters. Within each run, assigning a calibration order to all blocks served as a verification method to ensure proper connectivity of model blocks. While performing the calibration, those blocks that could not be calibrated were further investigated. Often issues with the configuration of the blocks were found and resolved in this phase.

Manual and visual calibration was the basis of the calibration efforts. Therefore, the resultant calibrated parameter values are not necessarily optimal values; they are instead values that produces acceptable results. Because blocks were sequentially calibrated from upstream to downstream, it's possible that the calibration of some values compensates for the poor value assignment of others. However, the systemized procedure was developed in hopes of reducing this possibility as much as possible. To fully avoid this potential issue, each block would have to be isolated from the rest of the model and calibrated individually. This method is not often employed for it would take immense amounts of time and the calibration of some blocks in isolation from the others may still result in imperfect representation if upstream or downstream conditions need to be considered.

The manual calibration process was somewhat tedious because only specific combinations of sets of linear reservoirs were created in the model library for both the DWF and WWF routing in the catchments. Calibrating catchments involved simultaneously changing the number of linear reservoirs with the hydraulic retention times, the diurnal patterns (for DWF) and the split-up factor between the fast and slow responses in RDII (for WWF). Automatic calibration is sometimes used to speed up this calibration process, and tools to do so are available in WEST. The issue however, is that convergence to specific parameter values is not guaranteed due to the model's complexity. In addition, because the number of reservoirs in the sewer and the catchment models was not explicitly stated as a parameter in the model code (but instead selected as a choice of model), automatic calibration of these parameters could not be used. In the newer version of WEST, Modelica will replace the MSL language currently used. This change will allow the number of reservoirs-in-series to be stated as a parameter, and hence the automatic calibration tools could be considered for use.

8.1.4 Validation

Assessing the results from the validation phase allowed for the evaluation of the conceptual models' ability to perform under new conditions. This phase did confirm that the initial calibration of the model, which ignored a long time-series calibration, resulted in higher, and thus more conservative, flows in the conceptual model. In addition, the Janus coefficient results from this validation period indicated that the conceptual models produce less good results for the validation phase compared to the calibration phase, as expected. However, because the Janus coefficient is less than 2 for the V2 model, the validation differences in this model are not significant, while the slightly higher Janus coefficient for the V1 model may indicate some model inadequacies. In this case, a return to one of the previous steps is justified. Two new data sets would then have to be used for the second iteration of calibration and validation.

8.2 Aggregation level

The level of aggregation in both the V1 and V2 models was discussed in Section 7.6, which indicated that the V2 model used about half the number of blocks and reservoirs, as shown in Figure 47. As seen in the Results section (Chapter 7), the additional aggregation that was applied to create the V2 model did not seem to affect this model's ability to produce good results. Therefore, the conclusion could be drawn, at least for this case study, that areas can be aggregated significantly, while taking into consideration the special structures' locations during the aggregation process. However, this statement only holds true for the modified configuration of the catchment model, in which multiple sets of linear reservoirs are used to represent the DWF and WWF routing. The large variation in catchment sizes in the V2 model, due to catchments being aggregated based on special structure locations and major trunk sewer confluences, results in a large variety of flow routing dynamics. As shown in the case study, the modified catchment configuration model has the required flexibility to properly represent these varied dynamics. All catchment and sewer blocks of varying size were well calibrated in both the V1 and V2 models, therefore no maximum limits for catchment size or sewer lengths could be determined from this project.

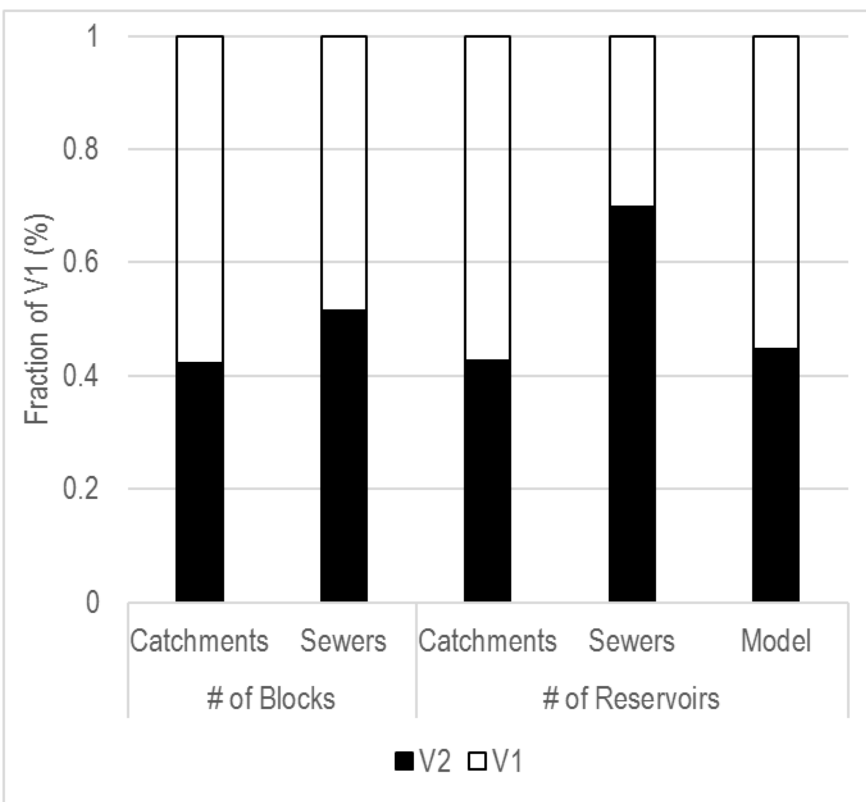

Figure 47: Number of blocks and reservoirs in V2 model compared to V1 model

Another important conclusion that relates to aggregation can be drawn by referring to Table 11 from Section 7.6. This table indicates that the number of sewer reservoirs in either model in comparison to the number of catchment reservoirs is significantly less. Therefore, further simplifying the sewers does not provide the same level of aggregation as catchment simplification could provide, given that the suggested catchment and sewers configurations are used.

The two conceptual models, one further aggregated than the other, each have advantages and disadvantages, which are summarized in Table 13 below. In summary, depending on the purpose and objective of the conceptual model, different levels of aggregation could be used to build a suitable conceptual model.

Table 13: Advantages and disadvantages of increased aggregation in conceptual models

	Less aggregated model (V1)	More aggregated model (V2)
Advantages	• More detail provides additional flow information throughout the system • Retains overall structure of sewer system being represented	• Faster simulating model • Simpler representation makes transfer of knowledge about the system easier • Less blocks to calibrate
Disadvantages	• Longer simulation time • Complex visual representation may be intimidating for future user, and complicates their understanding of the model • More blocks to create and calibrate, thus increasing model development time	• Potential loss of accuracy, if oversimplified and raingauge-influence zones not respected • Loss of information at intermediate locations

8.3 Simulation time

In general, significant reductions in simulation time were achieved in both conceptual models compared to the detailed PCSWMM model. Speed-up factors (factor in reduction of simulation time) varying from 10 to 80 were observed for the various calibration and validation runs. These results confirm the usefulness of such conceptual models to provide faster simulating models that are required for IUWS modelling applications.

Although significant speed-up factors were obtained compared to the detailed model, other conclusions can be drawn about the simulation time of the conceptual models in this case study. The first conclusion about simulation time relates to the level of aggregation. Figure 48 mimics Figure 47, while providing additional information about the simulation time of the V1 and V2 models during the DWF, WWF and long time series validation runs. This graph indicates that although the V2 model only uses about 45% of the number of blocks and reservoirs compared to V1, the simulation time of the V2 model during the three runs is about 60-64% of the time it takes for the V1 model. This result suggests that the simulation time decrease obtained by further simplifying a model is not equivalent to the increased level of aggregation. The lesser aggregation of the sewers compared to the catchments in the V2 model could account for some of the additional calculation time, while another explanation for this phenomenon could be that there is a fixed amount of calculations required for any model to run.

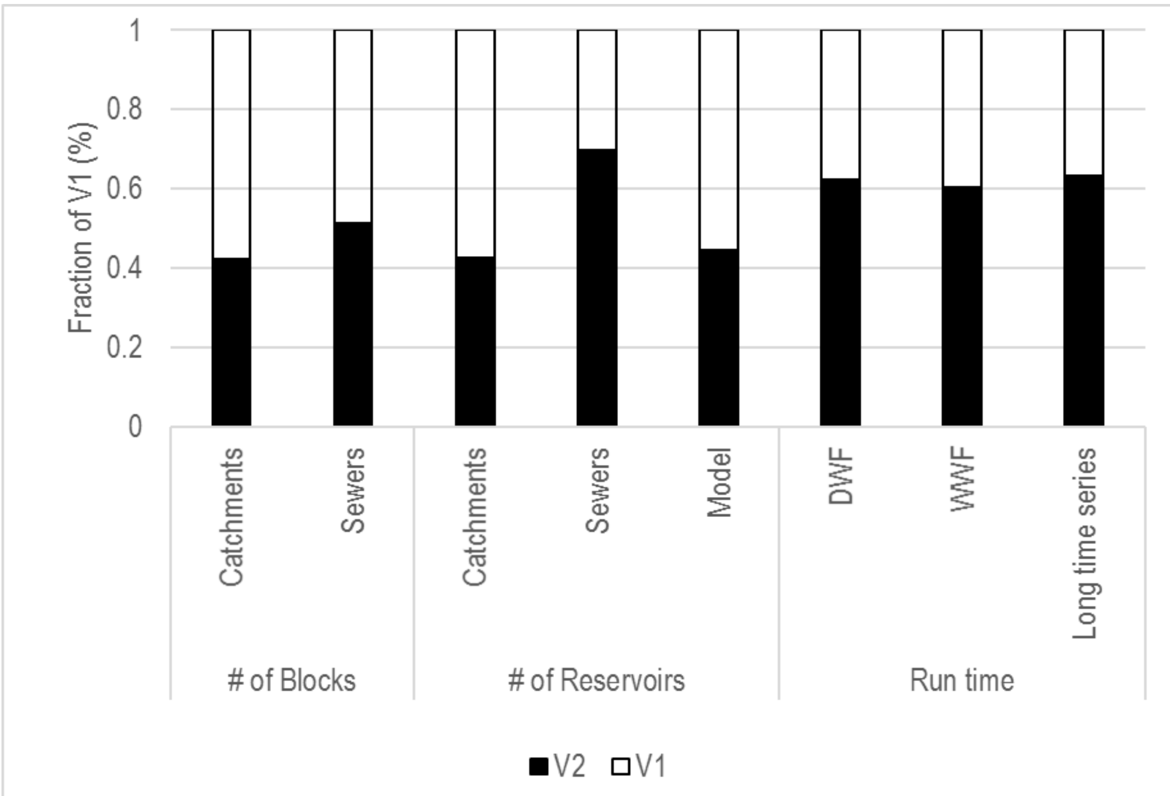

Figure 48: Aggregation of blocks and reservoirs of V2 model compared to V1, including simulation time comparison

Other methods that could be used to further reduce the simulation time of the conceptual model include using non-linear models for all sewers, not only those that do not have backwater, and for all routing components in the catchments. This modification would make each sewer and catchment represented by one and three non-linear reservoirs, respectively. As such, a reduction of one block would result in the equivalent reduction in reservoirs for the sewer and a three-fold reduction for the catchments. Because non-linear reservoirs were proven to run in similar simulation times compared to their linear counterparts (Vanrolleghem, et al., 2009), this change would result in significant overall simulation time reductions in all conceptual model blocks.

The second point to mention is that the simulation time of these conceptual models, created in KOSIM-WEST, is longer than the simulation time that could be obtained from a similar configuration using the original KOSIM code. The latter uses a fixed 5-minute timestep and an analytical solution to solve the model compared to the ordinary differential equations (ODE) solver used in KOSIM-WEST; however, KOSIM is only intended for catchment and sewer models and therefore could not be used for future water quality modelling purposes.

8.4 Software limitations

Chapter 4 reviewed some of the identified limitations with the default model code library available in KOSIM-WEST and the limitations related to the graphical user interface of the WEST modelling platform. In summary, a lot of time was spent understanding the model code and writing new code for the new catchment configuration and the corrected sewer models. Although these changes did provide the sought flexibility for the case study, writing the model code was somewhat tedious using the Model Specific Language (MSL); each combination of linear reservoirs (e.g. the DWF and two-part WWF routing the catchments represented by varying number of reservoir in-series) had to be written as separate model code. Performing a verification of parameter values input into the model was also a time-consuming manual task, due to the limitations mentioned in Chapter 4. In addition, the GUI in the WEST platform is well designed to represent process diagrams, such as those that would be built for wastewater treatment plant modelling; however, it is not optimal for the spatial representation of areas, such as the catchment and sewer layouts required for IUWS modelling. The result is visually complex IUWS models that may be unappealing to clients, stakeholders and future users.

8.5 Study limitations

This research project successfully used a case study to develop a modelling procedure for the representation of the conceptual catchments and sewers in IUWS models. Although the case study did allow for this project's objectives to be reached, there are certain limitations that must be identified. A list of the study limitations is provided below:

- The detailed model that was initially developed for larger events as the reference model proved to react differently for simulation of long time series, which explains the trend in the differences in the validation period. As such, conceptual models should ideally be made for the same objective as the detailed model, or the limitations of the detailed model should be somehow accounted for in the conceptual model. Alternatively, monitoring data, for events consistent with the conceptual model's objectives, could be used to verify the calibrated values in the conceptual model.

- The study area consisted of a mostly separated sanitary system, with predominantly partially separated and separated sewer areas, and a small portion of combined sewers. This fact makes the research unique compared to previously completed research projects that have focused primarily on combined sewer systems. Although the breakdown of separated, partially-separated and combined areas in this case study is similar to what is found in other cities in Canada, European case studies tend to have a much higher percentage of combined areas, and a higher number of associated overflows. The proposed procedure therefore provides a flexible method that should work well with combined areas, however further testing of different types of areas is required.

- Although rainfall variability was discussed and considered in the catchment and sewer delineation step, different rainfall data was not applied to the various raingauges, and therefore the spatial variability in rainfall was not actually assessed in this case study.

- Because this project did not focus on the representation of the operation of flow-regulators, diversion chambers and overflows, they were simplified in the PCSWMM model and further simplified in the conceptual models. Their simple representation is therefore partially responsible for the differences in the model results during the validation period. Alternatives to avoid oversimplifying these structures would be to either spend more time on properly representing these structures in the conceptual models or completely remove them from the both the detailed and conceptual models to isolate the research focus uniquely on the catchments and sewers.

- A long time series calibration was not completed due to lack of time. This decision explains the general tendency of the errors in the validation results.

Chapter 9 Conclusions and perspectives

The conclusions from this project relate back to the project objectives and summarize the main findings. Suggestions for perspective work follow.

9.1 Conclusions

This research project resulted in the development of a procedure to translate the catchments and sewers in detailed models into a conceptual IUWS model. A thorough literature review and a research tour in Europe provided the required background information related to IUWS modelling and model building approaches. The default model code in WEST was also reviewed and modified to accommodate the needs of the selected case study. The procedure was subsequently developed by building two conceptual models based on the case study's detailed model. The model results and discussion sections permitted the following conclusions to be drawn about this research project:

- A careful selection or review of the conceptual modelling software and model code that will be used is important in ensuring that the model will have the required capabilities. In this project, the KOSIM-WEST model code was altered, and modifications were suggested to improve the WEST GUI.

- The developed procedure follows a similar sequence as the protocols reviewed in the literature review, while taking into consideration specifics related to aggregating catchments and sewers. Although a structured procedure has been described in this project, some expert knowledge about catchments and sewer systems is still required to build conceptual models of catchments and sewers.

- A long time series calibration is required to calibrate the model's parameters that change over a long time. The general tendency of the errors for the validation period found in this case study are mostly attributed to the lack of such long time series calibration.

- A combination of both qualitative and visual observations with graphs and quantitative assessment with calculated criteria are required to illustrate the conceptual model's goodness-of-fit compared to the detailed model. The graphs provide a visualization of the dynamics and overall fits achieved, while the criteria provide a quantitative means to compare results.

- The conceptual catchments represent routing in both the detailed catchments and the local sewers located within the catchment. The re-configured catchment and sewer models (with 2 linear reservoirs in series) provided adequate flexibility to represent the expected large distribution of flows in varying-sized blocks in this project. This conclusion is substantiated by the good simulation results obtained by both conceptual models. Further tests may be conducted for other research projects to reconfirm whether 2 or 3 sets of linear reservoirs are required to properly simulate the complex RDII contributions.

- No definite conclusions can be drawn about the differences in results between the two conceptual models, and these differences cannot be attributed to the increased level of aggregation in the V2 model. Because of the sequential development of the models, the V2 model builds off the calibrated V1 model, thus resulting in potentially better calibrated values.

- A significant (~40%) decrease in simulation time is seen for the more aggregated V2 model, however this decrease is not as significant as the increased level of aggregation (~55%). This conclusion will vary based on the model or method by which the catchment and sewer blocks are represented in the conceptual model.

9.2 Recommendations for perspective work

Based on the findings of the research projects and identified limitations, additional work related to developing the procedure to represent the catchments and sewers in conceptual IUWS models have been provided below:

- Testing the developed procedure using other case studies is suggested to substantiate the proposed steps or modify them as required. These case studies should use different systems, potentially with a different breakdown of separated, partially-separated and combined sewer areas. Selecting a detailed model that was built using similar-sized storms to those intended to be used in the conceptual model may also lead to a simpler calibration and validation. The first test will be conducted by Julia Ledergerber, who is currently working on developing an IUWS model for a case study in Bordeaux, France.

- This case study looks at translating the information from a detailed model to a conceptual model. Some considerations are provided for the alternative approach for building a conceptual model from raw data; however, these considerations were not tested. It may be interesting to compare the conceptual models that would be created using raw data and flow monitoring data versus a calibrated detailed model.

- Specific numbers of linear reservoirs were used within the new catchment configuration. Optimizing this number of reservoirs, or providing more options, would increase the flexibility of users to calibrate catchments. The limitation related to the tedious manual calibration of the number of linear reservoirs may be fully or partially resolved with the introduction of the new modelling language Modelica. This language is already available in WEST, but not for the IUWS library, and will allow users to define the number of reservoirs (n) as a parameter. As such, catchments would be more flexible, and automatic calibration tools could potentially be used to significantly reduce calibration time.

- Determining a maximum catchment size and sewer length that can be properly represented by conceptual blocks, either linear or non-linear reservoirs, may also prove to be a valuable piece of information for future modelers.

- The spatial variability of rainfall should be considered in future models by applying different rainfall data to each of the raingauges. This task will ensure that the catchments are properly divided between raingauges, and that future application of different rainfall data to each raingauge will not cause issues in the simulation results.

- As described in Vanrolleghem et al. (2003) in Section 2.3.6.2, the non-linear pipe method provides very similar, slightly more realistic, and faster simulation results compared to the linear reservoir method. The non-linear pipe model could therefore be used for all pipe segments to speed up overall simulation time. The Kalinin-Miljukov would no longer be needed to characterize the sewer blocks. Non-linear pipes could also be used to represent the DWF and WWF routing in the catchment blocks to further reduce the simulation time. The potential issue with using these non-linear models for catchments may be increased calibration time due to lack of experience of the non-linear reservoir parameter values. To overcome this issue, the pipe parameters used to characterize non-linear reservoirs could be expressed as linear reservoir characteristics in the model, using the Kalinin-Miljokov equations. Overall, non-linear reservoirs would drastically decrease the simulation time of the models.

- Following the improvement of the model development methodology, additional tasks to validate the use of the produced models could include applying the developed tool to test solutions with the collection system. Such solutions include adding new storage facility, increasing conveyance (i.e. increasing pipe sizes), reducing infiltration and inflow sources, and installing green infrastructure.

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Appendices

Appendix A: Sample model code

A – 1: Model code for default coupled catchment model previously in WEST:

```
/*******************************************************************************
 *
 * Tornado - Advanced Kernel for Modelling and Virtual Experimentation
 * (c) Copyright 2004-2011 DHI
 *
 * This file is provided under the terms of a license and may not be
 * distributed and/or modified except where allowed by that license.
 *
 * This file is provided as is with no warranty of any kind, including the
 * warranty of design, merchantability and fitness for a particular purpose.
 *
 * $Revision: 1$
 * $Date: 15. april 2015 14:31:49$
 *
 ******************************************************************************/

#ifndef SEWER_CATCHMENTS_NORETENTION
#define SEWER_CATCHMENTS_NORETENTION


CLASS Catchment_NoRetention (* icon = "Catchment" *)
"Catchment model with evaporation, runoff and no retention (buffer tank)"
SPECIALISES CoupledModelType :=
{:

  comments <- "Catchment model with evaporation, runoff and no retention
(buffer tank)";

  interface <-
  {
    OBJ Rainfall (* terminal = "in_2"; manip = "1" *) "Rainfall" : Real
:= {: causality <- "CIN"; group <- "Data" :},
    OBJ Inflow (* terminal = "in_1" *) "Inflow" : InSewTerminal := {:
causality <- "CIN"; group <- "Inflow" :},
    OBJ Outflow (* terminal = "out_1" *) "Outflow from dry weather + wet
weather" : OutSewTerminal := {:causality <- "COUT"; group <- "Outflow":},
  };

  parameters <-
  {
    OBJ YearlyEvaporation "Average yearly potential evaporation
(mm/year)d" : Real := {: value <- 660; group <- "FRunoff" :};
```

```
    OBJ k "linear reservoir constant" : Time := {: value <-
0.0138888888888889; group <- "FRunoff" :};
    //LB   OBJ ta "time to peak" : Time := {:value <- 7;  unit <- "min" ;
group <- "FRunoff":};
    OBJ m "exponent (1 = linearity)" : Real := {: value <- 1.0; group <-
"FRunoff" :};
    OBJ Inhabitants (* is_favorite = "1" *) "Number of inhabitants" :
Real := {: value <- 1000; group <- "DWF" :};
    OBJ WastewaterPerIE (* is_favorite = "1" *) "Wastewater produced per
inhabitant per day" : FlowRate := {: value <- 0.19; group <- "DWF" :};
    OBJ Infiltration "Water infiltration flow (l/s/ha)" : Real := {:
value <- 0.21; group <- "FRunoff" :};
    OBJ FirstDayYear (* hidden = "1" *) "Week day at the start of the
year, Saturday = 1": Integer :={: value <- 1; group <- "Simulation" :};
    OBJ f_we_water (* hidden = "1" *) "Correction factor for flow rate
during weekends": Real := {: value <- 0.7; group <- "DWF" :} ;
    OBJ f_we_pollution (* hidden = "1" *) "Correction factor for
concentration during week-end": Real :={:value <- 0.5; group <- "DWF":};
    OBJ Tourist_Start (* hidden = "1" *) "Start of tourist season (day
nr)": Integer :={:value <- 162; group <- "DWF":};
    OBJ Tourist_End (* hidden = "1" *) "End of tourist season (day nr)":
Integer :={:value <- 300; group <- "DWF":};
    OBJ f_tourist_water (* hidden = "1" *) "Correction factor for flow
rate in tourist season": Real :={:value <- 1; group <- "DWF":};
    OBJ f_tourist_pollution (* hidden = "1" *) "Correction factor for
concentration in tourist season": Real :={:value <- 1.1; group <- "DWF"
:} ;
    OBJ NrPatternFlow (* is_favorite = "1" *) "Daily DWF pattern: 1 (0-
5kPE), 2 (5k-10kPE), 3 (10k-50kPE), 4 (Commercial), 0 (Custom)" : Integer
:={: value <- 1; interval <- {: lowerBound <- 0; upperBound <- 4; :};
group <- "General" :};
    OBJ NrPatternPollution (* is_favorite = "1" *) "Daily DWF pollution
pattern: 1 (0-5kPE), 2 (5k-10kPE), 3 (10k-50kPE), 4 (Commercial), 0
(Custom)" : Integer :={:value <- 1; interval <- {: lowerBound <- 0;
upperBound <- 4; :}; group <- "General" :};
    OBJ NrPatternInfiltration "Seasonal infiltration pattern: 0 (Custom),
1 (constant)" : Integer := {: value <- 0; interval <- {: lowerBound <- 0;
upperBound <- 1; :}; group <- "Catchment" :};
    OBJ MaxRunoff "Maximum runoff coefficient Psi_e, for impervious
areas" : Fraction := {: value <- 1.0; group <- "FRunoff" :};
    OBJ MaxWettingLosses "Maximum wetting losses" : Rainfall := {: value
<- 0.5; group <- "FRunoff" :};
    OBJ MaxDepressionStorage (* hidden = "1" *) "Maximum depression
storage for impervious areas" : Rainfall := {: value <- 1.8; group <-
"FRunoff" :};
    OBJ TotalArea (* is_favorite = "1" *) "Area of the subcatchment" :
Area := {: value <- 2000000; group <- "Catchment" :};
    OBJ Q_Industry (* is_favorite = "1" *) "Flow from industry": FlowRate
:= {: value <- 0.0; group <- "DWF" :};
    OBJ StartDay (* hidden = "1" *) "Day of the year when the simulation
```

```
starts" : Integer := {: value <- 1; group <- "Simulation":};
  };

  sub_models <-
  {
    OBJ Evaporation : EvaporationFlow;
    OBJ CRunoff : Tank_Runoff;
    OBJ Combi : SewThreeCombiner;
    OBJ DWF : DryWeatherFlow;
    OBJ FRunoff : Runoff_Flux;
  };

  coupling <-
  {
    // parameter coupling
    sub_models.Evaporation.parameters.StartDay.value :=
parameters.StartDay.value,
    sub_models.Evaporation.parameters.Evap_Year.value :=
parameters.YearlyEvaporation.value,
    sub_models.CRunoff.parameters.k.value := parameters.k.value,
    //LB   sub_models.CRunoff.parameters.ta.value := parameters.ta.value,
    sub_models.CRunoff.parameters.m.value := parameters.m.value,
    //   sub_models.comb.parameters.InfluentTimestep.value :=
parameters.InfluentTimestep.value,
    sub_models.DWF.parameters.Population.value :=
parameters.Inhabitants.value,
    sub_models.DWF.parameters.WastewaterPerIE.value :=
parameters.WastewaterPerIE.value,
    sub_models.DWF.parameters.Infiltration.value :=
parameters.Infiltration.value,
    sub_models.DWF.parameters.FirstDayYear.value :=
parameters.FirstDayYear.value,
    sub_models.DWF.parameters.f_we_water.value :=
parameters.f_we_water.value,
    sub_models.DWF.parameters.f_we_pollution.value :=
parameters.f_we_pollution.value,
    sub_models.DWF.parameters.Tourist_Start.value :=
parameters.Tourist_Start.value,
    sub_models.DWF.parameters.Tourist_End.value :=
parameters.Tourist_End.value,
    sub_models.DWF.parameters.f_tourist_water.value :=
parameters.f_tourist_water.value,
    sub_models.DWF.parameters.f_tourist_pollution.value :=
parameters.f_tourist_pollution.value,
    sub_models.DWF.parameters.NrPatternFlow.value :=
parameters.NrPatternFlow.value,
    sub_models.DWF.parameters.NrPatternPollution.value :=
parameters.NrPatternPollution.value,
    sub_models.DWF.parameters.NrPatternInfiltration.value :=
parameters.NrPatternInfiltration.value,
```

```
    sub_models.DWF.parameters.Q_Industry.value :=
parameters.Q_Industry.value,
    sub_models.FRunoff.parameters.MaxRunoff.value :=
parameters.MaxRunoff.value,
    sub_models.FRunoff.parameters.MaxWettingLosses.value :=
parameters.MaxWettingLosses.value,
    sub_models.FRunoff.parameters.MaxDepressionStorage.value :=
parameters.MaxDepressionStorage.value,
    sub_models.DWF.parameters.TotalArea.value :=
parameters.TotalArea.value,
    sub_models.FRunoff.parameters.TotalArea.value :=
parameters.TotalArea.value,
    // sub-model coupling
    connect(interface.Rainfall, sub_models.FRunoff.interface.Rain),
    connect(sub_models.Evaporation.interface.Evaporation,
sub_models.FRunoff.interface.Evaporation),
    connect(sub_models.FRunoff.interface.Outflow,
sub_models.CRunoff.interface.Inflow),
    connect(interface.Inflow, sub_models.Combi.interface.Inflow3),
    connect(sub_models.CRunoff.interface.Outflow,
sub_models.Combi.interface.Inflow1),
    connect(sub_models.DWF.interface.Outflow,
sub_models.Combi.interface.Inflow2),
    connect(sub_models.Combi.interface.Outflow, interface.Outflow),
  };

:};


#endif // SEWER_CATCHMENTS_NORETENTION
```

