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Modeling Seismic Effects on a Stormwater Network and Post-earthquake Recovery

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***Abstract*—** This paper summarises the impact of earthquakes on Christchurch's storm water network and the recovery strategies that are being applied to restore the performance of the network. Storm water hydraulic models are being used to determine the level of service in the storm water network, and the extent and severity of flooding pre- and post-quake for different extreme weather events. The modelling tools have been used extensively for land-drainage recovery works. To be suitable for use the storm water models must be sufficiently current and accurate to be a good representation of the actual operation of the storm water system. Thousands of earthquakes and earthquake aftershocks are continually changing the ground levels and the condition of different storm water infrastructure in Christchurch. The dynamic response of the surface water network and coastal plains due to earthquake-related topographical changes, lateral spreading, liquefaction, and subsidence posed a number of challenges for the local water authority. A case study on flood modelling for a flood-prone area of Christchurch has been reported in this paper. This paper outlines key challenges during the storm water model-building and updating process for a network which faces continual earthquakes and earthquake-related aftershocks.

***Keywords*—** Earthquake recovery, Hydraulic model, Restore stormwater network, Storm water, Surface water, Storm water model.

I. INTRODUCTION

Christchurch was hit by a series of massive earthquakes in 2010 and 2011. Some of the major earthquakes included a magnitude 7.1 on 4 September 2010, a magnitude 6.2 on 22 February 2011, and a magnitude 6.1 on 13 June 2011 [1]. Thousands of aftershocks were also notified in the area during these two years.

The three waters network (water supply, wastewater, stormwater) of the city was damaged significantly in many areas. A number of modern technologies such as pressure sewer, vacuum sewer, enhanced gravity sewer have been installed in Christchurch's earthquake-prone wastewater network [2]. In case of water supply network a number of rebuild projects have been completed to restore the performance of the water supply network. Earthquakes and earthquake-related aftershocks caused major changes in ground levels and geotechnical mechanisms such as ground settlements, vertical tectonic movement, liquefaction, and lateral spreading in different parts of the surface water network [3]. These have changed the extent and severity of flooding in different flood-prone areas of Christchurch. Christchurch is situated on a flat, coastal plain and has a number of urban rivers – the Avon, Heathcote, Styx, and Halswell – and open channels that convey storm water to the sea. The city was known for flooding and the earthquakes have made the situation worse in different areas.

This paper summarises the impact of the earthquakes on Christchurch's storm water network and the recovery strategies that are being applied to restore the performance of the network. It outlines a Christchurch-based case study on storm water modelling to demonstrate key challenges during the surface water model-building and update process for a network which faces continual earthquakes and earthquake-related aftershocks.

In this paper, Section I presents introduction. Section II outlines methodology of the research undertaken. Section III and IV discusses about Christchurch's stormwater network and post-earthquake damage extent. Section V outlines the post-earthquake recovery strategy being applied in Christchurch. Section VI illustrates the role of hydraulic models in Christchurch's surface water recovery works. Section VII discusses a case study of a Christchurch based stormwater network that is facing continual earthquakes. Section V concludes the work.

II. METHODOLOGY

As part of this research, Christchurch's current storm water network, history of flooding and recent post-earthquake recovery strategy documents have been reviewed. A case study on flood modelling for a small flood-prone area of Christchurch (Sumner) has been reported. Infoworks ICM (Integrated Catchment Management) hydraulic modelling platform was used to model the Sumner storm water network which is continually changing due to earthquakes since September 2010.

III. CHRISTCHURCH'S PRE-EARTHQUAKE FLOOD RISKS

The city of Christchurch is located on a low-lying, low gradient, coastal flood plain and its storm water network consists of rivers and tributaries, open drains and man-made storm water networks. Waterways are located throughout the city. As shown in figure 1, four main urban rivers, the Avon, Heathcote, Halswell and Styx, run through flat and low-lying areas. The Waimakariri River is situated to the north of the city.

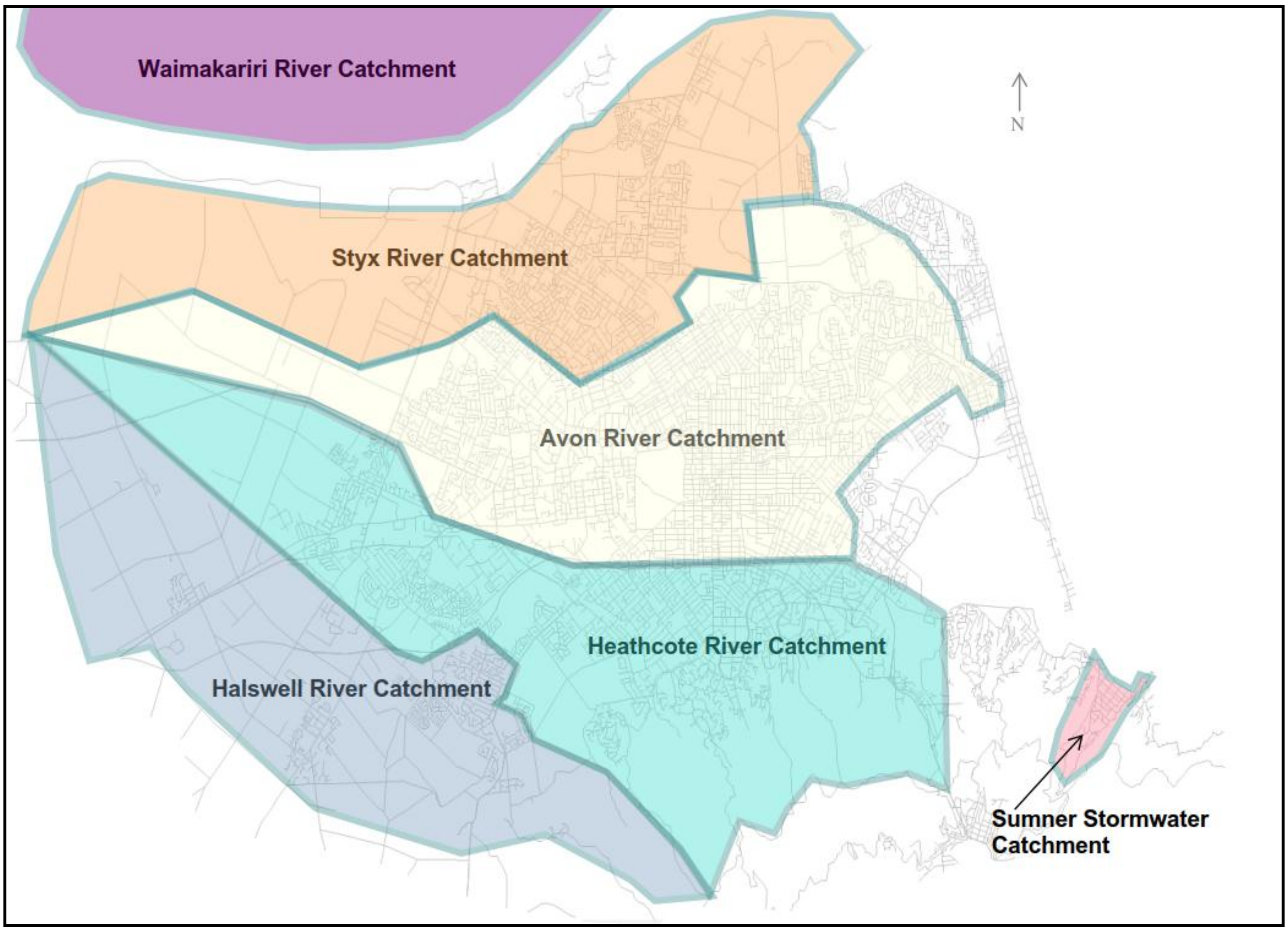

Fig.1. Christchurch river catchments and location of the Sumner storm water catchment

The city has a history of flooding. Major floods occur in the Waimakariri River area due to heavy rainfall in the mountainous, upper part of the catchment. Flood water from Waimakariri River has entered the city a number of times: in 1858, 1859, 1866, 1868 and 1957 [4]. Stopbanks along the Waimakariri River have been constructed to mitigate flooding.