A – 2: Sample model code for newly created coupled catchment model (with 2, 10, and 4 linear reservoirs for the slow WWF routing, fast WWF routing and DWF routing components, respectively):

```
/*********************************************************************************
 *
 * $Revision: LP1$
 * $Date: 14.october.2016$
 *
 *********************************************************************************/

#ifndef CATCHMENT_SLOW2_FAST10_DWF4_LP
#define CATCHMENT_SLOW2_FAST10_DWF4_LP


CLASS Catch_slow2_fast10_DWF4_LP (* icon = "Catchment" *)
```

```
"Catchment with 2 tanks for slow infiltration, 10 tanks for fast infiltration, 4 tanks for DWF routing"
SPECIALISES CoupledModelType :=
 {:

  comments <- "Catchment model with evaporation, runoff and no retention (buffer tank)";

  interface <-
  {
    OBJ Rainfall (* terminal = "in_2"; manip = "1" *) "Rainfall" : Real := {: causality <- "CIN"; group <- "Data" :},
    OBJ Inflow (* terminal = "in_1" *) "Inflow" : InSewTerminal := {: causality <- "CIN"; group <- "Inflow" :},
    OBJ f_fast (* terminal = "in_3"; manip = "1"; is_favorite = "1" *) "fraction of runoff to fast infiltration" : Real :=
{: causality <- "CIN"; value <- 0.7; group <- "FRunoff" :},
    OBJ Outflow (* terminal = "out_1" *) "Outflow from dry weather + wet weather" : OutSewTerminal :=
{:causality <- "COUT"; group <- "Outflow":},
  };

  parameters <-
  {
    OBJ YearlyEvaporation "Average yearly potential evaporation (mm/year)d" : Real := {: value <- 660; group
<- "FRunoff" :};
    OBJ KF "linear reservoir constant for all fast-infiltration tanks" : Time := {: value <- 0.3; group <- "FRunoff" :};
    OBJ KS "linear reservoir constant for all slow-infiltration tanks" : Time := {: value <- 0.4; group <- "FRunoff"
:};
    OBJ kDWF "linear reservoir constant for all DWF tank routing" : Time := {: value <- 0.1; group <- "DWF" :};
    OBJ mf "exponent-fast (1 = linearity)" : Real := {: value <- 1.0; group <- "FRunoff" :};
    OBJ ms "exponent-slow (1 = linearity)" : Real := {: value <- 1.0; group <- "FRunoff" :};
    OBJ Inhabitants (* is_favorite = "1" *) "Number of inhabitants" : Real := {: value <- 1000; group <- "DWF" :};
    OBJ WastewaterPerIE (* is_favorite = "1" *) "Wastewater produced per inhabitant per day" : FlowRate := {:
value <- 0.19; group <- "DWF" :};
    OBJ Infiltration "Water infiltration flow (l/s/ha)" : Real := {: value <- 0.21; group <- "DWF" :};
    OBJ FirstDayYear "Week day at the start of the year, Saturday = 1": Integer :={: value <- 1; group <-
"Simulation" :};
    OBJ f_we_water (* hidden = "1" *) "Correction factor for flow rate during weekends": Real := {: value <- 1;
group <- "DWF" :} ;
    OBJ f_we_pollution (* hidden = "1" *) "Correction factor for concentration during week-end": Real :={:value
<- 0.5; group <- "DWF":};
    OBJ Tourist_Start (* hidden = "1" *) "Start of tourist season (day nr)": Integer :={:value <- 162; group <-
"DWF":};
    OBJ Tourist_End (* hidden = "1" *) "End of tourist season (day nr)": Integer :={:value <- 300; group <-
"DWF":};
    OBJ f_tourist_water (* hidden = "1" *) "Correction factor for flow rate in tourist season": Real :={:value <- 1;
group <- "DWF":};
    OBJ f_tourist_pollution (* hidden = "1" *) "Correction factor for concentration in tourist season": Real
:={:value <- 1.1; group <- "DWF" :} ;
```

```
   OBJ NrPatternFlow (* is_favorite = "1" *) "Daily DWF pattern: 0 (0-30% RES), 1 (30-50% RES), 2 (50-70%
RES), 3 (70-85% RES), 4 (85-100% RES)" : Integer :={: value <- 1; interval <- {: lowerBound <- 0;
upperBound <- 4; :}; group <- "General" :};
   OBJ NrPatternPollution (* is_favorite = "1" *) "Daily DWF pollution pattern: 1 (0-5kPE), 2 (5k-10kPE), 3 (10k-
50kPE), 4 (Commercial), 0 (Custom)" : Integer :={:value <- 1; interval <- {: lowerBound <- 0; upperBound <- 4;
:}; group <- "General" :};
   OBJ NrPatternInfiltration "Seasonal infiltration pattern: 0 (Custom), 1 (constant)" : Integer := {: value <- 0;
interval <- {: lowerBound <- 0; upperBound <- 1; :}; group <- "Catchment" :};
   //OBJ PerviousFraction "Fraction of the catchment that is pervious" : Fraction := {: value <- 0.8; group <-
"FRunoff":};
   OBJ MaxRunoff "Maximum runoff coefficient Psi_e, for impervious areas" : Fraction := {: value <- 1.0; group
<- "FRunoff" :};
   OBJ MaxWettingLosses "Maximum wetting losses" : Rainfall := {: value <- 0.5; group <- "FRunoff" :};
   OBJ MaxDepressionStorage "Maximum depression storage for impervious areas" : Rainfall := {: value <-
1.8; group <- "FRunoff" :};
   OBJ TotalArea (* is_favorite = "1" *) "Area of the subcatchment" : Area := {: value <- 2000000; group <-
"Catchment" :};
   OBJ Q_Industry (* is_favorite = "1" *) "Flow from industry": FlowRate := {: value <- 0.0; group <- "DWF" :};
   OBJ StartDay (* hidden = "1" *) "Day of the year when the simulation starts" : Integer := {: value <- 1; group
<- "Simulation":};
  };

  sub_models <-
  {
   OBJ Evaporation : EvaporationFlow;
   OBJ DWF : DryWeatherFlow;
   OBJ DWFrout : Tanks04_Cascade_Runoff;
   OBJ FRunoff : Runoff_Flux;
   OBJ Splitter : SewRelTwoSplitter;
   OBJ CRunoffFAST : Tanks10_Cascade_Runoff;
   OBJ CRunoffSLOW : Tanks02_Cascade_Runoff;
   OBJ CombRUNOFF : SewTwoCombiner;
   OBJ Combi : SewThreeCombiner;

  };

  coupling <-
  {
   // parameter coupling
   sub_models.Evaporation.parameters.StartDay.value := parameters.StartDay.value,
   sub_models.Evaporation.parameters.Evap_Year.value := parameters.YearlyEvaporation.value,
   sub_models.DWFrout.parameters.k.value := parameters.kDWF.value / 4.0,
   sub_models.CRunoffFAST.parameters.k.value := parameters.KF.value / 10.0,
   sub_models.CRunoffFAST.parameters.m.value := parameters.mf.value,
```

```
    sub_models.CRunoffSLOW.parameters.k.value := parameters.KS.value / 2.0,
    sub_models.CRunoffSLOW.parameters.m.value := parameters.ms.value,
    sub_models.DWF.parameters.Population.value := parameters.Inhabitants.value,
    sub_models.DWF.parameters.WastewaterPerIE.value := parameters.WastewaterPerIE.value,
    sub_models.DWF.parameters.Infiltration.value := parameters.Infiltration.value,
    sub_models.DWF.parameters.FirstDayYear.value := parameters.FirstDayYear.value,
    sub_models.DWF.parameters.f_we_water.value := parameters.f_we_water.value,
    sub_models.DWF.parameters.f_we_pollution.value := parameters.f_we_pollution.value,
    sub_models.DWF.parameters.Tourist_Start.value := parameters.Tourist_Start.value,
    sub_models.DWF.parameters.Tourist_End.value := parameters.Tourist_End.value,
    sub_models.DWF.parameters.f_tourist_water.value := parameters.f_tourist_water.value,
    sub_models.DWF.parameters.f_tourist_pollution.value := parameters.f_tourist_pollution.value,
    sub_models.DWF.parameters.NrPatternFlow.value := parameters.NrPatternFlow.value,
    sub_models.DWF.parameters.NrPatternPollution.value := parameters.NrPatternPollution.value,
    sub_models.DWF.parameters.NrPatternInfiltration.value := parameters.NrPatternInfiltration.value,
    sub_models.DWF.parameters.Q_Industry.value := parameters.Q_Industry.value,
    //sub_models.FRunoff.parameters.PerviousFraction.value := parameters.PerviousFraction.value,
    sub_models.FRunoff.parameters.MaxRunoff.value := parameters.MaxRunoff.value,
    sub_models.FRunoff.parameters.MaxWettingLosses.value := parameters.MaxWettingLosses.value,
    sub_models.FRunoff.parameters.MaxDepressionStorage.value :=
parameters.MaxDepressionStorage.value,
    sub_models.DWF.parameters.TotalArea.value := parameters.TotalArea.value,
    sub_models.FRunoff.parameters.TotalArea.value := parameters.TotalArea.value,
    // sub-model coupling
    connect(interface.Rainfall, sub_models.FRunoff.interface.Rain),
    connect(sub_models.Evaporation.interface.Evaporation, sub_models.FRunoff.interface.Evaporation),
    connect(sub_models.FRunoff.interface.Outflow, sub_models.Splitter.interface.Inflow),
    connect(interface.f_fast, sub_models.Splitter.interface.f_Out2),
    connect(sub_models.Splitter.interface.Outflow1, sub_models.CRunoffSLOW.interface.Inflow),
    connect(sub_models.Splitter.interface.Outflow2, sub_models.CRunoffFAST.interface.Inflow),
    connect(sub_models.CRunoffSLOW.interface.Outflow, sub_models.CombRUNOFF.interface.Inflow1),
    connect(sub_models.CRunoffFAST.interface.Outflow, sub_models.CombRUNOFF.interface.Inflow2),
    connect(sub_models.CombRUNOFF.interface.Outflow, sub_models.Combi.interface.Inflow1),
    connect(sub_models.DWF.interface.Outflow, sub_models.DWFrout.interface.Inflow),
    connect(sub_models.DWFrout.interface.Outflow, sub_models.Combi.interface.Inflow2),
    connect(interface.Inflow, sub_models.Combi.interface.Inflow3),
    connect(sub_models.Combi.interface.Outflow, interface.Outflow),
  };

:};

#endif //CATCHMENT_SLOW2_FAST10_DWF4_LP
```

Appendix B: Conceptual model configurations

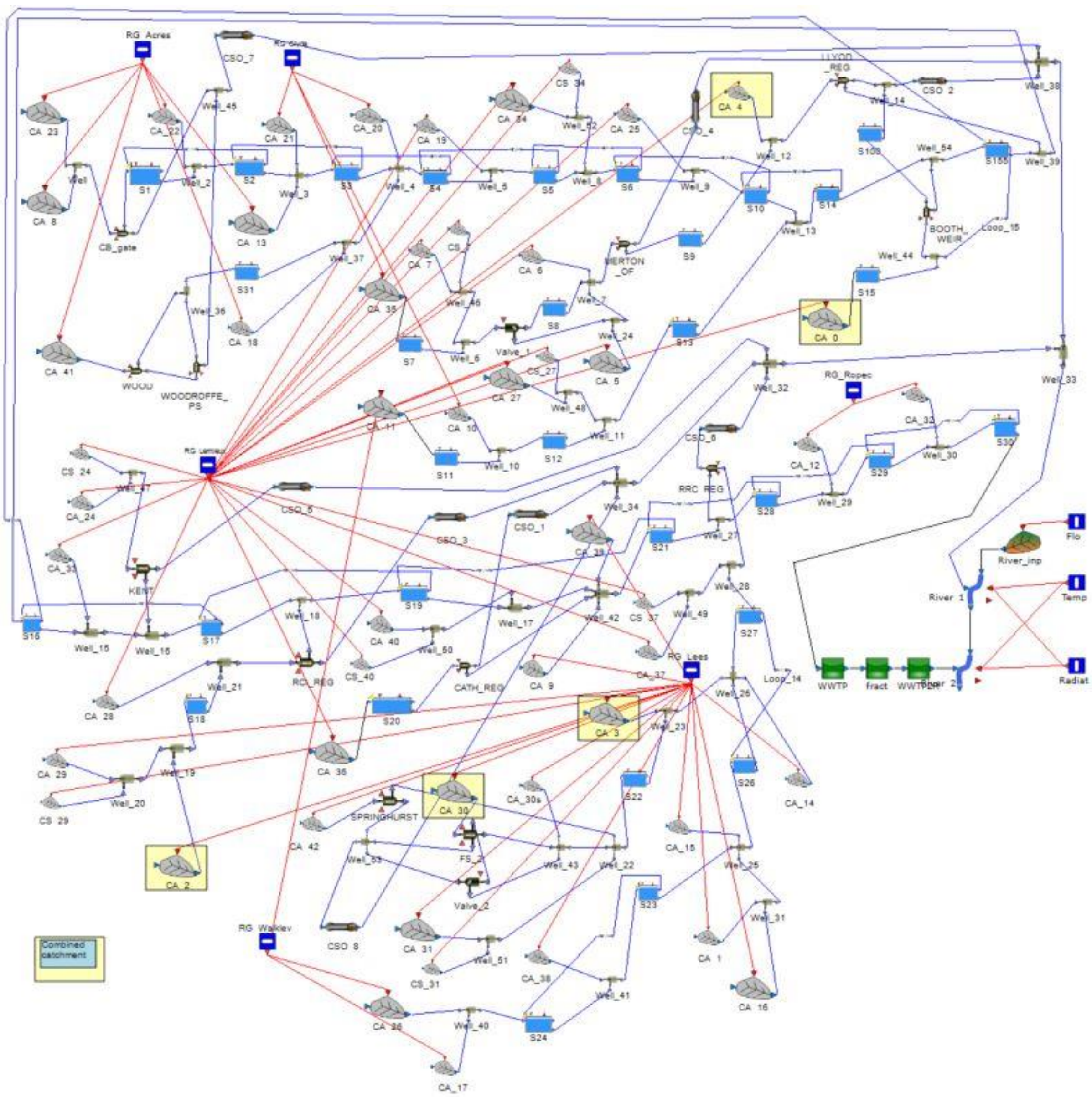

Figure B – 1: Model V1 configuration, including associated raingauges

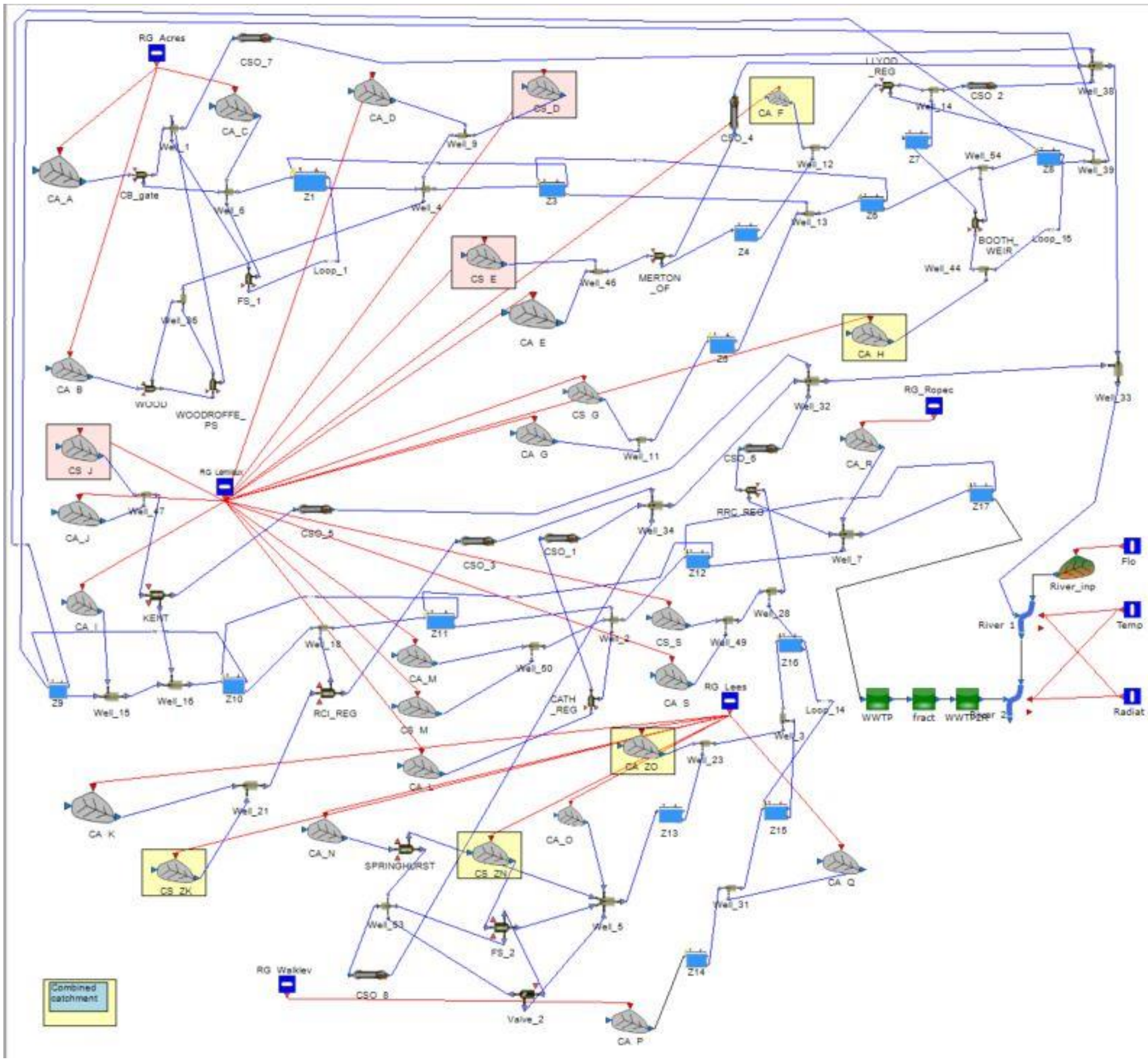

Figure B – 2: Model V2 configuration, including associated raingauges

Appendix C: Parameters of model block

Table B – 1: Sewer parameters for conceptual models V1 and V2

Note: Red sewer links use the non-linear models

Model sewer link		Main sewer characteristics (used for **non-linear pipes** in WEST)					**Linear reservoir** parameters; only applied to sewer with backwater or capacity constraints (bottlenecks)						Qback calculations					
V1	V2	Avg Diam	Length	Avg slope	Backflow or bottleneck	Linear/ non-linear pipe	Lc	L*	W	n	k total	k per tank	Calculated sewer capacity		Detailed model max flow		Qback for linear reservoirs (max of: flow seen in detailed model OR calculated sewer capacity)	
		(m)	(m)	(m/m)			(m)	(m)	(m)		(days)	(days)	(m3/s)	(m3/d)	(m3/s)	(m3/d)	(m3/s)	(m3/d)
S1	(Z1)	1.05	2,263	0.0009	backwater	linear	478	566	0.82	4	0.0060	0.0015	0.810	69,957	0.810	69,957		
S2	(Z1)	1.19	1,221	0.0010	backwater	linear	464	610	0.93	2	0.0055	0.0027	1.213	104,760	1.213	104,760	0.501	43,286
S3	(Z1)	1.47	1,474	0.0007	backwater	linear	886	1474	1.18	1	0.0142	0.0142	1.725	149,050	1.725	149,050	1.080	93,312
S4	(Z3)	1.72	1,276	0.0005	bottleneck	linear	1398	1276	1.36	1	0.0122	0.0122	2.262	195,477	2.299	198,650	2.074	179,194
S5	(Z3)	1.55	2,710	0.0006	bottleneck	linear	981	1355	1.22	2	0.0123	0.0061	1.948	168,313	2.504	216,325	2.605	225,072
S6	(Z3)	1.65	660	0.0008	bottleneck	linear	869	660	1.30	1	0.0053	0.0053	2.511	216,993	3.137	270,998	2.706	233,798
S7		1.03	1,739	0.0027	-	non-linear	151	158	0.84	11	0.0009	0.0001	1.355	117,114	1.355	117,114		
S8		1.31	1,200	0.0049	-	non-linear	107	109	1.06	11	0.0005	0.00004	3.481	300,740	3.481	300,740		
S9	Z4	1.18	1,492	0.0026	-	non-linear	180	187	0.94	8	0.0010	0.0001	1.917	165,628	1.917	165,628		
S10	(Z3)	1.65	533	0.0008	bottleneck	linear	836	533	1.30	1	0.0042	0.0042	2.560	221,224	3.228	278,931	2.738	236,563
S11		1.05	2,822	0.0022	-	non-linear	190	202	0.82	14	0.0013	0.0001	1.285	110,993	1.285	110,993		
S12		1.05	1,387	0.0024	-	non-linear	177	198	0.83	7	0.0013	0.0002	1.331	114,987	1.331	114,987		
S13	Z5	1.05	559	0.0054	-	non-linear	78	80	0.82	7	0.0004	0.0001	2.003	173,060	2.003	173,060	2.003	173,059.544
S14	Z6	1.65	787	0.0009	bottleneck	linear	755	787	1.30	1	0.0059	0.0059	2.695	232,872	4.571	394,969	3.539	305,770
S15		1.89	1,225	0.0037	-	non-linear	203	204	1.49	6	0.0007	0.0001	8.020	692,959	8.020	692,959		
S16	Z9	1.80	1,029	0.0009	bottleneck	linear	806	1029	1.41	1	0.0073	0.0073	3.435	296,814	5.574	481,635	4.708	406,771
S17	Z10	1.80	803	0.0015	bottleneck	linear	481	803	1.41	1	0.0044	0.0044	4.448	384,323	5.877	507,801	4.880	421,632
S18		2.10	1,171	0.0056	-	non-linear	149	167	1.65	7	0.0004	0.0001	12.960	1,119,727	12.960	1,119,727		
S19	Z11	2.10	1,263	0.0008	bottleneck	linear	1062	1263	1.65	1	0.0085	0.0085	4.877	421,403	5.852	505,655	7.055	609,552
S20		1.86	885	0.0047	-	non-linear	158	177	1.51	5	0.0006	0.0001	8.593	742,437	8.593	742,437		
S21	Z12	2.10	769	0.0012	bottleneck	linear	705	769	1.65	1	0.0042	0.0042	5.987	517,255	6.979	602,994	6.936	599,270
S22	Z13	1.46	2,566	0.0010	-	non-linear	591	641	1.15	4	0.0046	0.0011	2.075	179,318	2.226	192,307		
S23	Z14	1.38	2,642	0.0004	bottleneck	linear	1507	2642	1.09	1	0.0365	0.0365	1.085	93,761	1.788	154,458	1.788	154,458
S24		1.31	1,314	0.0006	backwater	linear	919	1314	1.04	1	0.0162	0.0162	1.172	101,264	1.172	101,264	1.172	101,264
S26	Z15	1.95	1,898	0.0012	-	non-linear	649	949	1.54	2	0.0053	0.0027	4.929	425,860	5.036	435,071	5.036	435,071

Model sewer link		Main sewer characteristics (used for **non-linear pipes** in WEST)					**Linear reservoir** parameters; only applied to sewer with backwater or capacity constraints (bottlenecks)						Qback calculations					
V1	V2	Avg Diam	Length	Avg slope	Backflow or bottleneck	Linear/ non-linear pipe	Lc	L*	W	n	k total	k per tank	Calculated sewer capacity		Detailed model max flow		Qback for linear reservoirs (max of: flow seen in detailed model OR calculated sewer capacity)	
		(m)	(m)	(m/m)			(m)	(m)	(m)		(days)	(days)	(m3/s)	(m3/d)	(m3/s)	(m3/d)	(m3/s)	(m3/d)
S27	Z16	2.07	1,186	0.0019	-	non-linear	429	593	1.63	2	0.0026	0.0013	7.361	635,979	7.361	635,979	7.361	635,979
S28	(Z17)	2.39	3,014	0.0010	backwater	linear	999	1005	1.88	3	0.0058	0.0019	7.570	654,053	7.570	654,053	8.871	766,454
S29	(Z17)	2.40	2,097	0.0009	bottleneck	linear	1065	2097	1.88	1	0.0121	0.0121	7.432	642,096	7.432	642,096	7.432	642,096
S30	(Z17)	2.40	2,605	0.0009	backwater	linear	1056	1302	1.88	2	0.0074	0.0037	7.466	645,035	7.483	646,524	8.801	760,406
S31		0.90	2,690	0.0043	-	non-linear	84	84	0.71	32	0.0005	0.00002	1.186	102,453	1.186	102,453		
S260		1.67	1,316	0.0011	-	non-linear	603	658	1.34	2	0.0044	0.0022	3.142	271,448	3.142	271,448		
S100	Z7	1.80	125	0.0064	-	non-linear	113	125	1.41	1	0.0003	0.0003	9.172	792,440	9.172	792,440		
S155	Z8	1.80	89	0.0098	backwater	linear	73	89	1.41	1	0.0003	0.0003	11.402	985,170	11.402	985,170	3.460	298,944
	Z1	1.21	4,957	0.0009	backwater	linear	568	991	0.98	5	0.0095	0.0019	1.725	149,050	1.725	149,050	1.080	93,312
	Z3	1.62	5,179	0.0006	bottleneck	linear	1025	1036	1.28	5	0.0092	0.0018	2.560	221,224	3.228	278,931	2.738	236,563
	Z17	2.40	7,716	0.0009	backwater	linear	1035	1543	1.88	5	0.0113	0.0023	7.466	645,035	7.483	646,524	8.801	760,406

Table C – 2: Catchment parameters for conceptual Model V1

Catchment	Area (ha)	Inhabitants	WW_PerIE	Q_intustry (m3/d)	GWI (L/s/ha)	DWF Pattern number	k-dwf	n-dwf	Raingauge	RTK	Runoff coefficient	F_fast	Kf	Ks	nS	nF
CA_0	156.7	18,284	0.196	0	0.07	2	0.10	1	Lemieux	Combined	0.50	1.00	0.01	0.17	10	2
CA_1	82.4	9,258	0.197	0	0.11	0	0.10	1	Lees	Riverlane/hazeldean	0.27	0.37	0.21	0.21	10	2
CA_10	46.7	2,266	0.190	0	0.06	0	0.10	1	Clyde	Hazeldean	0.08	0.13	0.06	0.17	10	2
CA_11	435.2	21,607	0.190	0	0.06	4	0.10	1	Walkley	Hazeldean/rideauriver	0.08	0.13	0.06	0.17	10	2
CA_12	223.2	13,242	0.294	0	0.10	4	0.10	1	Ropec	hazeldean/sherbourne	0.08	0.13	0.06	0.17	10	2
CA_13	383.4	26,640	0.236	0	0.13	3	0.10	1	Acres	parkway	0.11	0.80	0.30	1.25	10	2
CA_14	270.9	28,484	0.247	0	0.10	3	0.10	1	Lees	Riverlane/some sherbourne	0.27	0.37	0.21	0.21	10	2
CA_15	186.2	21,101	0.224	0	0.13	2	0.10	1	Lees	Riverlane/some riverlane	0.27	0.37	0.21	0.21	10	2
CA_16	193.0	15,072	0.251	0	0.10	4	0.10	1	Lees	Hazeldean/sherbourne	0.27	0.37	0.21	0.21	10	2
CA_17	65.8	4,819	0.230	0	0.10	2	0.10	1	Walkley	Riverlane/sherbourne	0.27	0.37	0.21	0.21	10	2
CA_18	171.7	8,507	0.198	0	0.26	3	0.10	1	Clyde	Sherbourne	0.24	0.46	0.25	0.29	10	2

Catchment	Area (ha)	Inhabitants	WW_PerIE	Q_intustry (m3/d)	GWI (L/s/ha)	DWF Pattern number	k-dwf	n-dwf	Raingauge	RTK	Runoff coefficient	F_fast	Kf	Ks	nS	nF
CA_19	235.0	25,163	0.195	0	0.16	1	0.10	1	Lemieux	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_2	278.8	39,260	0.266	0	0.07	3	0.10	1	Lees	Combined	0.60	1.00	0.01	0.17	10	2
CA_20	206.0	10,273	0.197	0	0.16	3	0.10	1	Clyde	Sherbourne/hazeldean	0.24	0.46	0.25	0.29	10	2
CA_21	60.3	6,232	0.198	0	0.16	4	0.10	1	Clyde	Hazeldean(mostly), plus sherbourne	0.08	0.13	0.06	0.17	10	2
CA_22	164.3	11,927	0.199	0	0.16	4	0.10	1	Acres	hazeldean (mostly), plus sherbourne, rideauriver	0.08	0.13	0.06	0.17	10	2
CA_23	143.9	8,475	0.195	0	0.08	2	0.10	1	Acres	hazeldean/rideauriver	0.08	0.13	0.06	0.17	10	2
CA_24	60.2	29,596	0.216	0	0.07	1	0.10	1	Lemieux	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_25	39.2	2,616	0.199	0	0.08	4	0.10	1	Lemieux	hazeldean/sherbourne	0.08	0.13	0.06	0.17	10	2
CA_26	406.1	24,184	0.231	0	0.12	3	0.10	1	Walkley	Riverlane/hazeldean/sherbourne	0.27	0.37	0.21	0.21	10	2
CA_27	121.2	13,510	0.190	0	0.05	2	0.10	1	Lemieux	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_28	45.4	34,810	0.195	0	0.07	0	0.10	1	Lemieux	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_29	31.3	10,898	0.250	0	0.07	2	0.10	1	Lees	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_3	81.1	6,264	0.255	0	0.11	4	0.10	1	Lees	Combined	0.43	1.00	0.01	0.17	10	2
CA_30	58.0	4,848	0.246	0	0.11	3	0.10	1	Lees	Combined	0.56	1.00	0.01	0.17	10	2
CA_31	177.6	13,309	0.237	0	0.11	3	0.10	1	Lees	Riverlane	0.27	0.37	0.21	0.21	10	2
CA_32	368.5	11,757	0.282	0	0.07	4	0.10	1	Ropec	hazeldean/some sherbourne	0.075	0.13	0.06	0.17	10	2
CA_33	30.7	3,536	0.217	0	0.07	1	0.10	1	Lemieux	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_34	26.2	2,691	0.195	0	0.06	1	0.10	1	Lemieux	Sherbourne/some hazeldean	0.24	0.46	0.25	0.29	10	2
CA_35	359.2	27,537	0.198	0	0.14	3	0.10	1	Clyde	Sherbourne/hazeldean	0.24	0.46	0.25	0.29	10	2
CA_36	25.7	7,804	0.212	0	0.07	0	0.10	1	Lemieux	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_37	191.5	13,767	0.253	0	0.10	4	0.10	1	Lemieux	Riverlane/some sherbourne	0.27	0.37	0.21	0.21	10	2
CA_38	150.5	5,093	0.251	0	0.10	4	0.10	1	Lees	Riverlane	0.27	0.37	0.21	0.21	10	2
CA_39	55.0	7,957	0.282	0	0.07	4	0.10	1	Lees	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_4	43.5	5,863	0.198	0	0.14	3	0.10	1	Lemieux	combined	0.24	0.46	0.25	0.29	10	2
CA_40	51.9	11,428	0.235	0	0.07	2	0.10	1	Lemieux	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_41	273.0	17,256	0.197	0	0.14	2	0.10	1	Clyde	woodroffe	0.21	0.38	0.08	0.21	10	2
CA_42	41.5	6,584	0.256	0	0.10	4	0.10	1	Lees	Riverlane	0.27	0.37	0.21	0.21	10	2
CA_5	51.1	4,324	0.199	0	0.14	4	0.10	1	Lemieux	Sherbourne	0.24	0.46	0.25	0.29	10	2

Catchment	Area (ha)	Inhabitants	WW_PerIE	Q_intustry (m3/d)	GWI (L/s/ha)	DWF Pattern number	k-dwf	n-dwf	Raingauge	RTK	Runoff coefficient	F_fast	Kf	Ks	nS	nF
CA_6	31.1	4,112	0.197	0	0.14	3	0.10	1	Lemieux	Sherbourne	0.24	0.46	0.25	0.29	10	2
CA_7	75.4	3,978	0.197	0	0.14	3	0.10	1	Lemieux	Sherbourne(mostly), some hazeldean	0.24	0.46	0.25	0.29	10	2
CA_8	204.2	13,227	0.197	0	0.08	3	0.10	1	Acres	hazeldean/rideau river	0.025	0.40	0.13	0.10	10	2
CA_9	56.3	15,174	0.230	0	0.07	1	0.10	1	Lees	Sherbourne	0.24	0.46	0.25	0.29	10	2

Table C – 3: Catchment parameters for conceptual Model V2

Catchment	Merged areas	Area (ha)	Inhabitants	WW_PerIE	GWI (L/s/ha)	Q_intustry (m3/d)	DWF Pattern number	k-dwf	n-dwf	Runoff coefficient	F_fast	Kf	Ks	nS	nF
A	CA_8, CA_23	348.1	21,702	0.084	0.08	570	3	0.15	2	0.12	0.18	0.24	0.76	2	5
B	CA_41	273.0	17,256	0.190	0.14	2,800	2	0.13	4	0.25	0.68	0.38	0.80	6	2
C	CA_22, CA_21, CA_13	608.0	44,800	0.192	0.12	1,495	2	0.10	8	0.17	0.50	0.24	0.61	2	5
D	CA_18, CA_19, CA_20, CA_34, CA_25	678.0	49,250	0.167	0.12	1,574	1	0.15	4	0.33	0.39	0.28	0.90	2	10
E	CA_35, CA_7, CA_6, CA_5	516.8	39,952	0.193	0.13	935	3	0.10	4	0.27	0.29	0.27	0.76	2	10
F	CA_4	43.5	5,863	0.240	0.14	95	4	0.05	2	0.60	0.60	0.04	0.80	2	3
G	CA_11, CA_10, CA_27	603.1	37,383	0.150	0.06	1,000	2	0.11	4	0.18	0.28	0.28	0.81	2	10
H	CA_0	156.7	18,284	0.160	0.07	165	4	0.10	1	0.60	0.90	0.05	1.00	2	15
I	CA_33	30.7	3,536	0.190	0.07	30	0	0.10	1	0.33	0.35	0.26	0.83	2	10
J	CA_24	60.2	29,596	0.090	0.07	65	4	0.10	2	0.33	0.35	0.26	0.83	2	10
K	CA_28, CA_29, CA_2	76.7	45,708	0.051	0.07	85	3	0.05	2	0.34	0.34	0.27	0.83	2	5
L	CA_36	25.7	7,804	0.070	0.07	75	3	0.03	1	0.33	0.48	0.27	0.83	2	4
M	CA_40, CA_9, CA_39	163.2	34,558	0.156	0.07	175	3	0.10	2	0.31	0.50	0.29	0.95	2	5
N	CA_42	41.5	6,584	0.200	0.10	1,000	1	0.07	4	0.50	0.25	0.06	0.65	2	4
O	CA_31, CA_30	192.6	14,739	0.169	0.11	1,000	1	0.13	4	0.37	0.20	0.19	0.65	2	4
P	CA_25, CA_38	622.4	34,096	0.224	0.08	1,550	2	0.17	4	0.23	0.19	0.20	0.67	2	5
Q	CA_15, CA_1, CA_14	732.4	73,915	0.167	0.11	7,150	1	0.13	5	0.25	0.29	0.27	0.77	2	4
R	CA_12, CA_32	591.8	24,998	0.274	0.08	2,590	4	0.15	1	0.11	0.36	0.30	1.00	2	10
S	CA_37	191.5	13,767	0.200	840	0.10	0	0.13	4	0.45	0.20	0.20	0.80	3	2

Table C – 4: Special hydraulic structures – conceptual model parameters

	PCSWMM links			WEST Parameters					Model V1
REGULATOR	**Cal_out1**	**Cal_out2**	**PCSWMM RTC structure simplified?**	**Block name**	**Out1**	**Out2**	**Qout2 (L/s)**	**m3/d**	**Calibration order**
Woodroffe Diversion Gate	SAN43854	SAN65694_2	simplified	WOOD	WOODROFFE_PS	Well_36	250	21,600	1
Woodroffe Pump Station	SAN43852	TOWOODPS	simplified	WOODROFFE_PS	Well_36	CSO_7	540	46,656	1
Merton Overflow	STM37909	SAN64125		Merton OF	CSO_4	S9	1,300	112,320	3
West Nepean Regulator	COM10422_2	BOOTH_REG	simplified	Booth	Well_16	Well 15	1,500	129,600	9.5
Llyod Weir	Weir_lloydp_of	SAN00197	simplified	Llyod REG	CSO_2	Well_16	1,100	95,040	9.5
Kent Overflow	SAN38407	SAN46391		KENT	CSO_5	Well_17	500	43,200	11.5
Cathcart Regulator	STM39847_2	Cathreg_flowLIM	simplified	Cathcart REG	CSO_1	Well_42	800	69,120	2
Rideau Canal Interceptor (RCI) Regulator	STM38559	RCI_pipe	simplified	RCI REG	CSO_3	Well_18	3,500	302,400	3
Rideau River Collector Regulator (RRC) Regulator	SAN50754	Keefer	simplified	RRC_REG	CSO_6	Well_17	2,000	172,800	13.5
Clegg Gate	na	na		FS_2	Well_53	Well_43	135	11,664	3
Cleeg Reel	SAN52814	SAN52066		Valve_2	Well_39	Well_22	135	11,664	2
Springhurst Overflow	SAN38680	SAN52735		Springhurst	Well_39	Well_22	1,752	151,373	2
Crystal Beach PS	SAN50686	SAN-0143		crystal_beach	well_45	S1	230	19,872	2

Appendix D: Calibrated parameters

Table D – 1: Conceptual models' sewer calibration information

Model sewer link		Calibration information				
V1	V2	Detailed model comparison location	WEST Comparison location	Calibration order (model V1)	Calibration order (model V2)	Calibration notes
S1		SAN01825	NA	1		cannot calibrate due to varying input location of CA_22
S2		SAN01814	S2	2		calibrate CA_22 using S2
S3		SAN01802	S3	3		use to calibrate CA_21; modelled will be a tiny bit higher because some of CA21 is after comparison link
S4		SAN01792	S4	4		use to calibrate CA_20
S5		SAN01775	S5	5		use to calibrate CA_19
S6		SAN51576	Well_9	6		
S7		COM10522	Well_6	1		use Well6 (includes CA_7)
S8		SAN00218_1	Well_7	2		use to calibrate CA6
S9	Z4	SAN00200	Well_12	4	2	use Well 12 to calibrate CA4
S10		SAN01767	S10	7		
S11		SAN00985	Well_10	1		includes CA10, compare to Well 10
S12		SAN00975	NA	2		assume ok, calibrate CA_27 using S13
S13	Z5	SAN00968	S13	3	2	calibrate CA_27 using S13
S14	Z6	SAN01761	S14	8	4	
S15		COM10422_1	S15	1		do not calibrate S15, use to Calibrate CA_0
S16	Z9	SAN00778	Well_15	10	6	use to calibrate CA33
S17	Z10	SAN00777	S17	11	7	use to calibrate CA24
S18		COM11219	Well_21	2		use for CA_28 as well
S19	Z11	SAN44049_1	Well_17	12	8	
S20		STM39847_1	S20	4		look at cathcart regulator
S21	Z12	SAN00774	S21	13	9	
S22	Z13	SAN56801	S22	3	2	use to calibrate CA_42
S23	Z14	SAN52890	Well_25	3	2	use to check CA 1, 15, 16, compare with WEST Well

Model sewer link		Calibration information				
V1	V2	Detailed model comparison location	WEST Comparison location	Calibration order (model V1)	Calibration order (model V2)	Calibration notes
S24		SAN01455	S24	1		includes CA 17; use to calibrate CA_17
S26	Z15	SAN01411	Well_26	4	3	use to calibrate CA14
S27	Z16	SAN01399	Well_28	5	4	use to calibrate CA37
S28		SAN01292	Well_29	14		use to calibrate CA12; use Well 29
S29		SAN01290	NA	15		cannot calibrate because CA 32 is added between S29 and S30
S30		SAN01286	S30	16		use to calibrate CA32
S31		SAN01707	Well_37	2		use S31 and Well to calibrate CA_18
S260		NA	NA	2		
S100	Z7	COM10609	S100	9	5	
S155	Z8	SAN00782	S155		5	
	Z1	SAN01802	S3		2	
	Z3	SAN01767	S10		3	
	Z17	SAN01286	S30		10	

Table D – 2: Calibrated catchment parameters for conceptual Model V1

Catchment	Detailed model comparison location	WEST comparison location	Calibration location notes	Calibration order	WW_PerIE	Q_intustry (m3/d)	GWI (L/s/ha)	DWF Pattern number	k-dwf	n-dwf	Runoff coefficient	F_fast	Kf	Ks	nS	nF
CA_0	COM15555	CA_0	S15	1	0.16	165		4		1	0.6	0.9	0.045	1	15	2
CA_1	sum: SAN29767, SAN29713; missing some flow	na	NA	1	0.17	2000		2	0.1	8	0.1	0.17	0.33	0.7	3	2
CA_10	cannot explicitly compare	Well_10	Well_10; includes CA 11, 10	1	0.52	40		4	0.11		0.2	0.29	0.17	0.833	10	3
CA_11	SAN01014	CA_11	CA_11	0	0.155	590		2	0.1	4	0.13	0.21	0.28	0.75	10	2
CA_12	use S28	Well_29	Well 29	14.5	0.25	1000			0.15		0.11	0.36	0.3	1	10	2
CA_13	SAN01296	CA_13	CA_13	0	0.18	800			0.08	8	0.16	0.7	0.2	0.375	3	2

Catchment	Detailed model comparison location	WEST comparison location	Calibration location notes	Calibration order	WW_PerIE	Q_intustry (m3/d)	GWI (L/s/ha)	DWF Pattern number	k-dwf	n-dwf	Runoff coefficient	F_fast	Kf	Ks	nS	nF
CA_14	cannot calibrate explicitly: use avg values from CA: 12, 16	Well_26	S26	4.5	0.18	3000			0.13		0.4	0.27	0.25	0.7	3	2
CA_15	sum: SAN30148; SAN30118 (but missing small bit of flow from apartment complex that goes straight to collector)	na	flow monitor on 2 main sewers in Ca 15	1	0.11	700			0.1	8	0.16	0.26	0.25	0.7	5	2
CA_16	SAN29728	CA_16	CA_16	0	0.22	1450		2	0.12	4	0.19	0.4	0.28	0.95	5	2
CA_17	cannot explicitly calibrate; same as CA_38? Use S24 to calibrate CA_17	S24	S24; check parameters against 38 and 26	2		0					0.26	0.22	0.24	0.8	5	2
CA_18	SAN01708	Well_37	Well_37 and compare to S31; for sum of CA_41 & CA_18	2.5		0			0.14		0.31	0.33	0.28	0.83	10	2
CA_19	SAN44049_1	S5	S5	5	0.15	0	0.1	1	0.15	4	0.37	0.33	0.26	0.9	10	2
CA_2	COM11861_2	CA_2	CA_2	0	0.16	3000		3	0.1	2	0.95	0.85	0.04	0.3	3	2
CA_20	STM39847_1	S4	S4	3.5	0.2	1500	0.1	1	0.1		0.33	0.51	0.31	1	5	2
CA_21	SAN00774	S3	S3; sum 23, 8, 13, 22, 21;	3	0.19	145			0.1		0.11	0.36	0.3	1	10	2
CA_22	cannot explicitly compare; use S2	S2	Use S2: Well_2: sum CA_23, CA_8; use same properties as CA_23, CA_8, 22	1.5	0.22	550	0.12	2	0.1	4	0.2	0.1	0.3	1	15	2
CA_23	SAN01845	CA_23	CA_23	0		170		3	0.13	4	0.17	0.22	0.28	0.7	10	2
CA_24	SAN38406	CA_24	CA_24	1	0.09	65		4		2	0.33	0.35	0.26	0.83	10	2
CA_25	use S6	Well_9	Use Well_9: includes all upstream; same comparison pipe as for WEST_pipe S_6	6.5		50					0.29	0.38	0.29	0.8	10	2
CA_26	SAN01468	CA_26	CA_26	0	0.24	0	0.08	2	0.17	8	0.16	0.19	0.2	0.65	4	2
CA_27	SAN01399	S13	calibrate using S13	3	0.08	370		4	0.1	8	0.33	0.51	0.31	1	5	2
CA_28	COM11043, plus more	Well_21	This link does not include some of 28, therefore WEST flow will be a bit high; use S18 to calibrate	2	0.014	50		3	0.01		0.35	0.33	0.28	0.83	10	2

Catchment	Detailed model comparison location	WEST comparison location	Calibration location notes	Calibration order	WW_PerIE	Q_intustry (m3/d)	GWI (L/s/ha)	DWF Pattern number	k-dwf	n-dwf	Runoff coefficient	F_fast	Kf	Ks	nS	nF
CA_29	SAN38143	CA_29	CA_29	1	0.17	35		4	0.05	2	0.33	0.35	0.26	0.83	10	2
CA_3	COM12190	CA_3	CA_3	0	0.19	485		2	0.11	4	0.9	0.7	0.045	0.5	3	2
CA_30	SAN38516	CA_30	Well_43	0	0.16	0		2	0.2	2	0.3	0.2	0.19	0.65	4	2
CA_31	SAN38574	CA_31	Well_51	0	0.17	800		2	0.13	4	0.38	0.2	0.19	0.65	4	2
CA_32	cannot explicitly calibrate; use parameters from CA 12 as a check	S30	check S30	16	0.3	1590		4	0.15	1	0.11	0.36	0.3	1	10	2
CA_33	cannot explicitly compare; use similar values from 4 & 28	Well_15	Well_17; compare flow in sewer S_16 but includes all upstream	10.5		30					0.33	0.35	0.26	0.83	10	2
CA_34	SAN61883	CA_34	Well_52	0	0.1	24		3		1	0.29	0.38	0.29	0.8	10	2
CA_35	SAN65674	CA_35	CA_35	0	0.2	760			0.04	4	0.24	0.26	0.27	0.7	10	2
CA_36	SAN48759	CA_36	CA_36	0	0.07	75		3	0.03	1	0.33	0.48	0.27	0.83	4	2
CA_37	SAN01399	Well_28	S27	5.5	0.2	840		0	0.13	4	0.45	0.2	0.2	0.8	3	2
CA_38	SAN30314;	CA_38	CA_38	1	0.18	500		2		4	0.39	0.18	0.17	0.65	4	2
CA_39	SAN39552	CA_39	CA_39	0	0.27	60		4	0.04	1	0.33	0.52	0.29	0.95	4	2
CA_4	cannot explicitly compare; use similar values from CA 5, 25, 27 or 6	Well_12	Well_12 compare to S9; includes some upstream and based on proper flow-split at merton overflow	4.5	0.24	95			0.05		0.6	0.6	0.035	0.8	3	2
CA_40	SAN39651; can not do direct comparison	na	Well_50	1	0.15	55				4	0.35	0.6	0.31	1	5	2
CA_41	SAN01749	CA_41	CA_41	0	0.19	2800		2	0.13	4	0.25	0.68	0.38	0.8	2	6
CA_42	cannot explicitly calibrate;	S22	S22 to calibrate CA_42	3	0.2	1000		1	0.07	4	0.5	0.25	0.06	0.65	4	2
CA_5	SAN37472	Well_24	Well_24	2	0.24	110		4	0.1	2	0.35	0.55	0.28	1	5	2
CA_6	Calibrate using S8	Well_7	Well_7; includes 35, 7, 5, 6	2.5		65		4	0.05	8	0.6	0.6	0.26	0.83	10	2
CA_7	COM10522	Well_6	Well 6; includes 35, 7	1.5	0.1	0	0.1	4	0.05		0.2	0.1	0.25	0.833	5	2
CA_8	SAN00525	CA_8	CA_8	0	0.1	400			0.15	2	0.085	0.145	0.22	0.8	5	2
CA_9	SAN39604	CA_9	CA_9	2.5	0.1	60		3			0.25	0.4	0.28	0.9	10	2

Table D – 3: Calibrated catchment parameters for conceptual Model V2

Catchment	Merged areas	Detailed model comparison location & notes	WEST comparison link	Calibration order	DWF Pattern number	k-dwf	n-dwf	Runoff coefficient	F_fast	Kf	Ks	nS	nF
A	CA_8, CA_23	SAN50685	CA_A	1	3	0.15	2	0.12	0.17	0.28	0.70	2	10
B	CA_41	same as CA41-do not change		0	2	0.13	4	0.25	0.68	0.38	0.80	6	2
C	CA_22, CA_21, CA_13	use Z1 -- S3		2	4	0.1	4	0.15	0.45	0.20	0.61	2	5
D	CA_18, CA_19, CA_20, CA_34, CA_25	use Z3 -- S10		3	4	0.2	8	0.34	0.35	0.03	0.90	2	10
E	CA_35, CA_7, CA_6, CA_5	S8	Well_46	1	4	0.06	2	0.27	0.29	0.27	0.76	2	10
F	CA_4	same as CA4-which had no comparison		0	4	0.05	2	0.60	0.60	0.04	0.80	2	3
G	CA_11, CA_10, CA_27	use Z5	Well11	1	3	0.14	4	0.20	0.28	0.30	0.81	2	10
H	CA_0	S15		1	4	0.04	2	0.62	0.75	0.04	0.04	2	5
I	CA_33	same as CA33-do not change		0	0	0.1	1	0.33	0.35	0.26	0.83	2	10
J	CA_24	same as CA24-do not change	CA_J	0	4	0.1	2	0.33	0.35	0.26	0.83	2	10
K	CA_28, CA_29, CA_2	COM11219	Well_21	1	3	0.05	1	0.34	0.34	0.27	0.83	2	5
L	CA_36	same S20	CA_L	1	4	0.07	1	0.33	0.48	0.27	0.83	2	4
M	CA_40, CA_9, CA_39	use Z12 -- S21		9	3	0.1	2	0.31	0.70	0.29	0.95	2	5
N	CA_42	same as CA30-do not change		0	1	0.07	4	0.50	0.25	0.06	0.65	2	4
O	CA_31, CA_30	use Z13	Well_5	2	2	0.13	8	0.43	0.25	0.19	0.65	2	4
P	CA_25, CA_38	SAN01454	CA_P	1	2	0.18	8	0.20	0.19	0.20	0.65	2	5
Q	CA_15, CA_1, CA_14	use Z15 -- S26		3	1	0.13	4	0.27	0.24	0.22	0.77	2	4
R	CA_12, CA_32	use Z17 -- S30		10	4	0.15	1	0.11	0.36	0.30	1.00	2	10
S	CA_37	same as CA_37		3	0	0.13	4	0.45	0.20	0.20	0.80	3	2