Flooding of the urban rivers is mainly influenced by rainfall events, river breakouts, storm water ponding in different low-lying areas, and tidal influence from the downstream estuary. The urban rivers flooded significantly in July 1955, March 1957, August 1992 and July 2003 [4]. Floods from these rivers are typically generated by moderate intensity, long-duration rainfall [4].

A number of flood control measures such as stopbanks, tidal control gates, flow diversion and storm water maintenance actions were implemented to control drainage and flooding. These measures have proven effective over the past several years for controlling flooding up to a certain level.

IV. Earthquake Damage to Stormwater Systems

The earthquakes significantly damaged the land-drainage network of Christchurch. This damage has increased the flood risks in some parts of the city by changing the topography of the land and also by narrowing the open storm water channels. Seismic-induced geotechnical mechanisms have caused tectonic movement and liquefaction, lateral spreading, settlement and changes in stream-bed slopes. A number of storm water structures such as bridges, culverts, flood protection structures, pump stations, retaining structures and concrete channels were found to be vulnerable to ground movement in different areas [5].

The pre-earthquake LiDAR (light detection and ranging) data were compared with the post-earthquake data. Ground movement caused subsidence of around 0.4 m to 1.2 m in different parts of the flood plain of the Avon and Heathcote Rivers enhancing flood hazards. In some areas ground elevation is now nearer to the water table decreasing the soil's capacity to absorb water. The more earthquakes the city faces the more challenging it becomes to assess flood hazards as assessments need to go through a dynamic process.

V. Post-earthquake Recovery

A land-drainage recovery programme has been launched to rebuild and restore the performance of the storm water network and manage or mitigate flood risks where feasible. The main purpose of this programme is to understand post-earthquake damage in the land-drainage network and deliver projects to repair damage to waterways and other land-drainage infrastructure.

The land-drainage recovery programme was established in 2012 by the local government and it is currently in operation. The programme follows a number of steps to improve the performance of storm water network.

a) Identify the earthquake-damaged parts of the storm water network and assess the consequences of the damage.
b) Investigate post-earthquake flood risks and compare them with the extent and severity of pre-earthquake flooding.
c) Identify appropriate land-drainage restoration projects.
d) Prioritise projects and cost estimation.
e) Concept design and optioneering for delivering the project to restore the performance of the network to a pre-earthquake level.

One of the main purposes of the land-drainage recovery programme is to return the level of service (flood risks) of the storm water network to pre-earthquake level [6]. To achieve this target, a team had to investigate the current risk of flooding and also the pre-earthquake risk of flooding. It is a massive rebuild programme and sophisticated tools such as hydraulic/hydrologic models and GIS tools are essential for success. It will take approxmately 30 years to complete the land-drainage recovery programme and it is estimated to cost around NZ$1.2 billion [6].

VI. Role of Hydraulic Models

The purpose of storm water modelling is to determine the level of service the storm water network provides, and the extent and severity of flooding during different extreme weather events [7] [8] [9]. In addition, the model can be used to develop different storm water concepts for detailed design and construction in future. To be suitable for use, the storm water models must be sufficiently current and accurate to be a good representation of the actual operation of the storm water system [10]. Thousands of earthquakes and earthquake aftershocks are continually changing the ground levels and the condition of different storm water infrastructure in Christchurch.

The model should represent the network accurately by including information on current ground levels, up-to-date infrastructure, and current operational patterns [11] [12]. It was a challenge to keep different storm water models current and up to date in the face of ongoing earthquakes and earthquake aftershocks.

Christchurch City Council (CCC) had built a number of storm water models to serve different purposes at different points in time pre-earthquake. The models were built using different standards and specifications to serve different purposes [13]. Many of these models did not include detail on the storm water network which caused uncertainty in some areas. There was a need to build a combined, detailed storm water model for the city to assess earthquake effects and also to take steps for post-earthquake recovery. As shown in figure 2, Christchurch's storm water network consists of around 350 km of waterways, around 800 km of pipes in an area of 17, 200 hectares.