Appendix E: Additional graphed results

This Appendix contains the following graphs:

E1

- DWF sewer flow comparison hydrographs: Figures E1 – 1 to E1 – 5

E2

- WWF sewer flow comparison hydrographs: Figures E2 – 6 to E2 – 10
- WWF sample catchment flow comparison hydrographs: Figures E2 – 11 to E2 – 14
- WWF outfall flow comparison hydrographs: Figures E2 – 17 to E2 – 19

E3

- Validation period sewer flow comparison hydrographs: Figures E3 – 20 to E3 – 29
- Validation period outfall sample flow comparison hydrographs for Booth: Figures E3 – 30 to E3 – 31

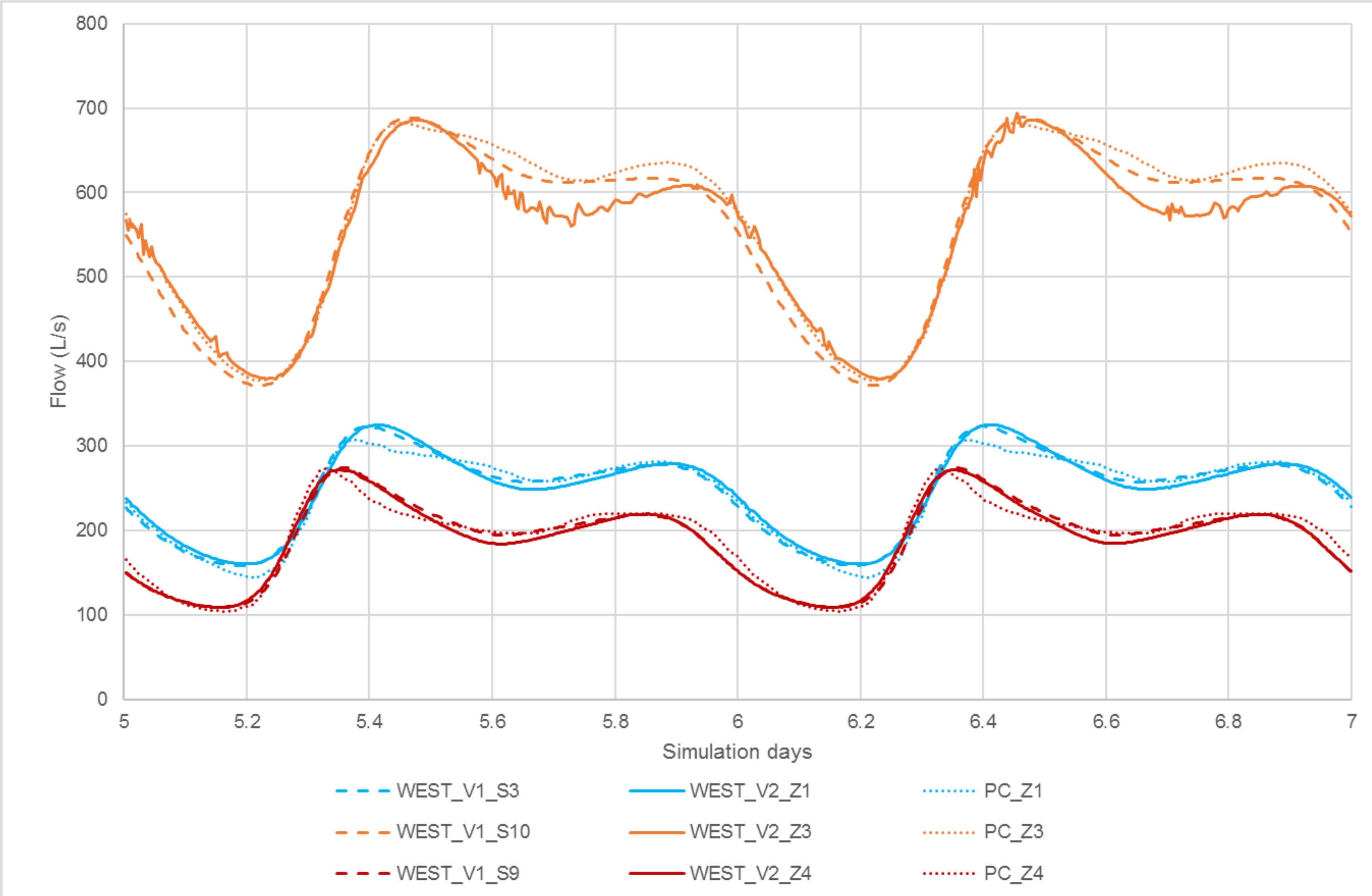

Figure E1 – 1: DWF results for West end (Z1, Z3, Z4)

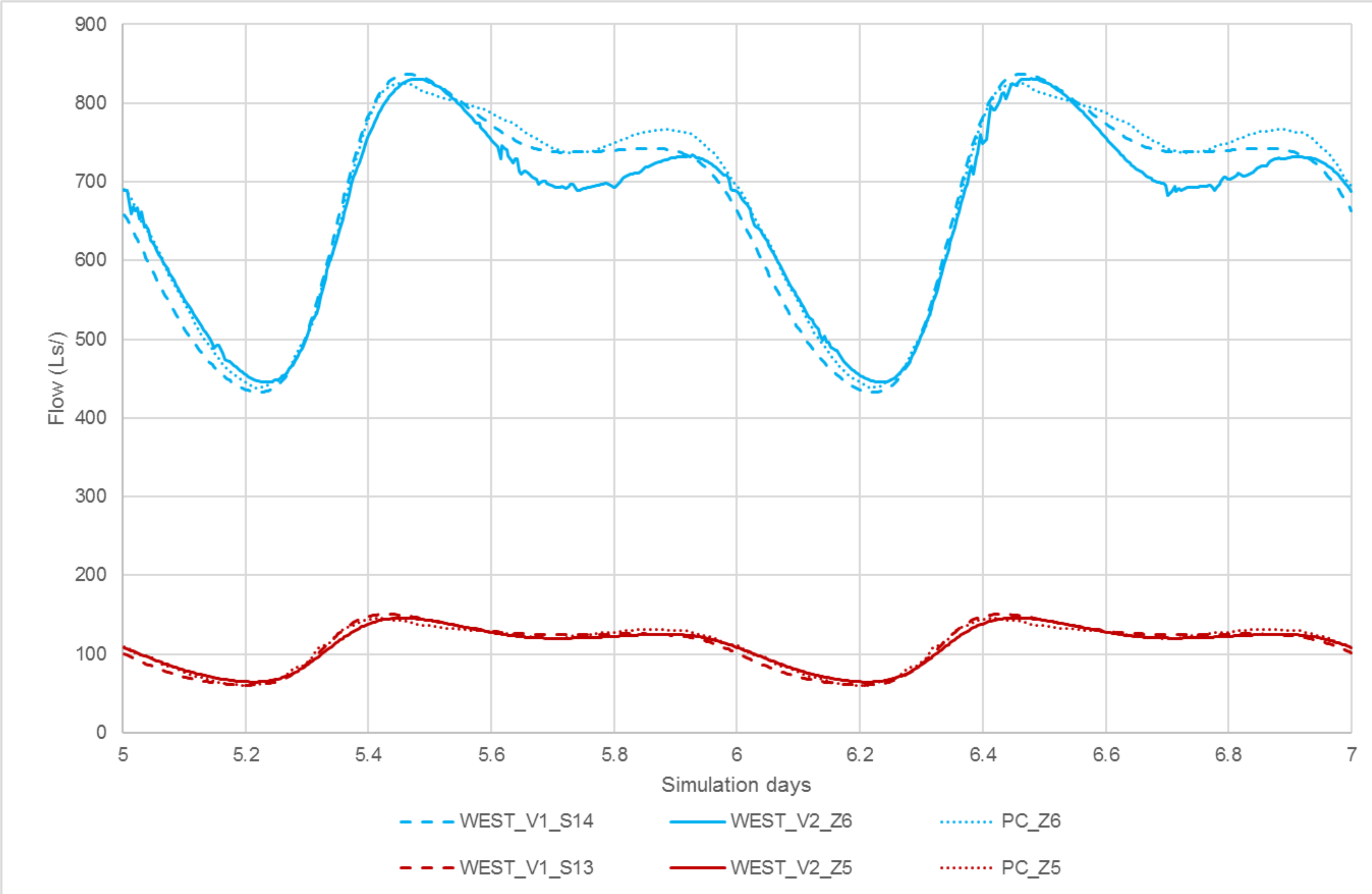

Figure E1 – 2: DWF results for Central area (Z5 & Z6)

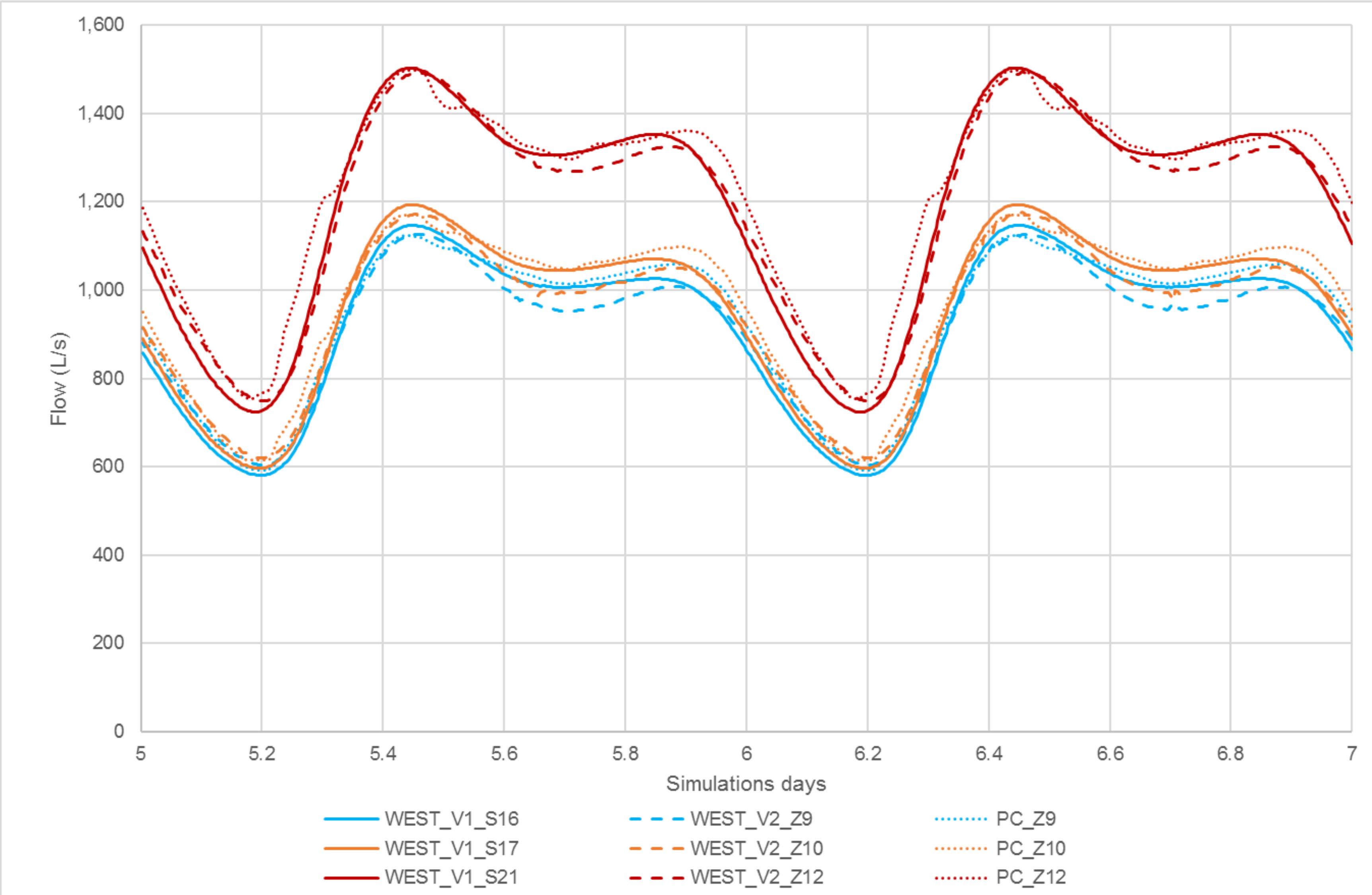

Figure E1 – 3: DWF results for Cathcart and RCI areas (Z9, Z10, Z12)

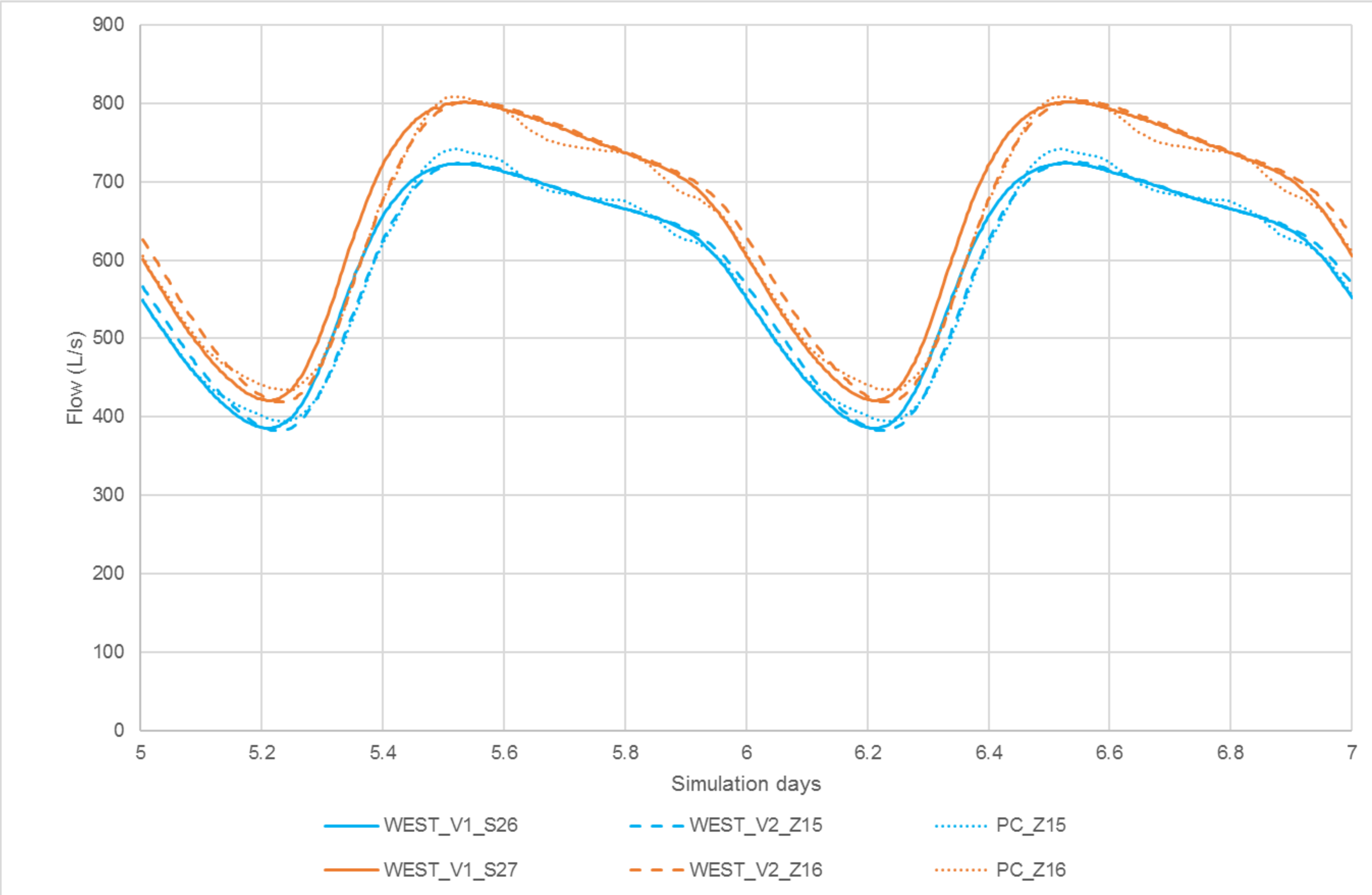

Figure E1 – 4: DWF results for RRC areas (Z9, Z10, Z12)

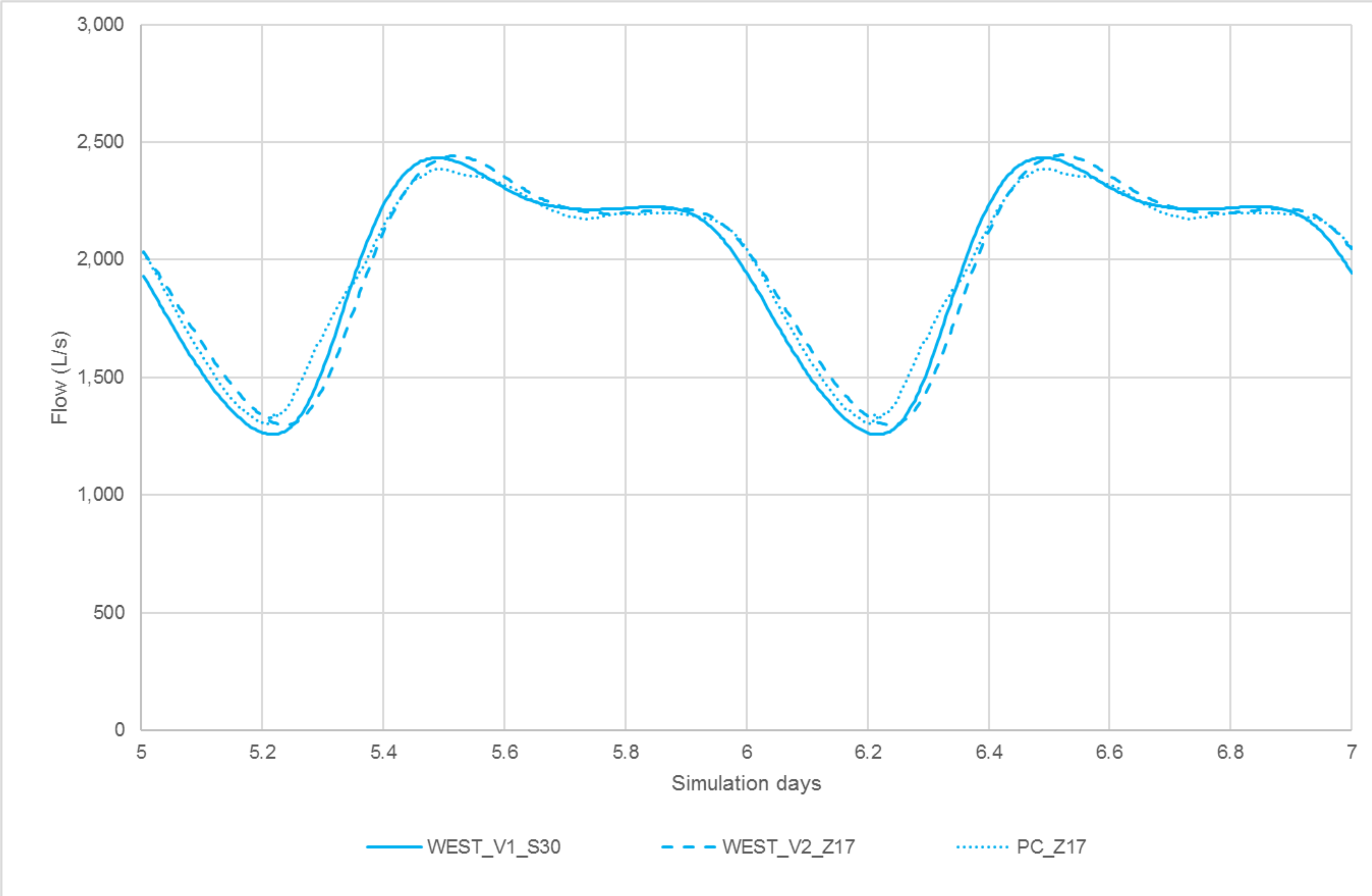

Figure E1 – 5: DWF results for downstream sewer (Z17)

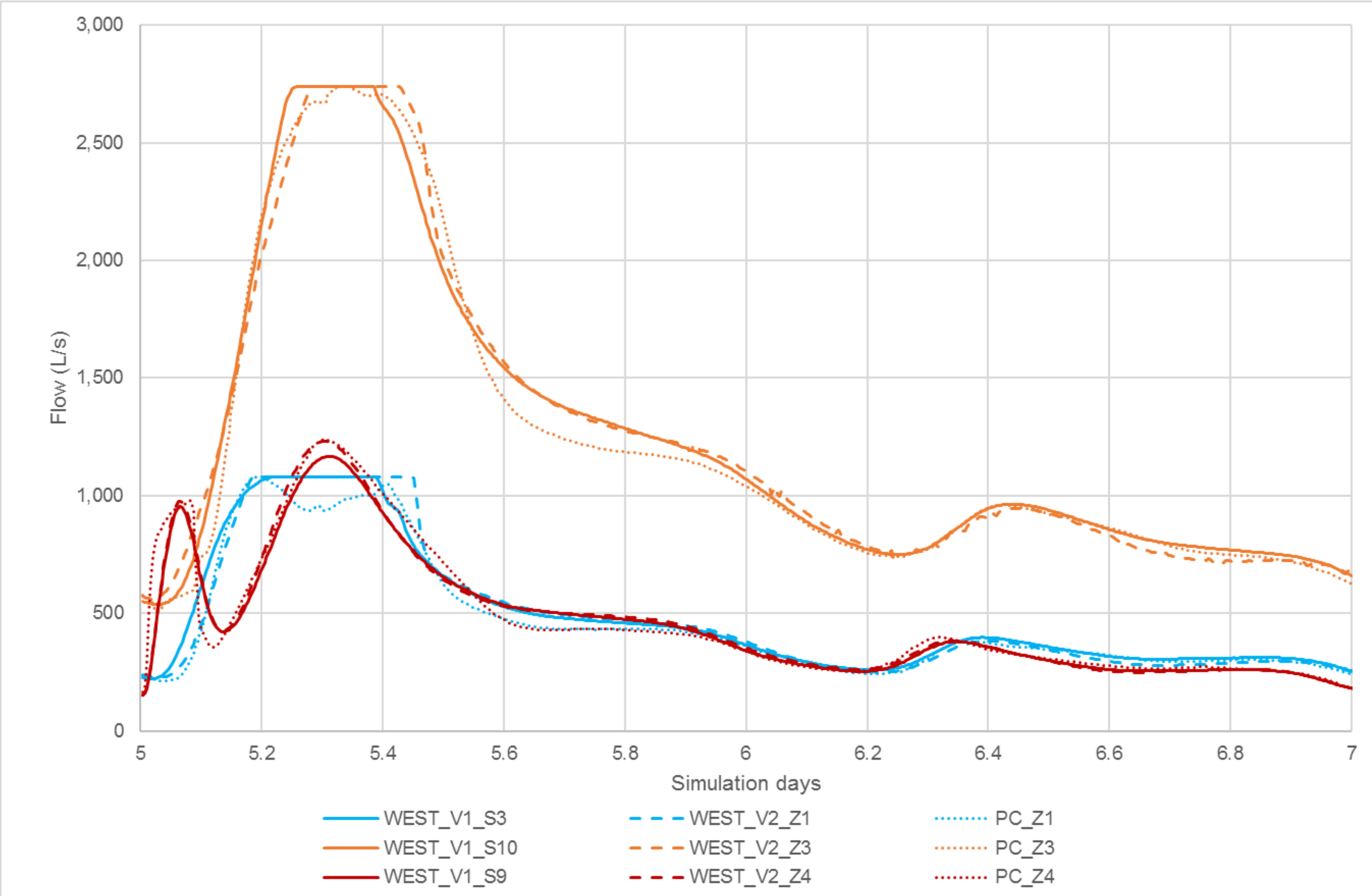

Figure E2 – 6: WWF results for West end (Z1, Z3, Z4)

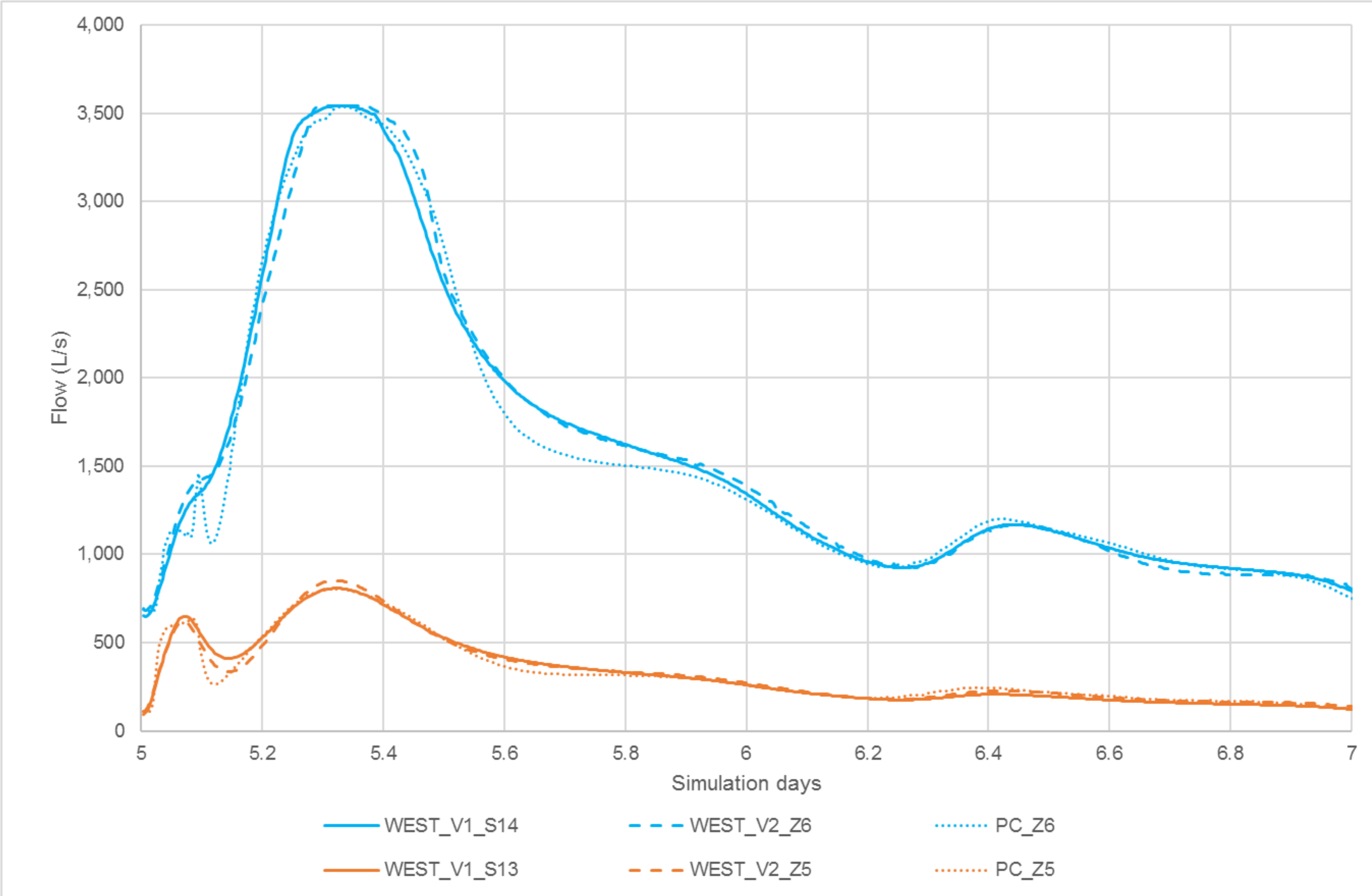

Figure E2 – 7: WWF results for Central area (Z5 & Z6)

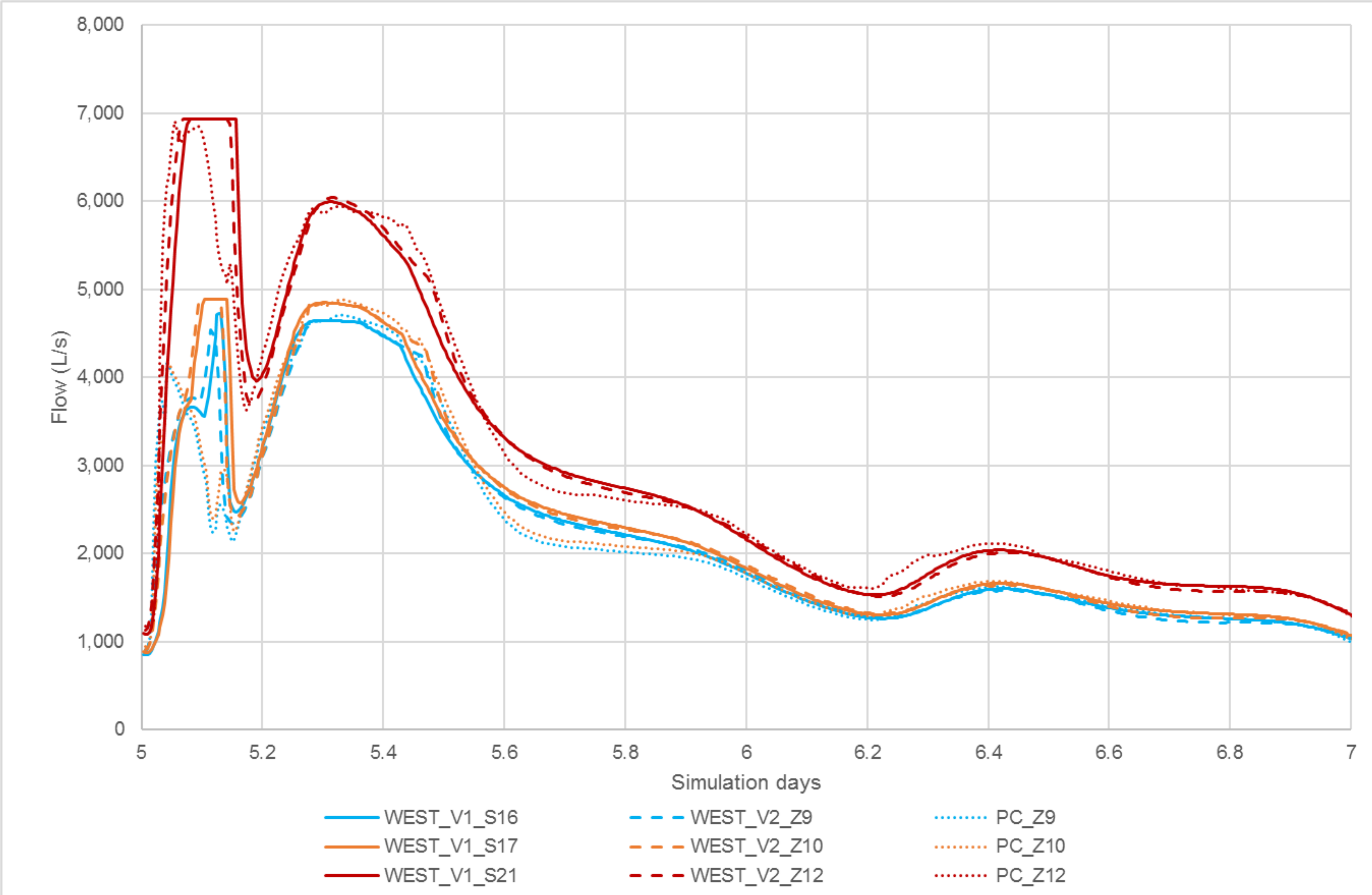

Figure E2 – 8: WWF results for Central area (Z5 & Z6)

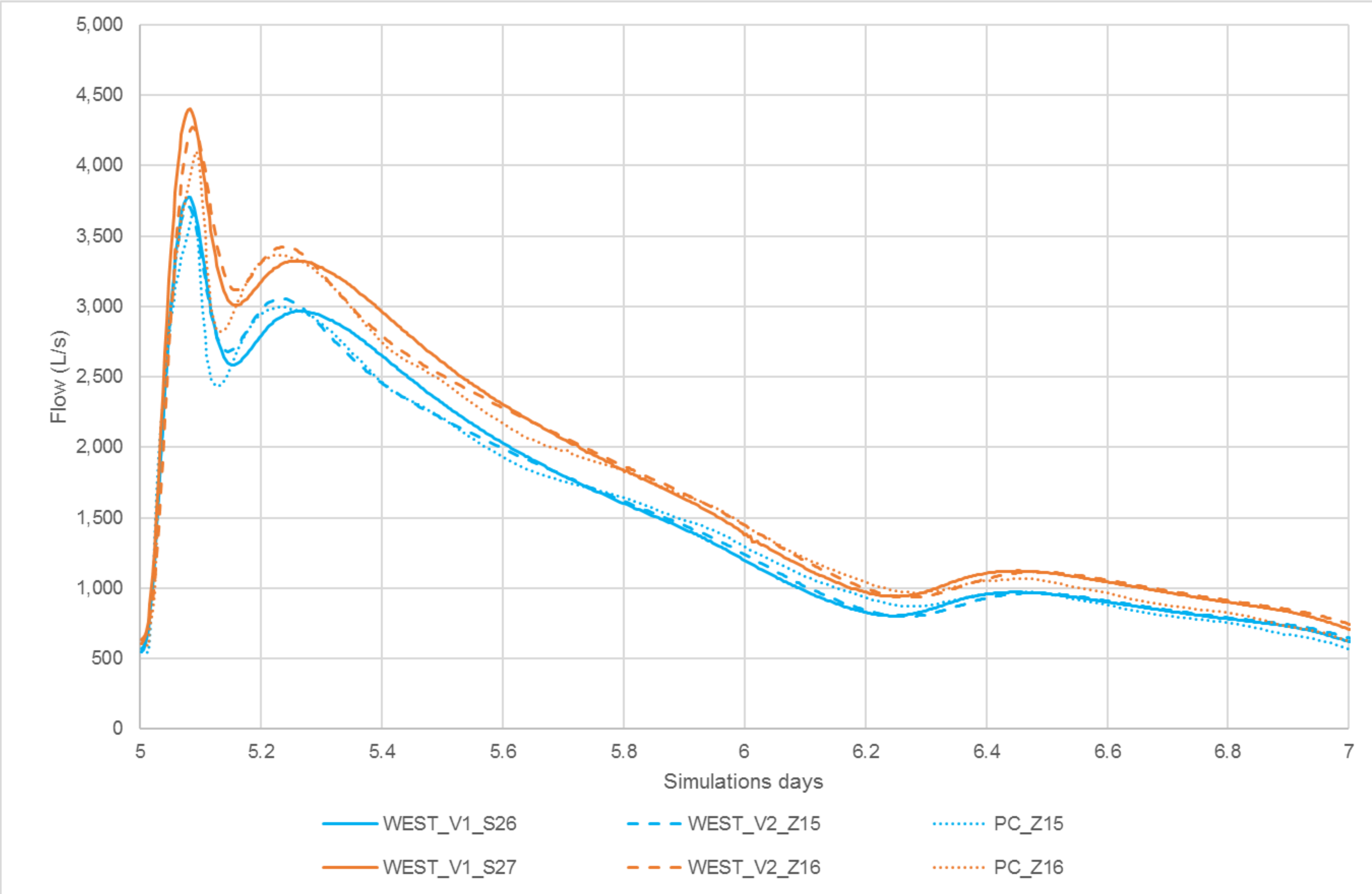

Figure E2 – 9: WWF results for RRC areas (Z9, Z10, Z12)

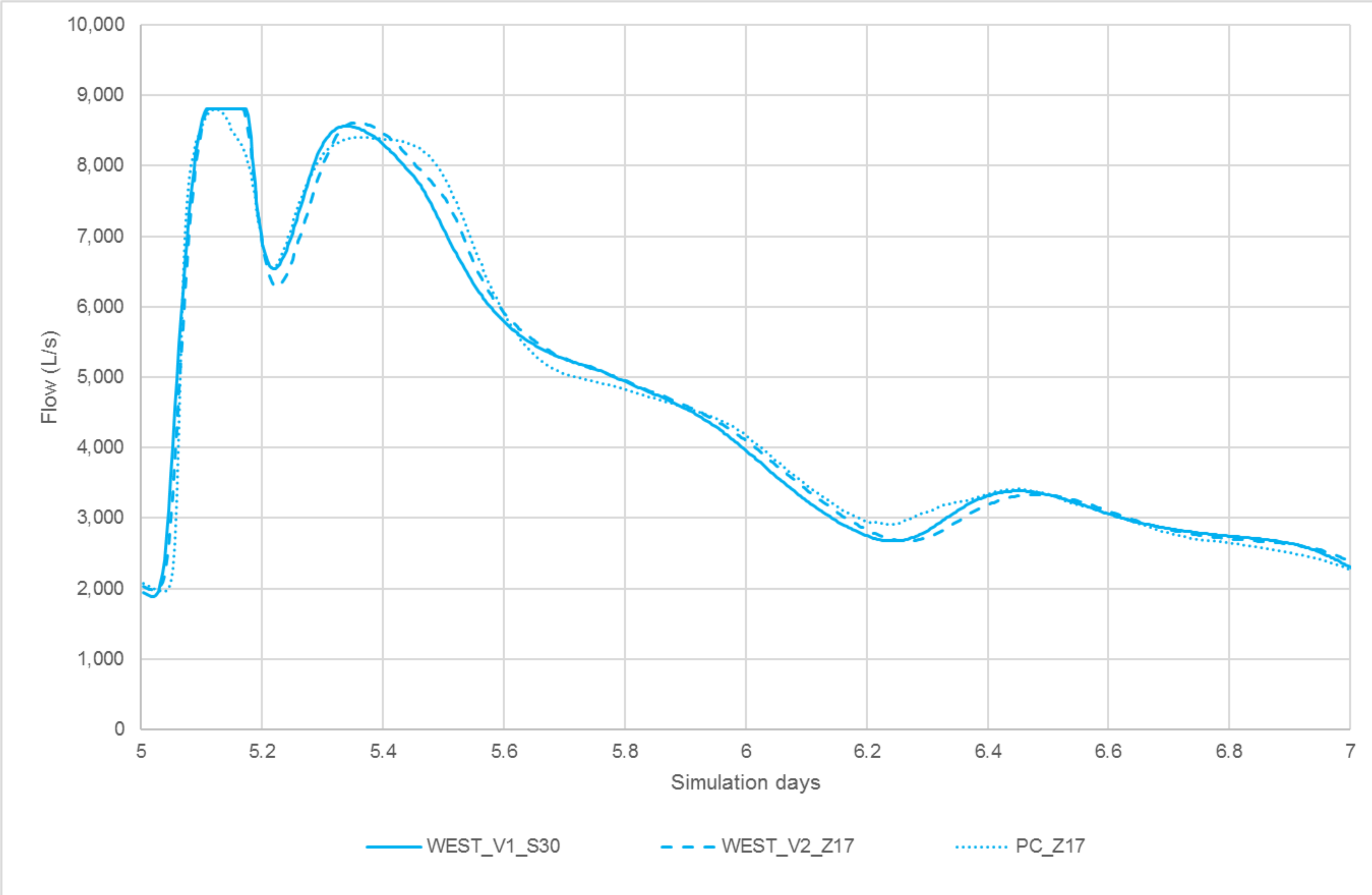

Figure E2 – 10: WWF results for downstream sewer (Z17)

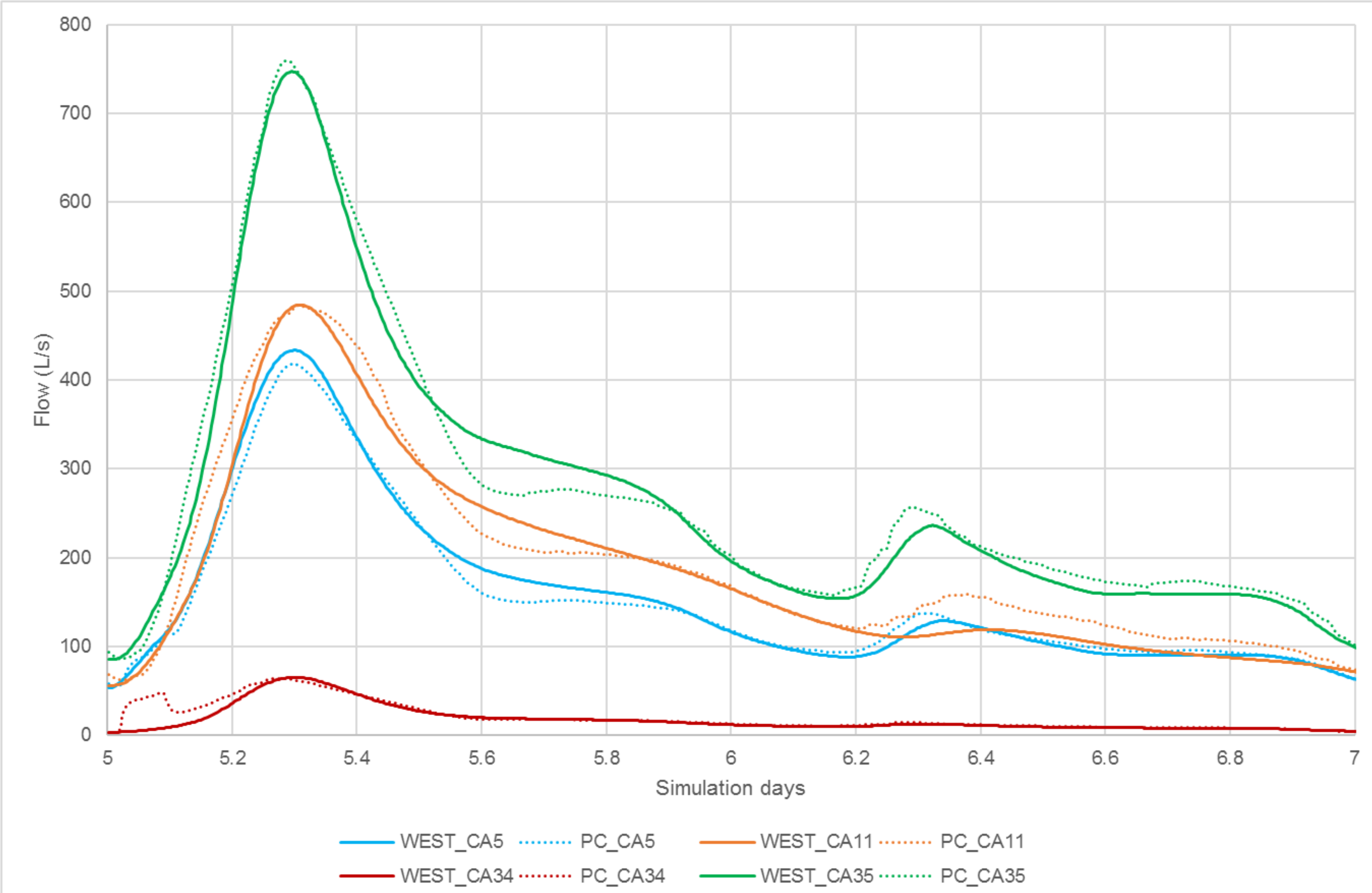

Figure E2 – 11: Model V1 WWF sample results for catchments in Cathcart and RCI areas (CA 5, 11, 34, 35)

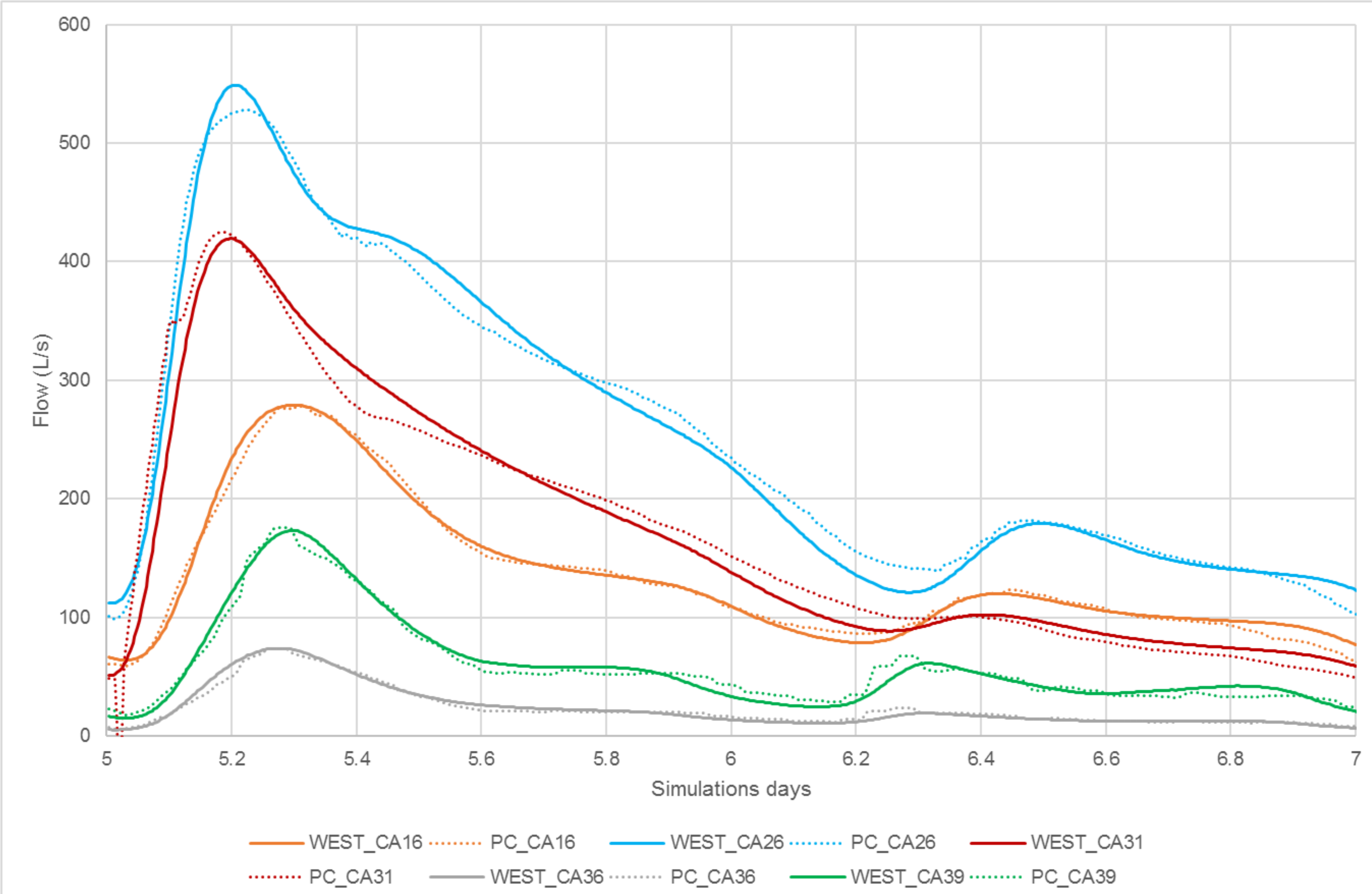

Figure E2 – 12: Model V1 WWF sample results for catchments in RRC areas (CA 16, 26, 31, 36, 39)

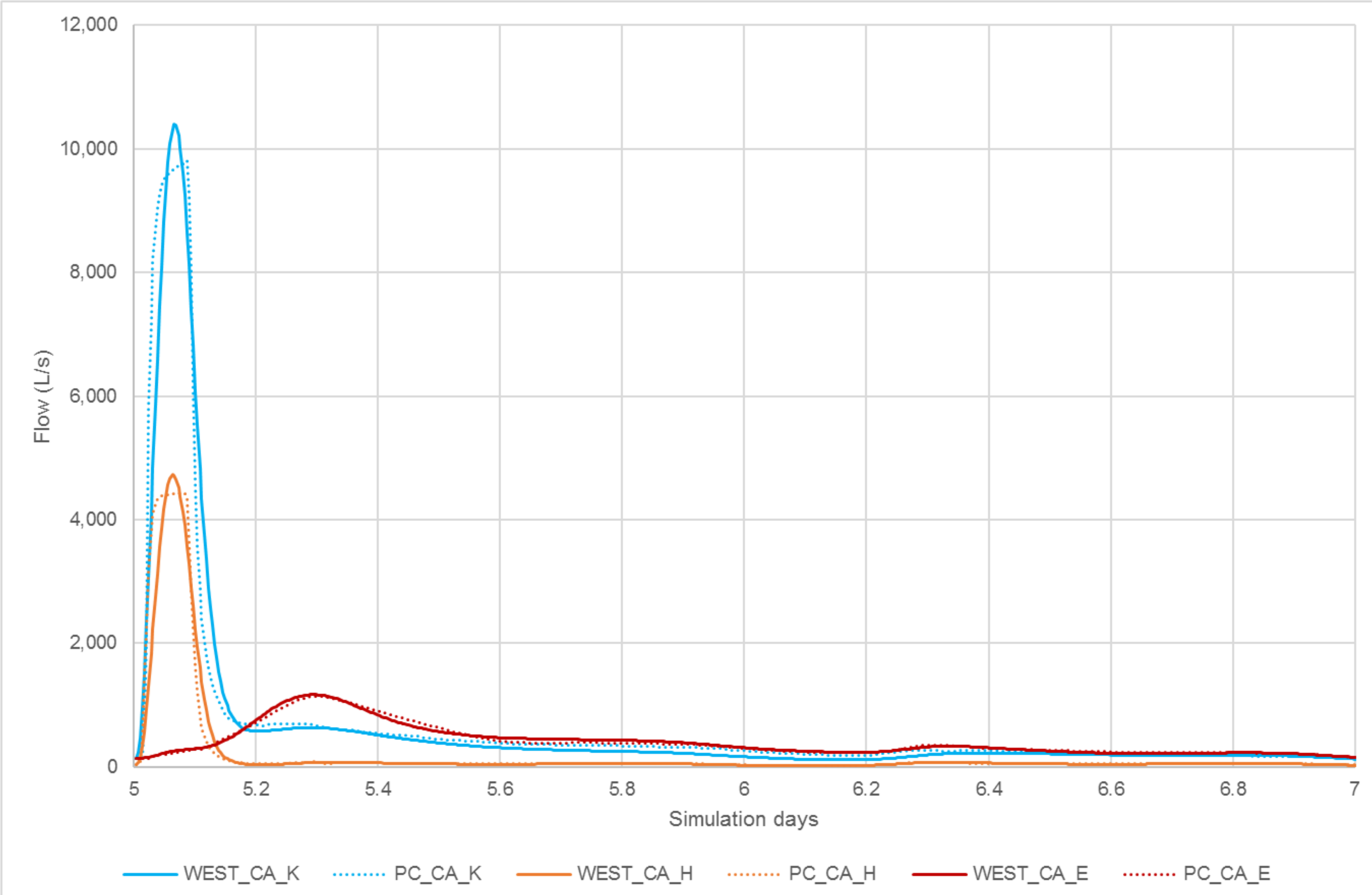

Figure E2 – 13: Model V2 WWF sample results for catchments with larger flows (CA K, H, E)