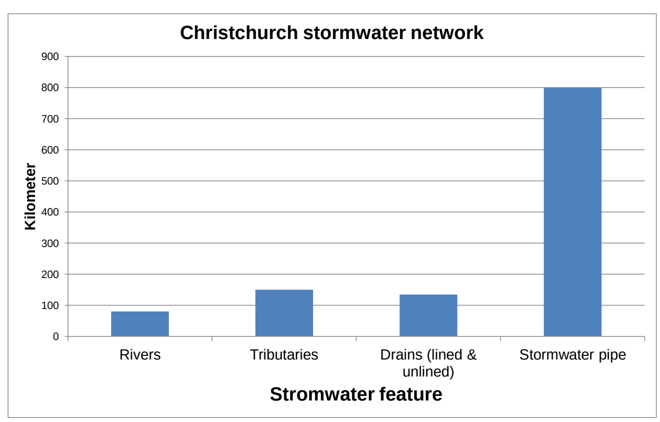

Fig.2: The Christchurch storm water network

A citywide combined flood-model building project was scoped and started to deliver storm water models with greater detail for Christchurch's waterways and pipe network (> 300 mm diameter) [13]. The DHI MIKE FLOOD hydraulic modelling platform was used for this project. A project of this immense size has not been done internationally in recent years. A number of challenges were anticipated during the project:

- Model simulation run-time could be large as the model would have to include almost the whole of Christchurch (around 17, 000 hectares.)
- Developing a digital terrain model (meshing) posed a number of challenges it was testing the capacity and capability of latest modelling technology [13].
- Christchurch's storm water network is continually changing due to earthquakes and related aftershocks. This posed some major challenges to keep the work up to date and accurate. Consequently the scope of the project changed continually to deliver the project successfully.
- Adding all the key waterways and storm water pipe network may pose some major technical challenges related to model stability in some areas. A strong comprehensive modelling investigation is very important for success.

The combined Christchurch model has been separated into multiple models (catchment-wise) for acceptable simulation run-time and also for better handling of the models. It made the process smoother and allowed urgent decision making in the flood affected areas. The model-building programme was prioritised based on the needs and purpose for the land-drainage recovery programme.

Part of this research article consists of a case study for a small, flood-prone area. The case study will help to conceptualise the challenges that a water authority may face when the network is continually changing due to earthquakes or similar events.

VII. Case Study : Sumner Flood Modelling

Sumner is a coastal area of around 10 square kilometres. It is situated in the south-east coastal area of Christchurch. The area is well known for historical flooding. Two hydrological and hydraulic models of the Sumner storm water system were developed using Infoworks ICM. One model was of the pre-earthquake network and the other for the post-earthquake network. The pre-earthquake Sumner model was developed using pre-earthquake (before 4 September 2010) storm water network GIS files, LiDAR information, aerial photography, and network survey files. The post-earthquake model was developed using post-earthquake information. Fig.1 shows the location of the Sumner catchment area.

A) Modelling Methods

The primary storm water system consists of open channels and pipes that convey flows during high frequency events. The pipes are based on Christchurch City Council's GIS data, and the open channels are based on available survey information and supplemented with LiDAR data. All piped storm water conveyance systems were included in the model, but 'bubble-up' connections that act to link kerb and channel flows across intersections were not included unless they formed a key component of the system. Sumps were represented where indicated in the GIS data, but not all sumps were included, as some serve simply to connect kerb and channel flow across intersections. Some structures that affect overland flow – such as solid walls and buildings – were included in the model. Building footprints were based on aerials.

The secondary storm water system is that which conveys flows once the primary system's capacity has been exceeded. Flows through the secondary system are routed using two-dimensional flow hydraulics in conjunction with a DTM (Digital Terrain Model). This is generally referred to as a '2D surface'. The DTM was formed as a Triangulated Irregular Network (TIN) based on the LiDAR data. Where the capacity of the modelled watercourse's channel is exceeded, flows then spill out onto the 2D surface and are routed overland by the 2D surface model. A dynamic boundary condition has been applied to the model based on seawater tide levels. This level has been attributed to all outlets into the sea.