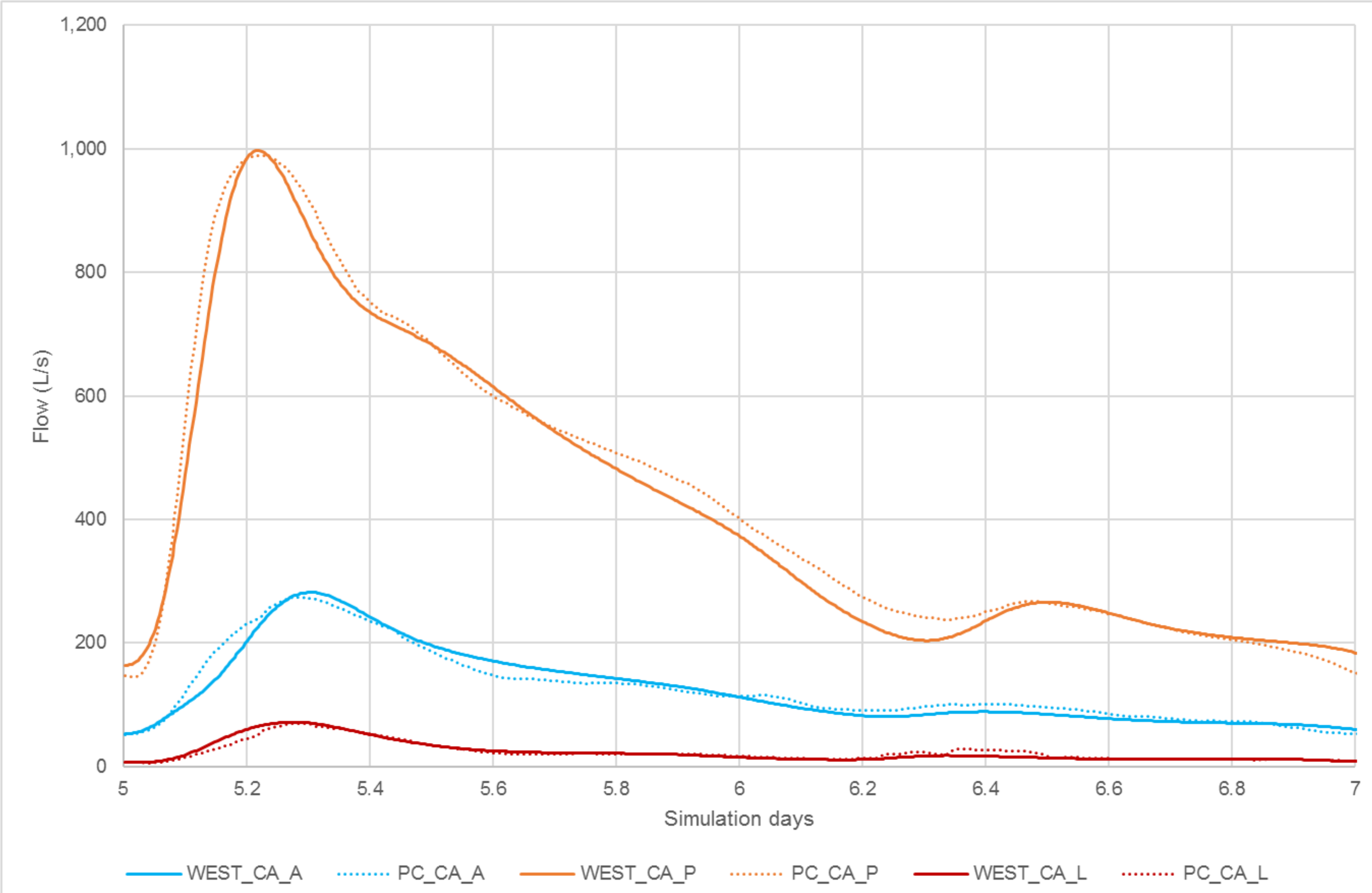

Figure E2 – 14: Model V2 WWF sample results for catchments with smaller flows (CA K, H, E)

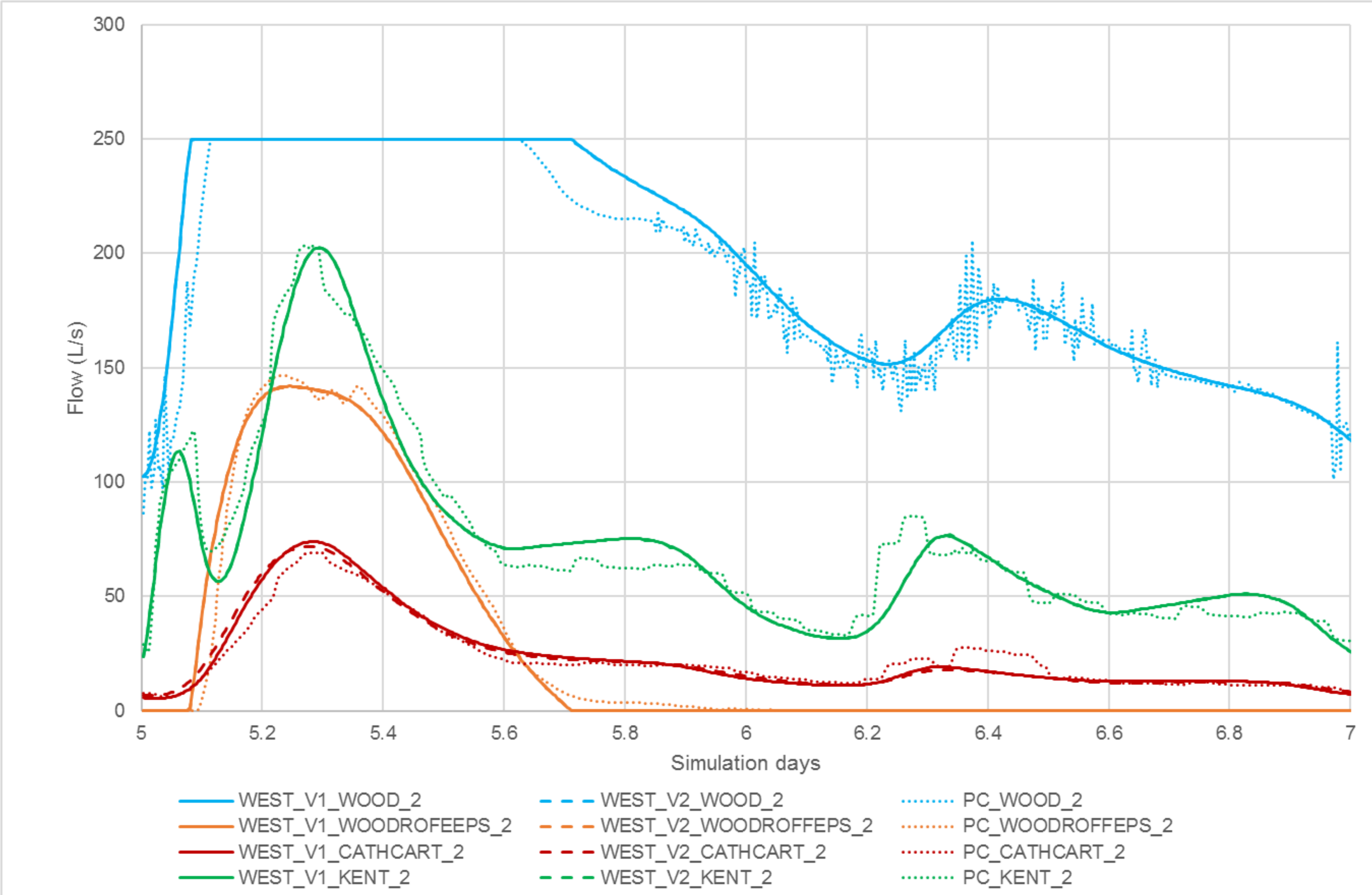

Figure E2 – 15: WWF sample results for regulators with smaller flows (Woodroffe, Cathcart, Kent)

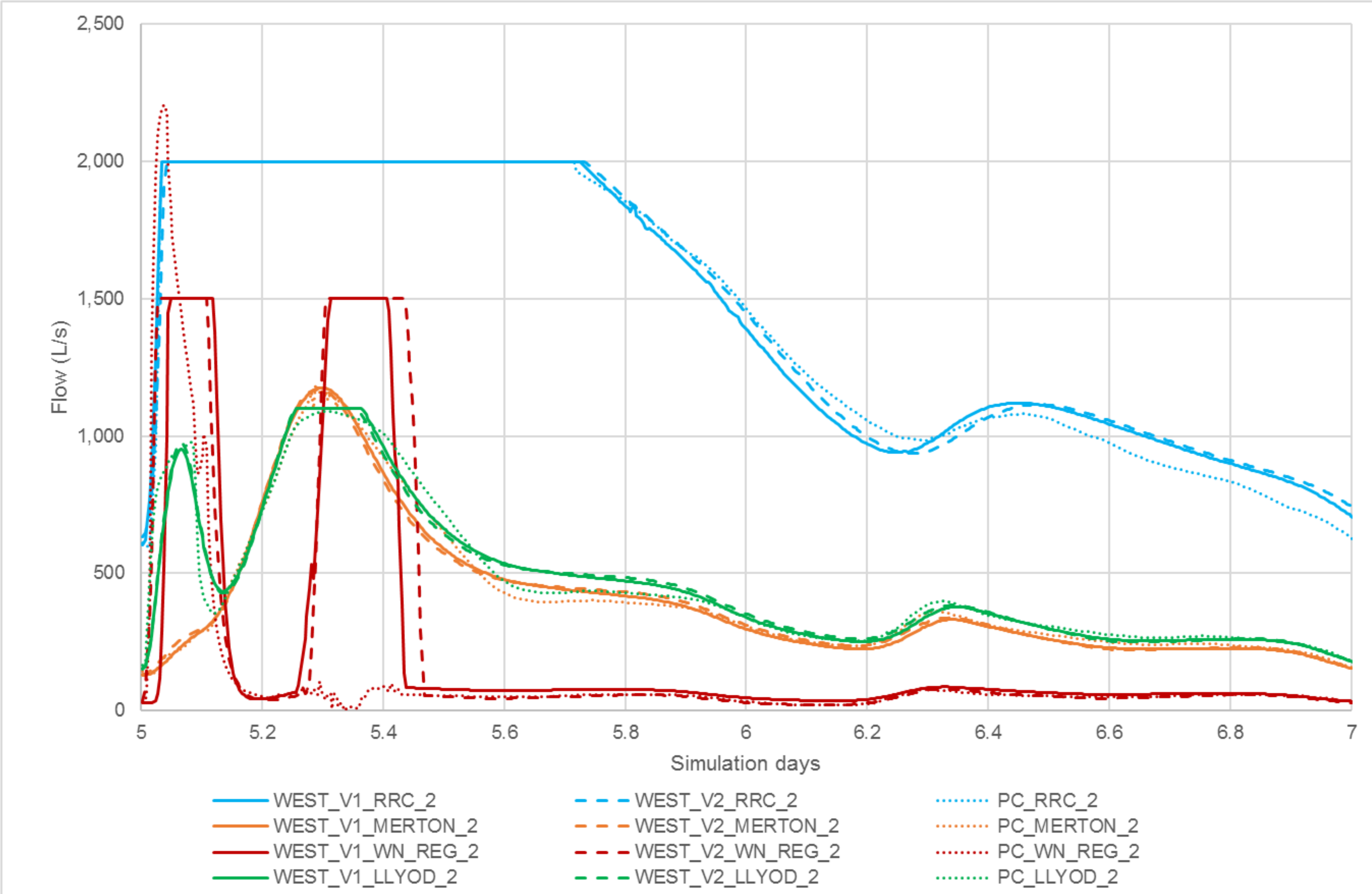

Figure E2 – 16: WWF sample results for regulators with larger flows (RCI, Merton, Booth, Llyod)

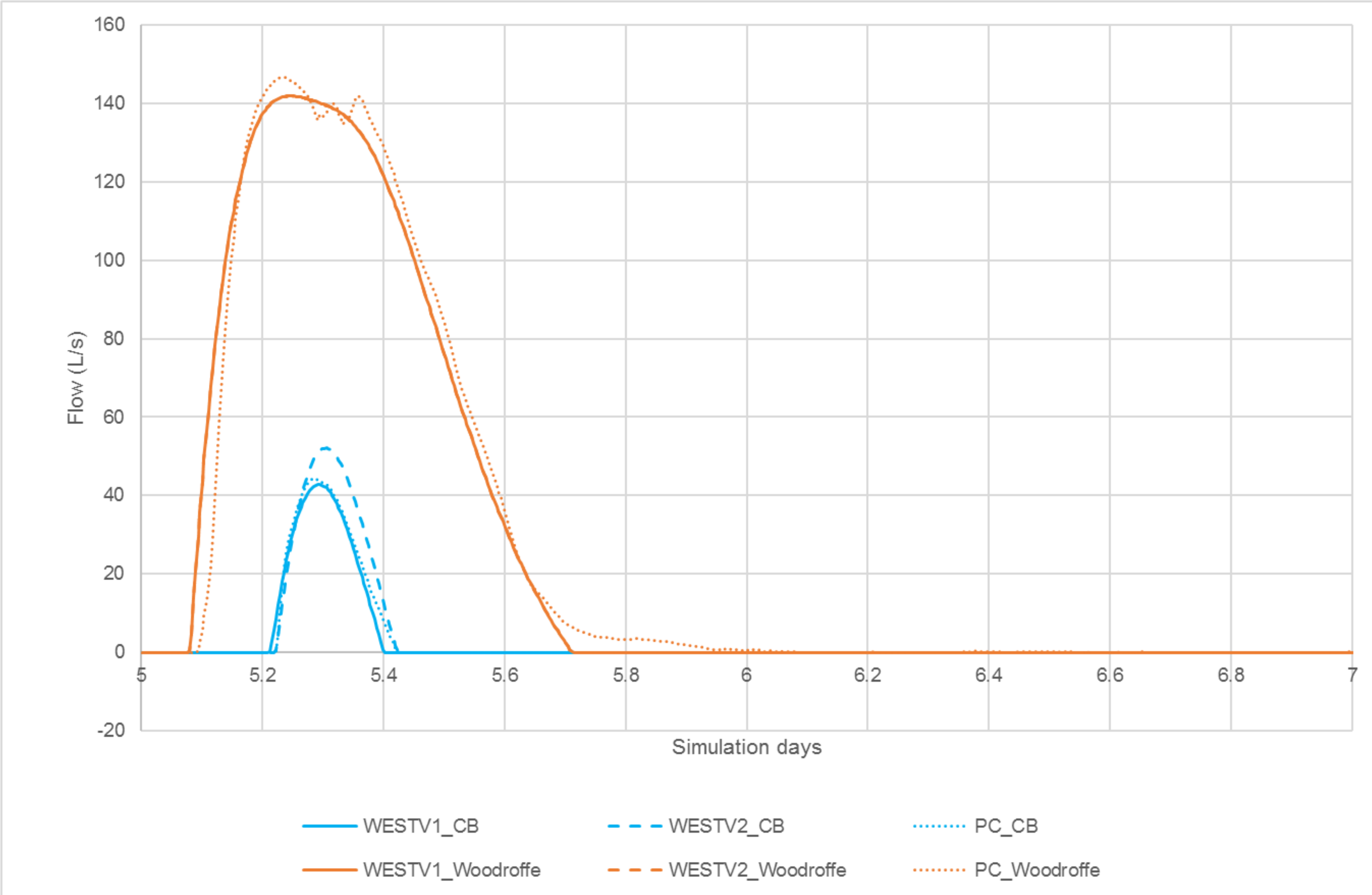

Figure E2 – 17: WWF results for Overflows in West end (Woodroffe & Crystal Beach)

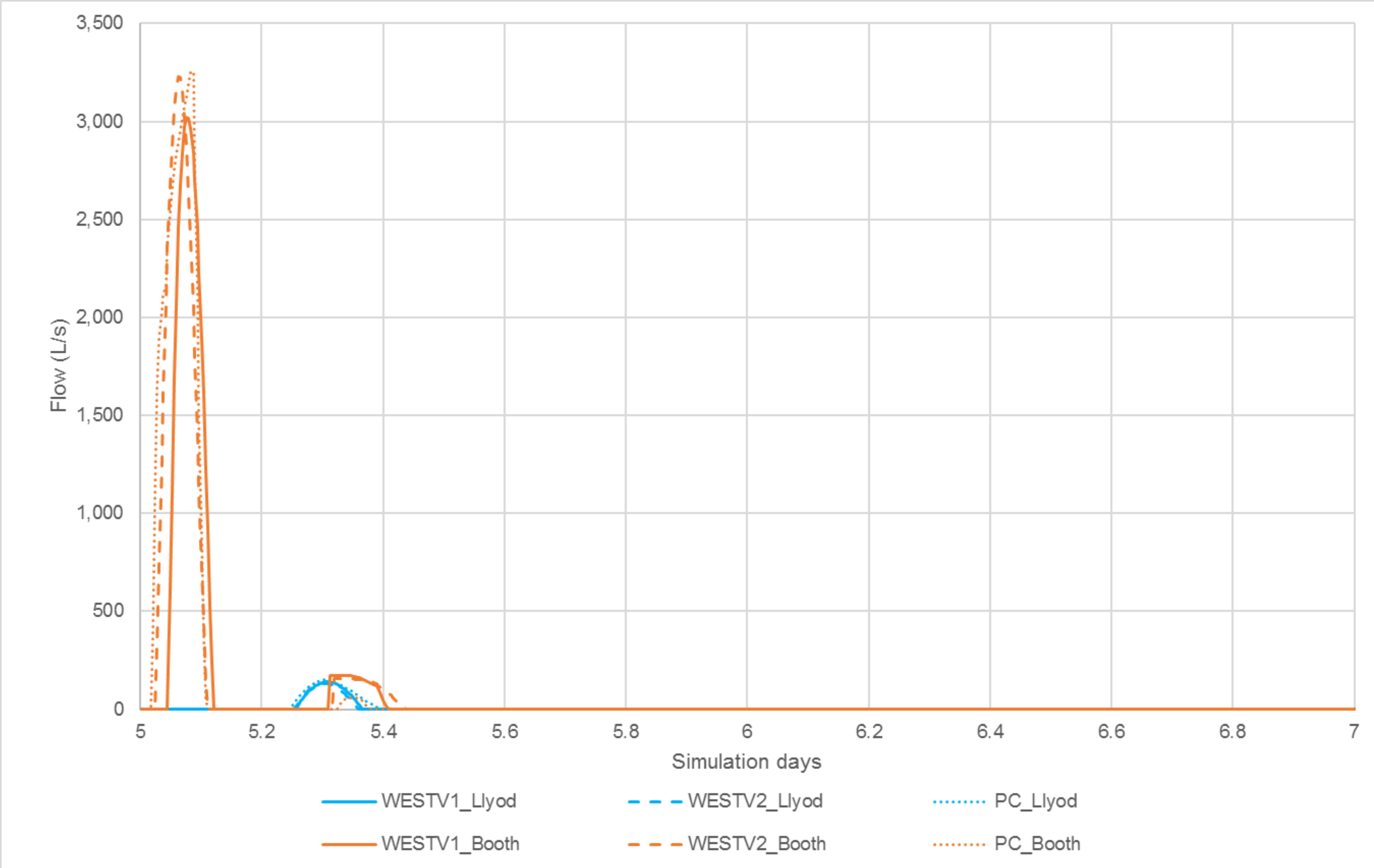

Figure E2 – 18: WWF results for Overflows in near West Nepean (Llyod & Booth)

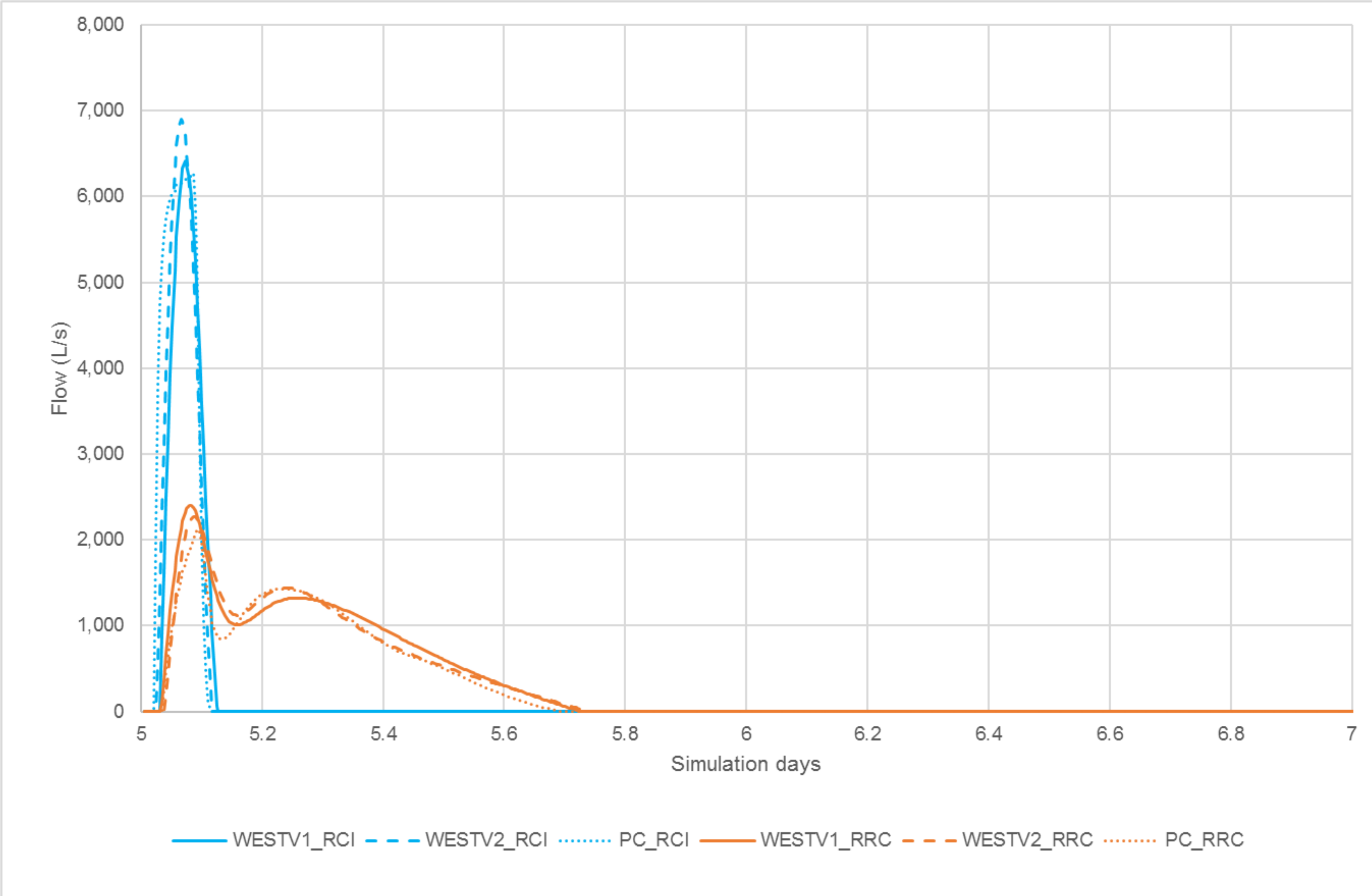

Figure E2 – 19: WWF results for Overflows in central area (RCI & RRC)

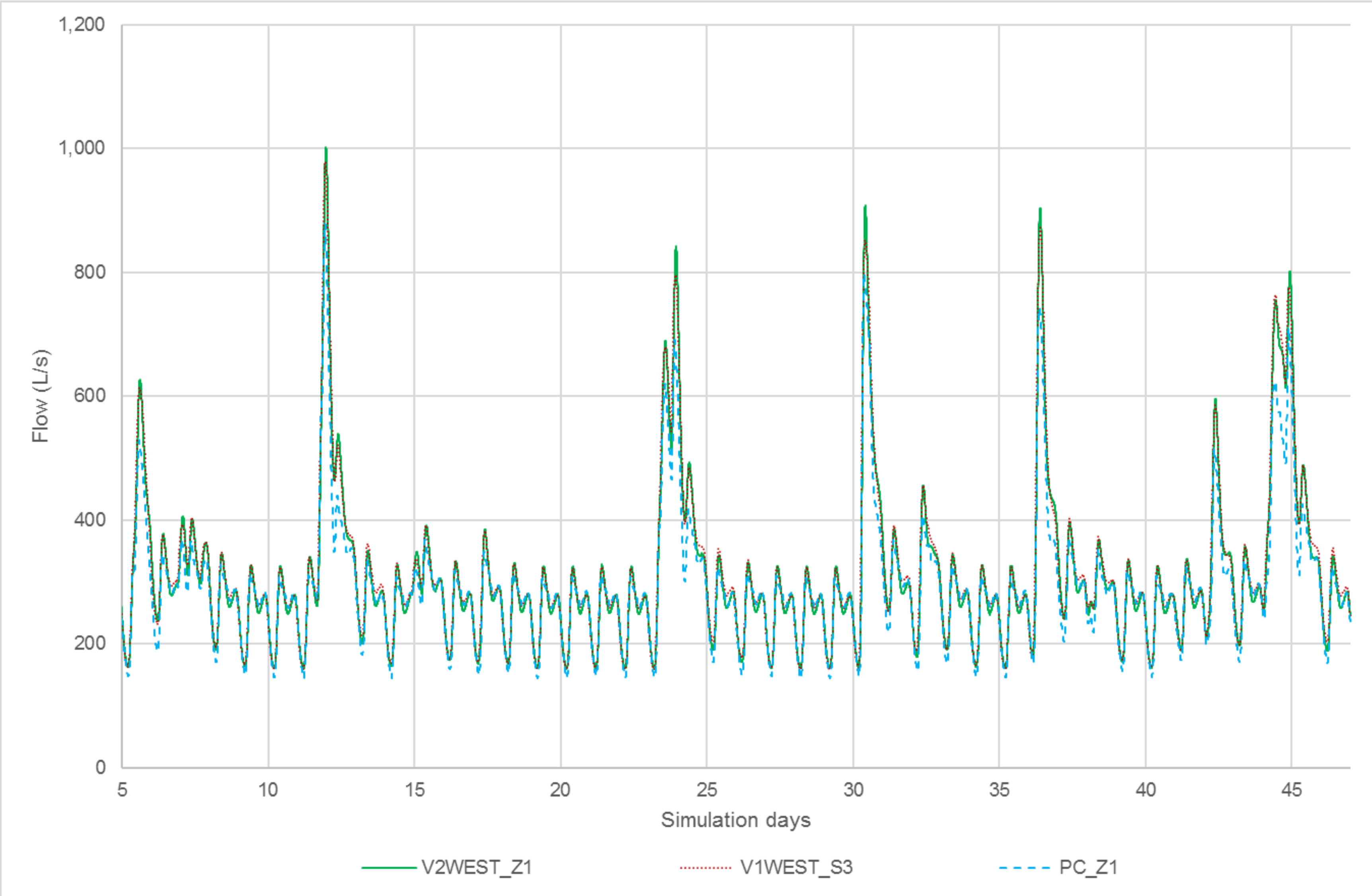

Figure E3 – 20: Validation period results for Z1

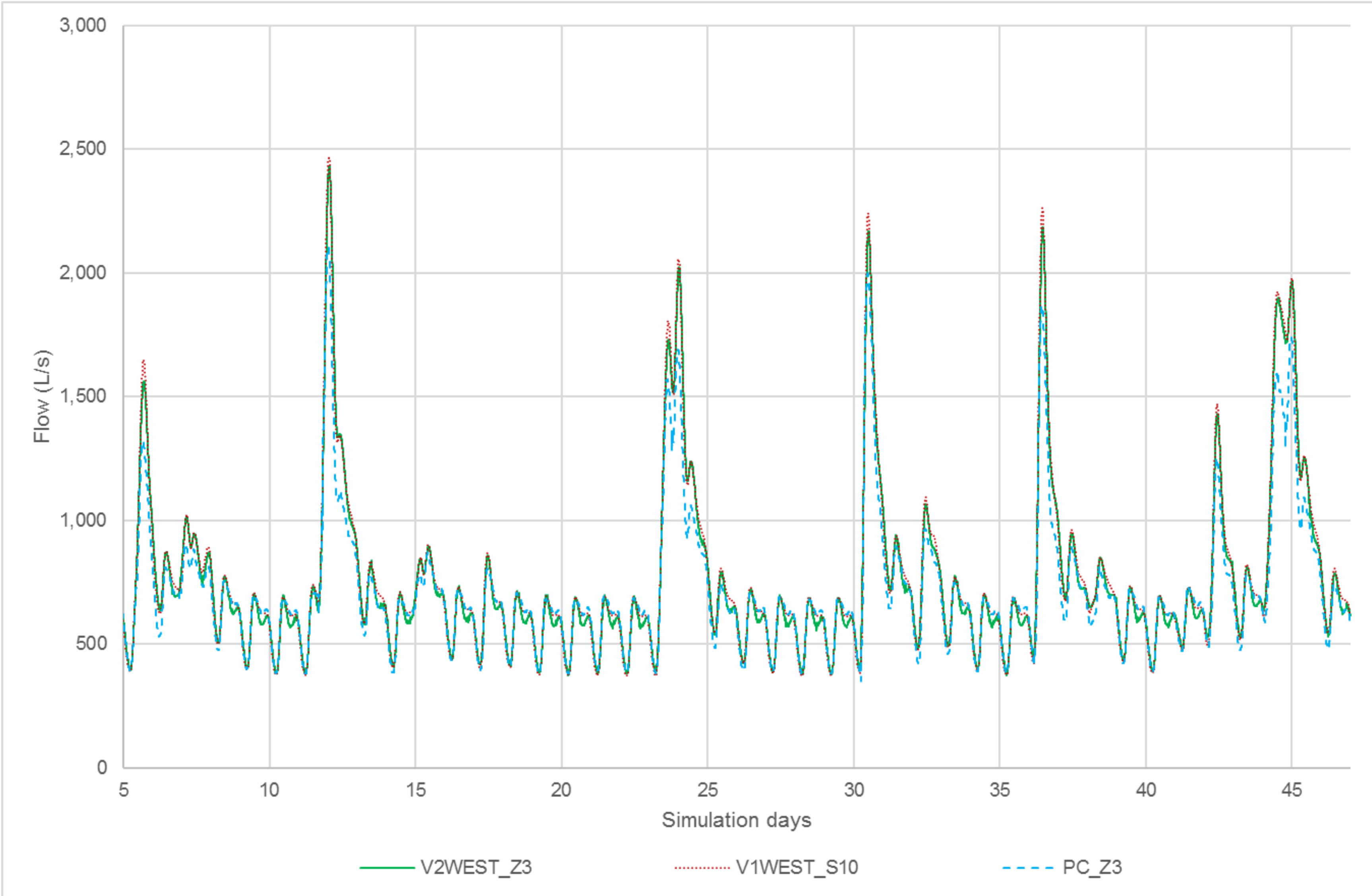

Figure E3 – 21: Validation period results for Z3

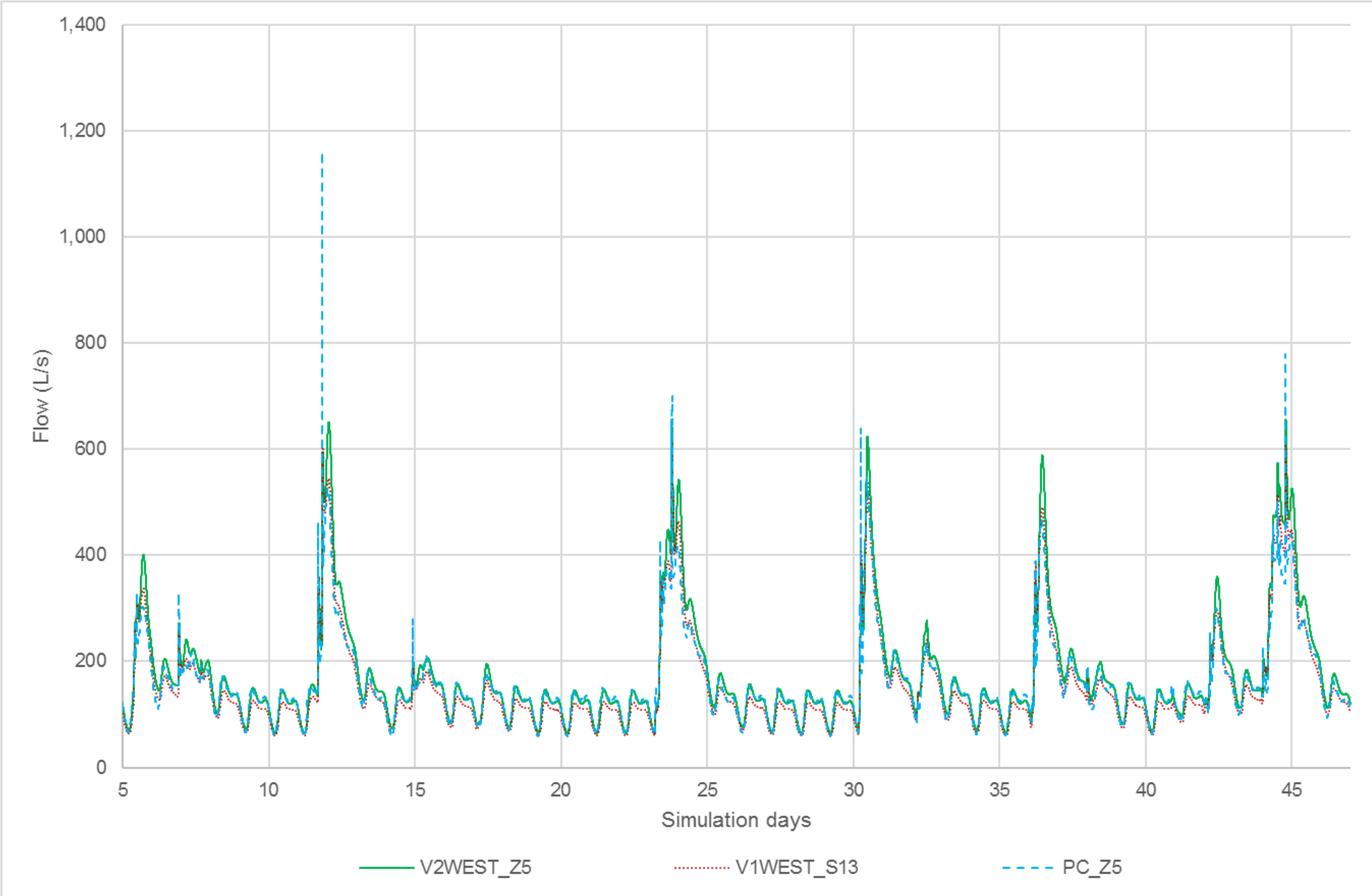

Figure E3 – 22: Validation period results for Z5

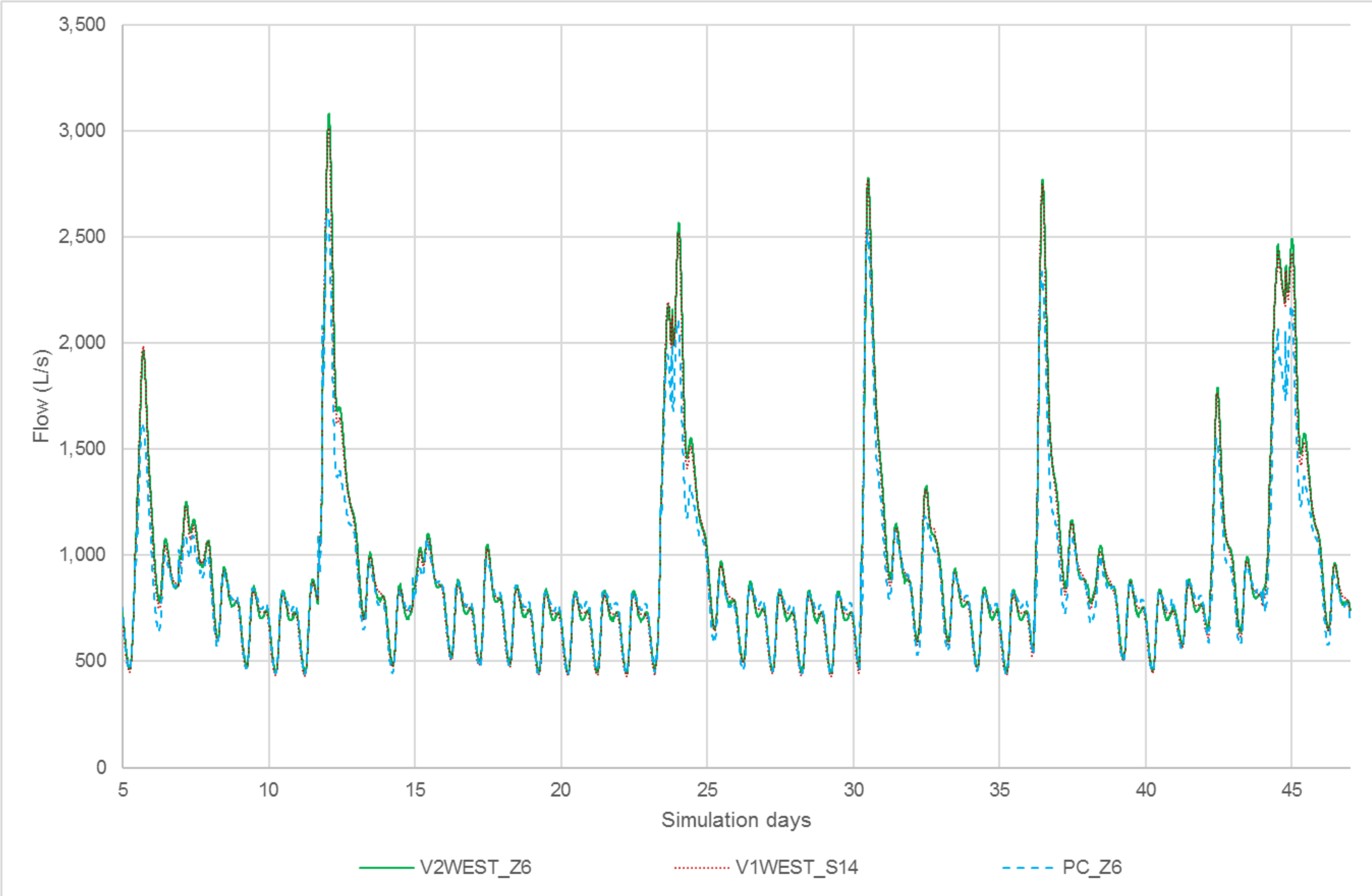

Figure E3 – 23: Validation period results for Z6

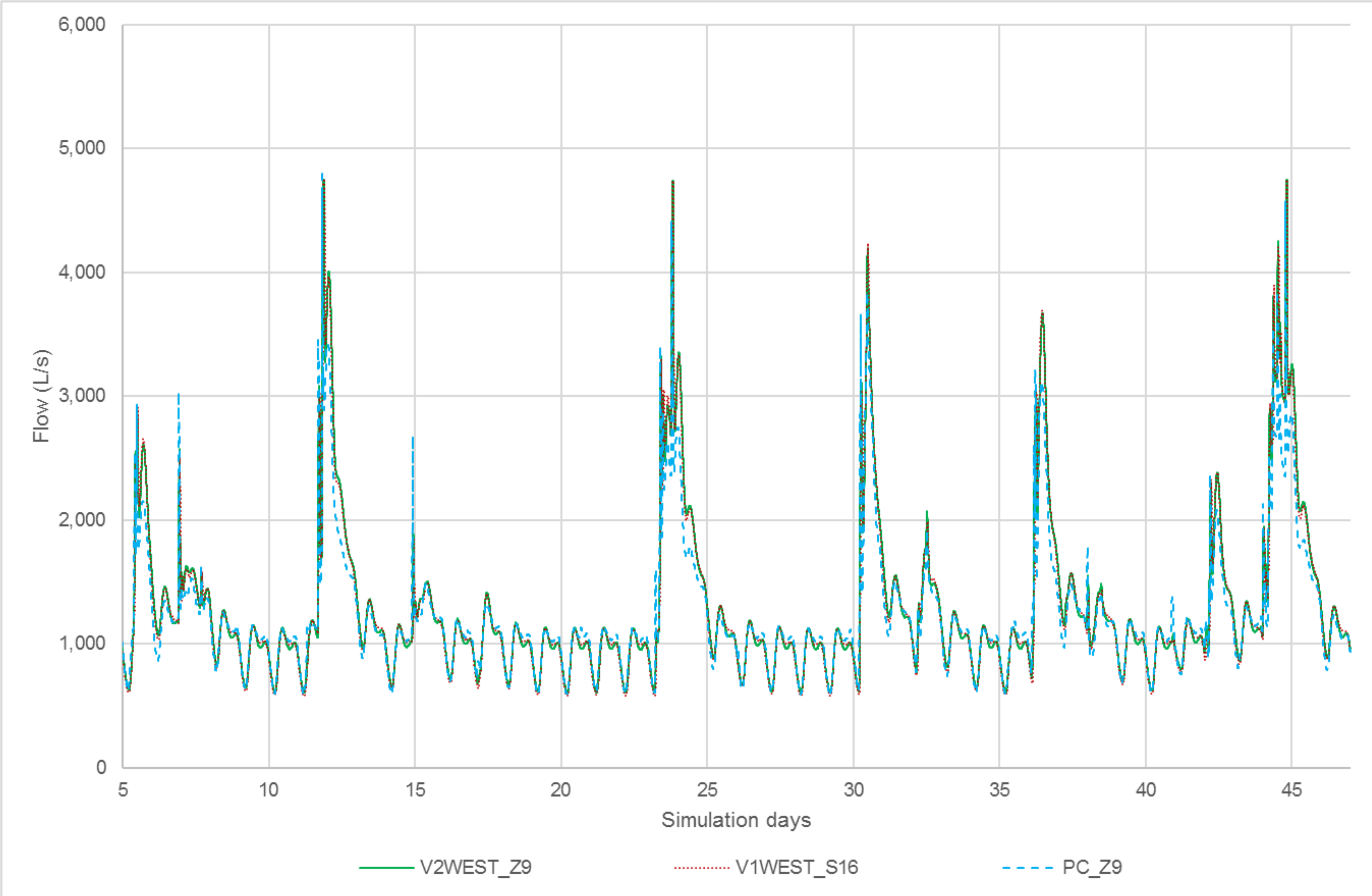

Figure E3 – 24: Validation period results for Z9

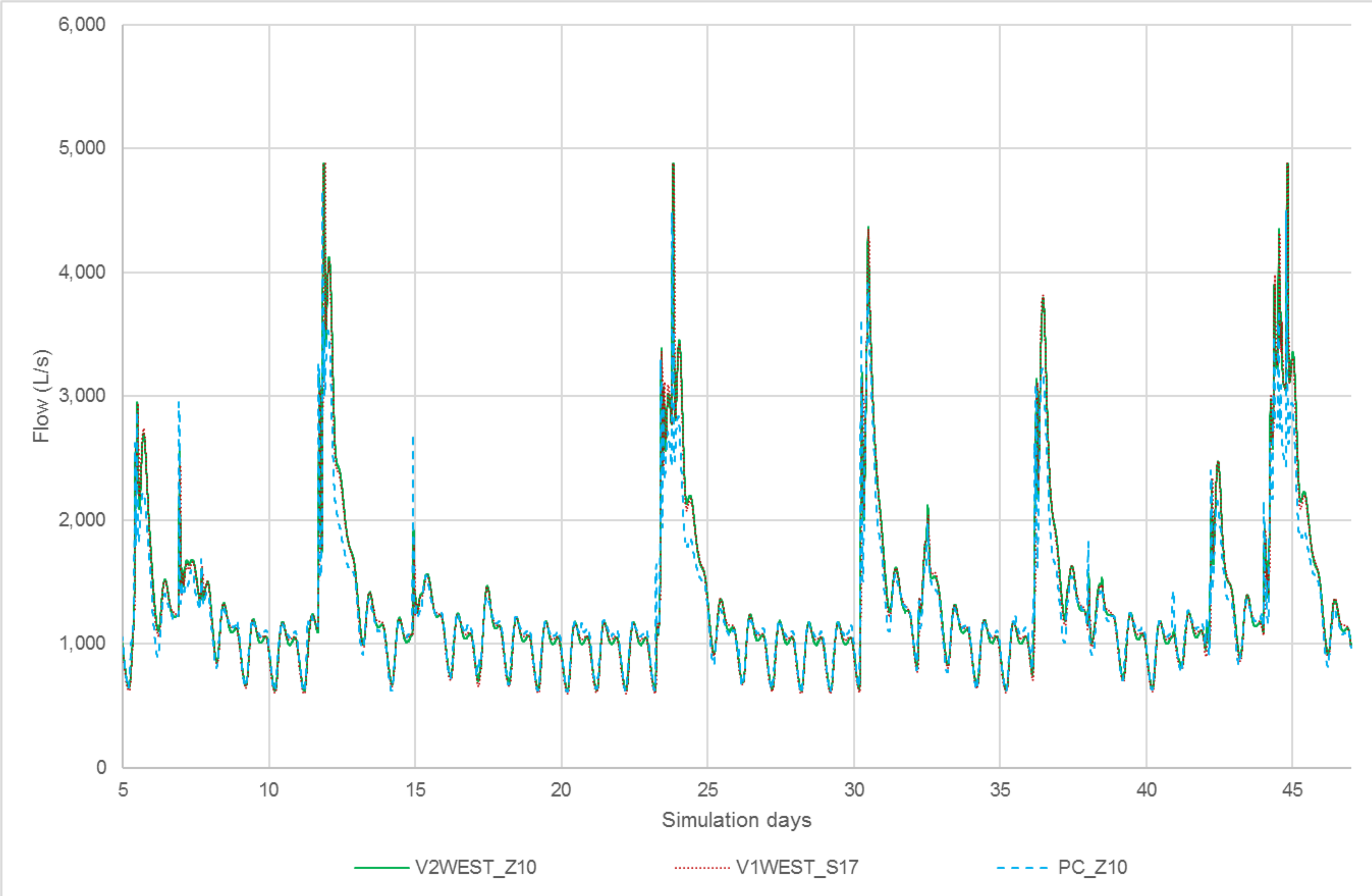

Figure E3 – 25: Validation period results for Z10

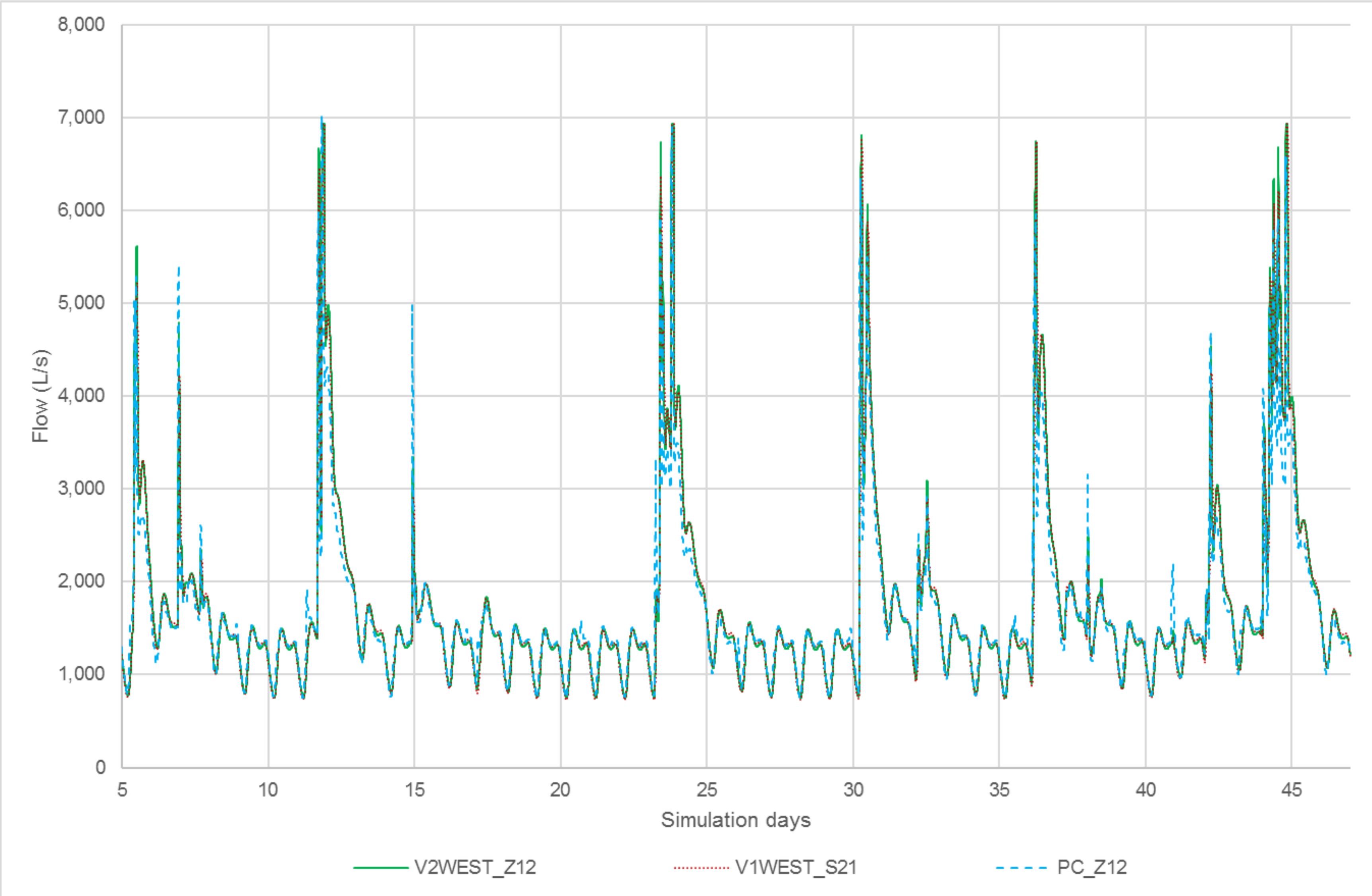

Figure E3 – 26: Validation period results for Z12

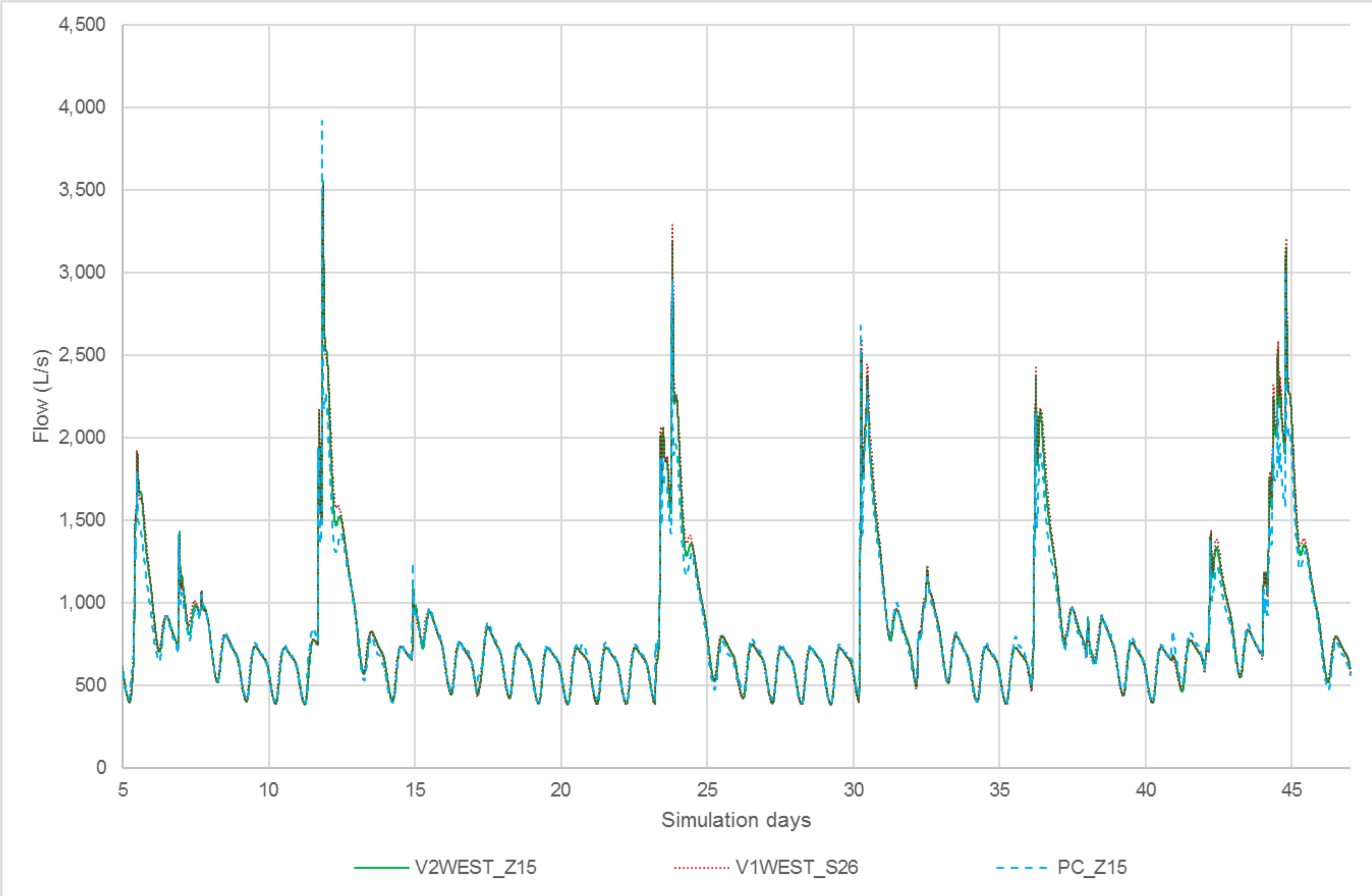

Figure E3 – 27: Validation period results for Z15

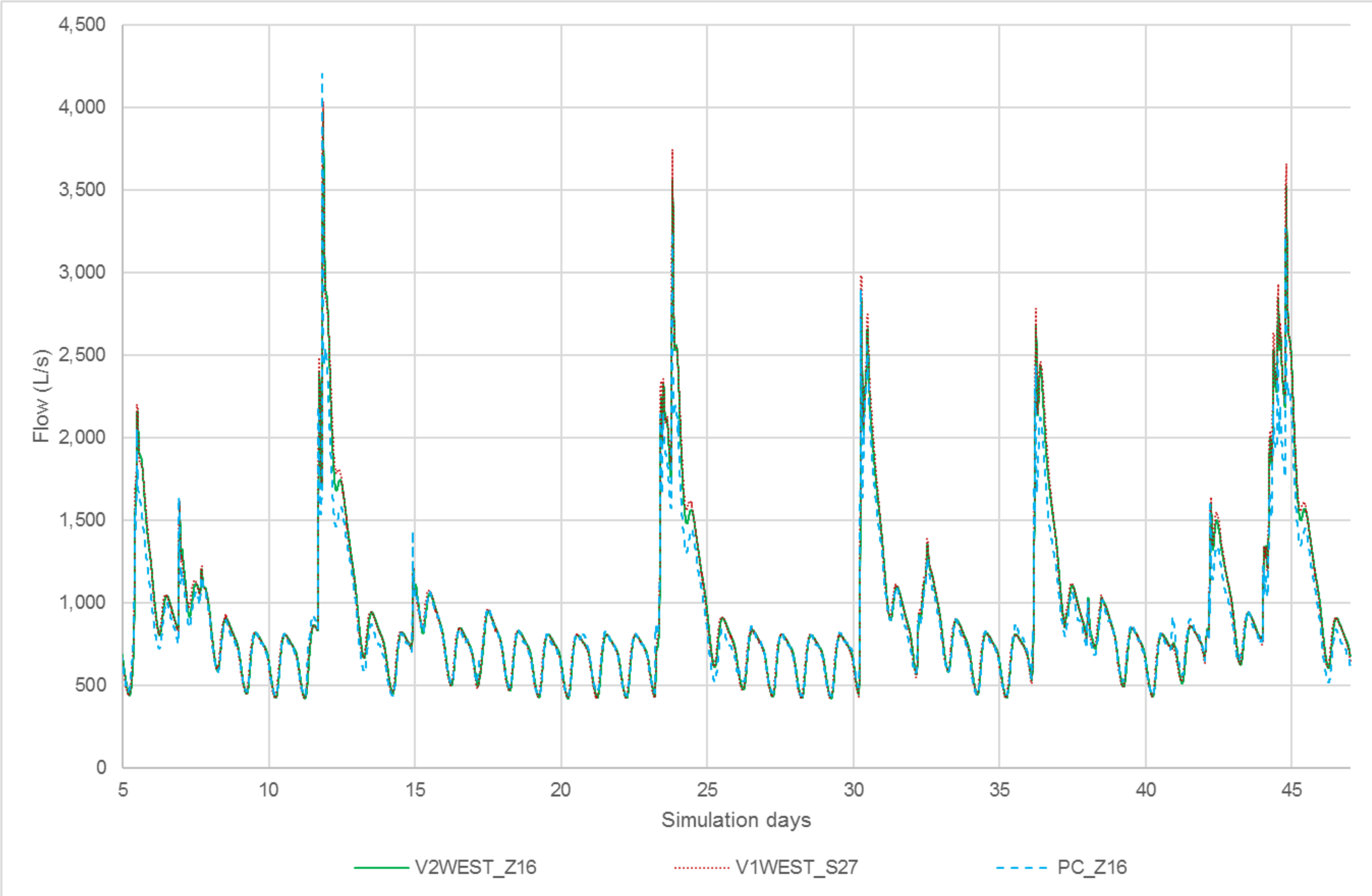

Figure E3 – 28: Validation period results for Z16

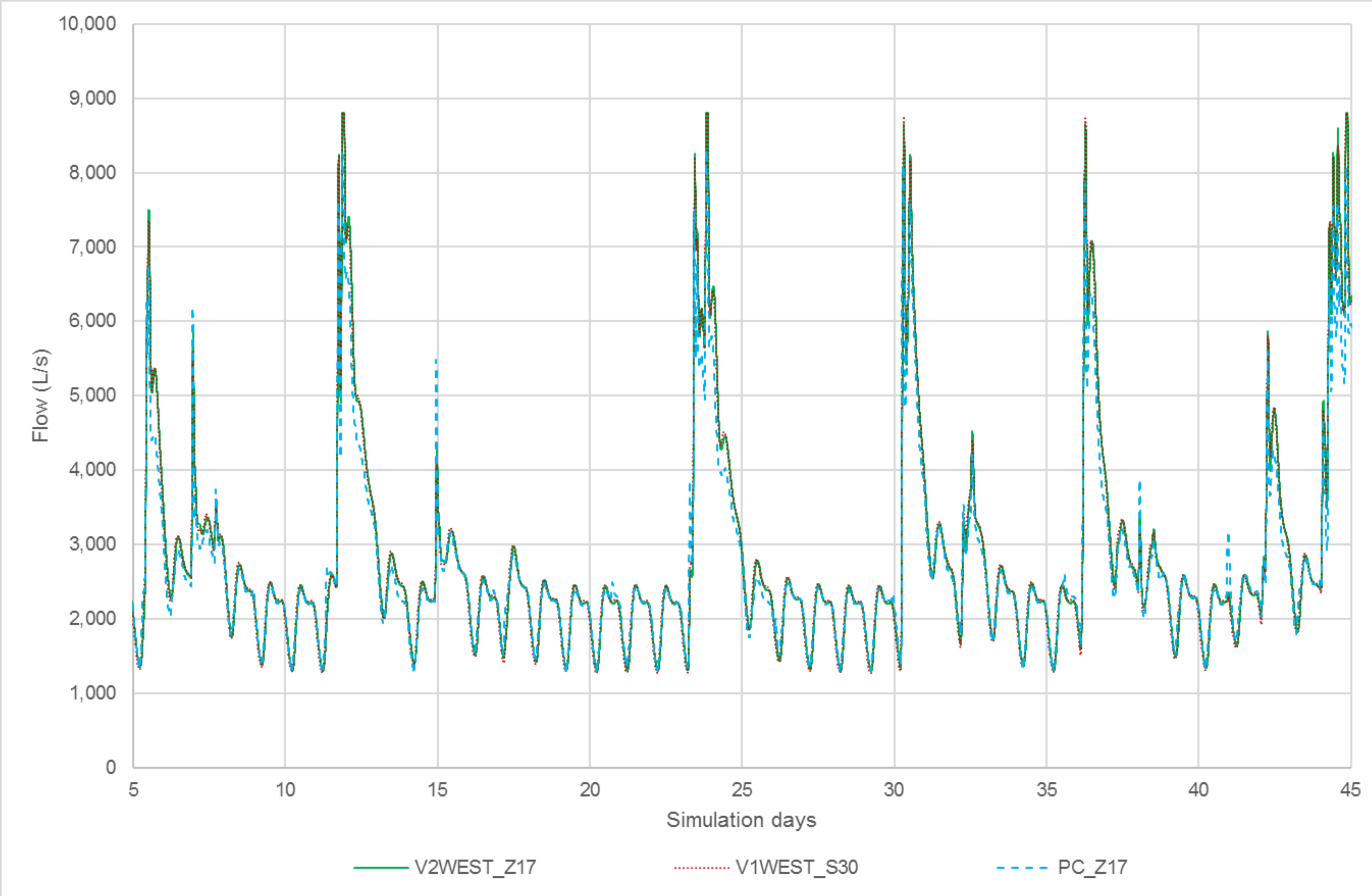

Figure E3 – 29: Validation period results for Z17

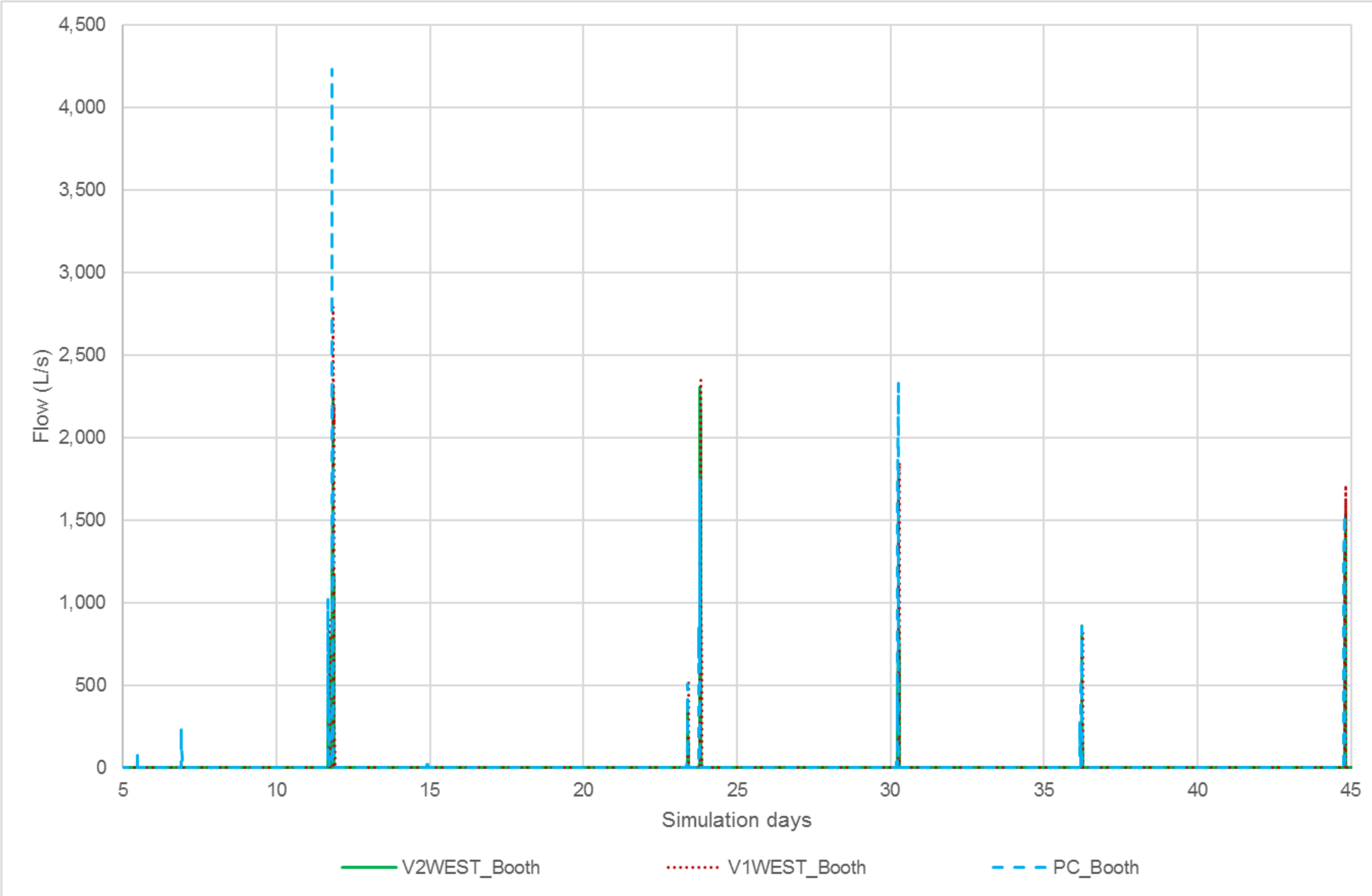

Figure E3 – 30: Validation period results for Booth overflow

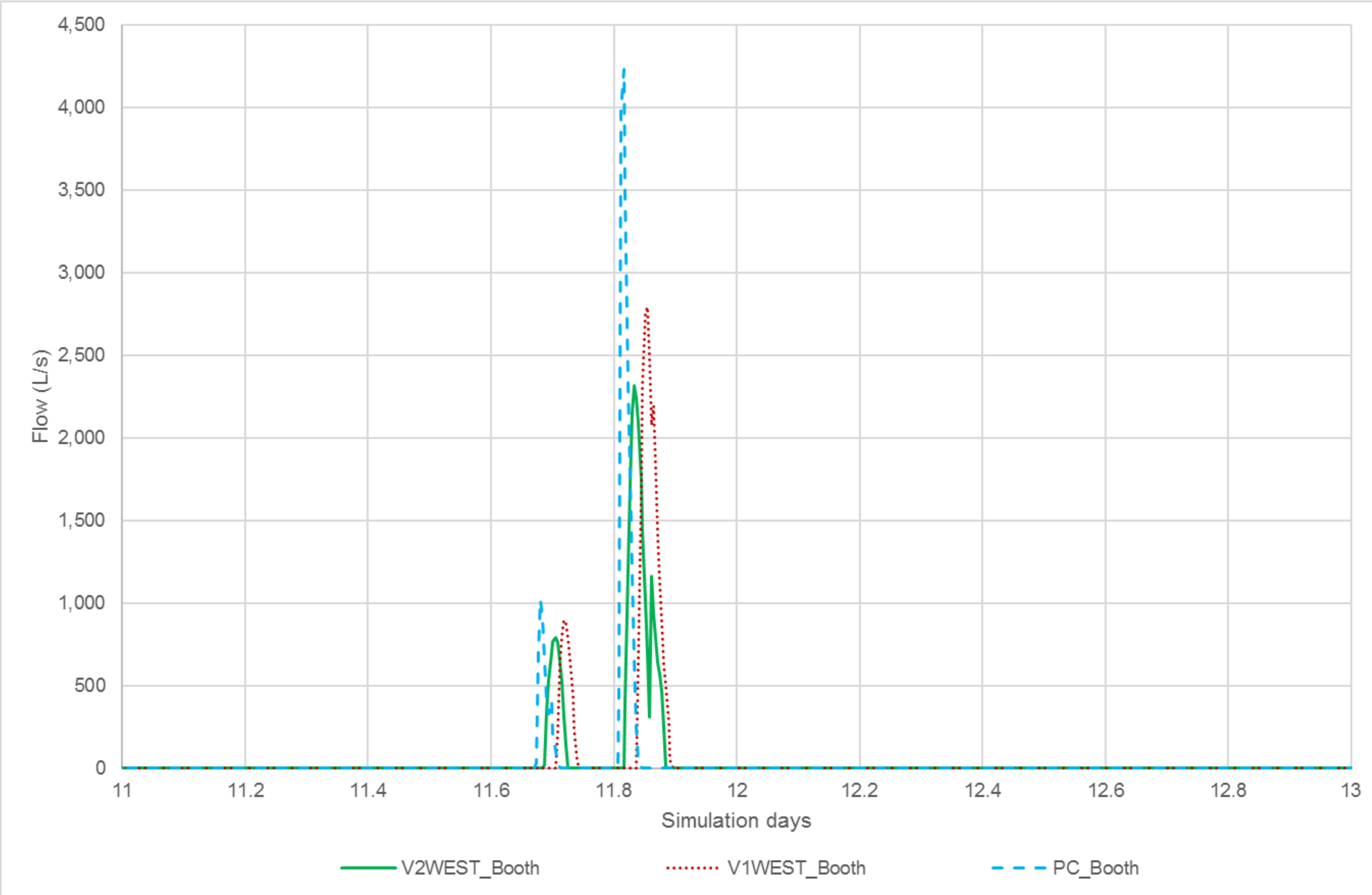

Figure E3 – 31: Validation period results for Booth overflow (Event 2)

Appendix F: Additional validation performance criteria tables

Table F – 1: WWF overflows performance criteria

Overflow	Volume (m3)	Peak Flow (L/s)	PVE (%)	PEP (%)
Booth				
PC	17,283	3,255	0.0%	0.0%
V1	15,732	3,228	9.0%	0.8%
V2	13,815	3,023	20.1%	7.1%
Crystal Beach				
PC	473	44	0.0%	0.0%
V1	565	52	-19.5%	-17.2%
V2	439	43	7.2%	3.5%
Llyod				
PC	1,150	149	0.0%	0.0%
V1	788	131	31.5%	12.1%
V2	869	139	24.4%	7.0%
RCI				
PC	37,394	6,276	0.0%	0.0%
V1	32,937	6,896	11.9%	-9.9%
V2	31,347	6,414	16.2%	-2.2%
RRC				
PC	48,157	2,121	0.0%	0.0%
V1	52,296	2,271	-8.6%	-7.0%
V2	54,202	2,404	-12.6%	-13.3%
Woodroffe				
PC	4,862	147	0.0%	0.0%
V1	4,770	142	1.9%	3.3%
V2	4,772	142	1.9%	3.3%

Table F – 2: Event 2 Performance criteria

Sewer link	Event volume (10^3 m^3)	Peak flow (L/s)	PVE (%)	PEP (%)	NSE
Z1					
PC	113	691			
V1	124	797	-10.2%	-15.2%	0.85
V2	122	843	-8.4%	-21.9%	0.85
Z3					
PC	283	1,689			
V1	312	2,059	-10.0%	-21.9%	0.85
V2	308	2,025	-8.8%	-19.9%	0.86
Z4					
PC	102	1,093			
V1	111	981	-9.2%	10.3%	0.80
V2	111	978	-9.1%	10.6%	0.80
Z5					
PC	67	700			
V1	67	613	-0.2%	12.4%	0.93
V2	75	640	-12.3%	8.6%	0.82
Z6					
PC	350	2,108			
V1	378	2,521	-8.1%	-19.6%	0.89
V2	383	2,566	-9.5%	-21.7%	0.85
Z9					
PC	496	4,430			
V1	535	4,738	-7.9%	-7.0%	0.71
V2	541	4,739	-9.0%	-7.0%	0.78
Z10					
PC	514	4,480			
V1	555	4,880	-7.9%	-8.9%	0.72
V2	560	4,880	-9.0%	-8.9%	0.78
Z12					
PC	675	6,901			
V1	723	6,936	-7.1%	-0.5%	0.76
V2	728	6,936	-7.8%	-0.5%	0.82
Z15					
PC	326	2,952			
V1	353	3,288	-8.4%	-11.4%	0.89
V2	348	3,181	-6.8%	-7.8%	0.92
Z16					
PC	360	3,247			
V1	400	3,744	-11.1%	-15.3%	0.87
V2	395	3,561	-9.7%	-9.7%	0.88
Z17					
PC	1,090	8,315			
V1	1,170	8,801	-7.1%	-5.8%	0.92
V2	1,170	8,801	-7.2%	-5.8%	0.92

Table F – 3: Event 3 Performance criteria

Sewer link	Event volume (10^3 m^3)	Peak flow (L/s)	PVE (%)	PEP (%)	NSE
Z1					
PC	113	797			
V1	121	852	-7.4%	-15.2%	0.94
V2	119	908	-5.6%	-21.9%	0.94
Z3					
PC	283	1,997			
V1	303	2,243	-6.7%	-21.9%	0.95
V2	299	2,169	-5.6%	-19.9%	0.95
Z4					
PC	102	1,013			
V1	107	892	-5.3%	10.3%	0.86
V2	107	888	-5.1%	10.6%	0.86
Z5					
PC	67	638			
V1	64	540	3.8%	12.4%	0.93
V2	72	624	-7.8%	8.6%	0.89
Z6					
PC	350	2,535			
V1	367	2,776	-4.7%	-19.6%	0.96
V2	371	2,781	-6.0%	-21.7%	0.94
Z9					
PC	496	3,846			
V1	514	4,238	-3.5%	-7.0%	0.83
V2	518	4,197	-4.4%	-7.0%	0.90
Z10					
PC	514	3,910			
V1	531	4,354	-3.5%	-8.9%	0.84
V2	536	4,365	-4.4%	-8.9%	0.90
Z12					
PC	672	6,371			
V1	690	6,783	-2.7%	-0.5%	0.78
V2	695	6,811	-3.3%	-0.5%	0.87
Z15					
PC	328	2,677			
V1	340	2,596	-3.5%	-11.4%	0.92
V2	335	2,518	-2.1%	-7.8%	0.95
Z16					
PC	363	2,898			
V1	385	2,980	-6.1%	-15.3%	0.92
V2	380	2,829	-4.8%	-9.7%	0.93
Z17					
PC	1,090	8,101			
V1	1,130	8,757	-3.4%	-5.8%	0.95
V2	1,130	8,650	-3.6%	-5.8%	0.94

Table F – 4: Event 4 Performance criteria

Sewer link	Event volume (10^3 m^3)	Peak flow (L/s)	PVE (%)	PEP (%)	NSE
Z1					
PC	107	743			
V1	117	872	-8.9%	-17.4%	0.87
V2	115	904	-7.3%	-21.7%	0.88
Z3					
PC	266	1,871			
V1	288	2,262	-8.4%	-20.9%	0.87
V2	285	2,184	-7.3%	-16.7%	0.89
Z4					
PC	95	664			
V1	102	823	-7.3%	-24.0%	0.83
V2	102	817	-7.1%	-23.1%	0.84
Z5					
PC	61	467			
V1	60	490	2.3%	-5.0%	0.93
V2	68	588	-10.4%	-26.0%	0.82
Z6					
PC	327	2,337			
V1	348	2,750	-6.4%	-17.6%	0.90
V2	353	2,770	-7.9%	-18.5%	0.87
Z9					
PC	466	3,214			
V1	490	3,690	-5.1%	-14.8%	0.79
V2	495	3,670	-6.2%	-14.2%	0.84
Z10					
PC	482	3,228			
V1	507	3,817	-5.0%	-18.3%	0.80
V2	512	3,792	-6.1%	-17.5%	0.84
Z12					
PC	635	5,968			
V1	661	6,752	-4.1%	-13.1%	0.77
V2	666	6,746	-4.9%	-13.0%	0.84
Z15					
PC	306	2,150			
V1	322	2,422	-5.4%	-12.6%	0.88
V2	319	2,376	-4.3%	-10.5%	0.92
Z16					
PC	338	2,433			
V1	364	2,783	-7.8%	-14.4%	0.86
V2	361	2,677	-6.7%	-10.0%	0.88
Z17					
PC	1,030	7,864			
V1	1,080	8,737	-4.9%	-11.1%	0.92
V2	1,090	8,652	-5.2%	-10.0%	0.92

Table F – 5: Event 5 Performance criteria

Sewer link	Event volume (10^3 m^3)	Peak flow (L/s)	PVE (%)	PEP (%)	NSE
Z1					
PC	194	710			
V1	214	776	-10.2%	-9.3%	0.81
V2	211	801	-8.3%	-12.8%	0.84
Z3					
PC	487	1,740			
V1	535	1,978	-9.8%	-13.6%	0.83
V2	529	1,968	-8.7%	-13.1%	0.85
Z4					
PC	175	1,185			
V1	191	999	-9.0%	15.8%	0.80
V2	190	1,006	-8.9%	15.1%	0.80
Z5					
PC	114	780			
V1	113	607	0.7%	22.1%	0.92
V2	128	657	-12.3%	15.8%	0.80
Z6					
PC	601	2,180			
V1	648	2,433	-7.8%	-11.6%	0.87
V2	657	2,492	-9.4%	-14.3%	0.84
Z9					
PC	856	4,592			
V1	917	4,746	-7.1%	-3.4%	0.76
V2	928	4,747	-8.3%	-3.4%	0.80
Z10					
PC	887	4,498			
V1	950	4,880	-7.1%	-8.5%	0.77
V2	960	4,880	-8.3%	-8.5%	0.80
Z12					
PC	1,170	6,611			
V1	1,250	6,936	-6.3%	-4.9%	0.77
V2	1,260	6,936	-7.2%	-4.9%	0.82
Z15					
PC	560	2,994			
V1	602	3,210	-7.5%	-7.2%	0.86
V2	596	3,150	-6.5%	-5.2%	0.89
Z16					
PC	620	3,261			
V1	684	3,658	-10.3%	-12.2%	0.83
V2	678	3,526	-9.3%	-8.1%	0.85
Z17					
PC	1,900	8,091			
V1	2,020	8,801	-6.3%	-8.8%	0.91
V2	2,020	8,801	-6.7%	-8.8%	0.91