B) Hydrology

Impervious and pervious areas were calculated based on planning zones, road parcel boundaries and aerial imagery. Ratios of impervious to pervious were in accordance with Chapter 21 of Council's Waterways and Wetlands Design Guidelines (WWDG) [14]. All impervious areas were assigned a C (run-off coefficient) value of 0.9, which accounts for typical surfaces. WWDG has been used for different permeability parameters: poor, moderate, and free [14]. 2D surfaces were generated from the pre-quake and post-quake LiDAR ASCII files for the Sumner pre-quake and post-quake models respectively. The Sumner model was calibrated with measured flood depths observed during pre- and post-earthquake flood events. Hydrology data were readjusted to get a good match between the model-predicted flood depth and measured/observed flood depth for pre-quake (for Sumner pre-quake model) and post-quake rainfall events (for post-quake model).

B) Results & Discussion

Sumner pre-earthquake and post-earthquake models have been run for a one-in-fifty year's synthetic rainfall event and compared. The rainfall event was developed using Council's WWDG guidelines [14]. As shown in figures 3 and 4 there are major changes in the extent and severity of flooding due to the February 2011 earthquake (magnitude 6.3) in the Sumner area of Christchurch.

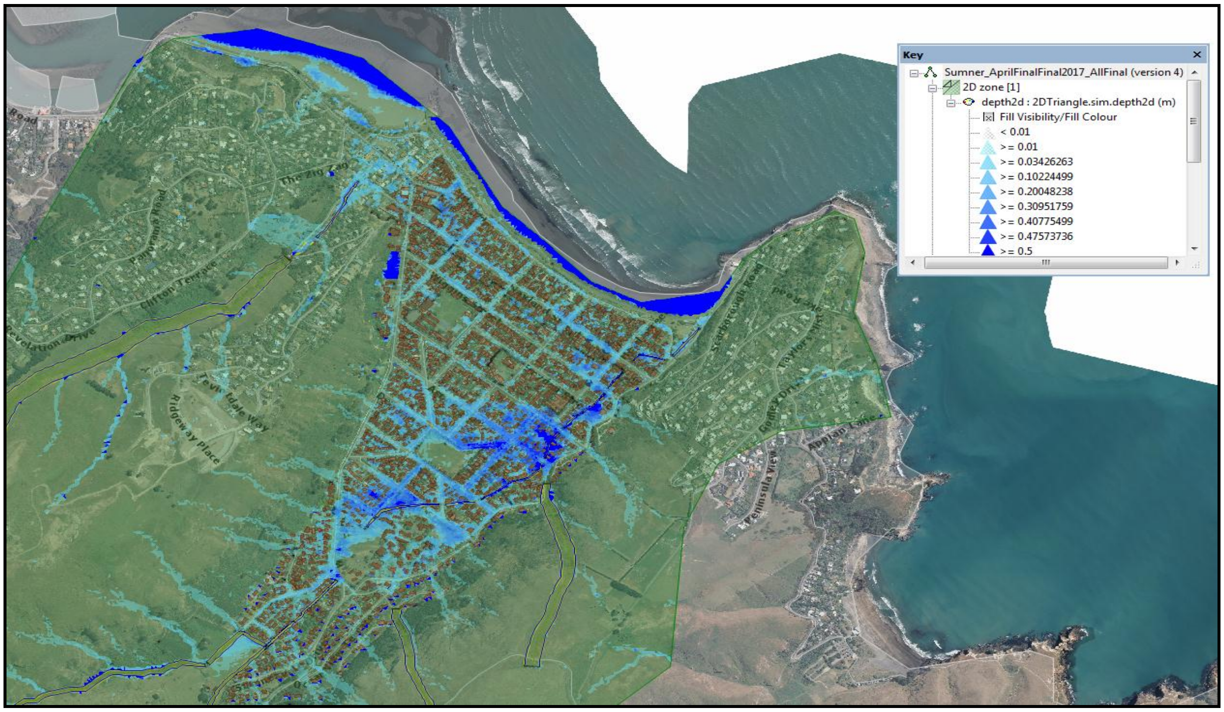

Fig.3:. Sumner pre-quake storm water flooding

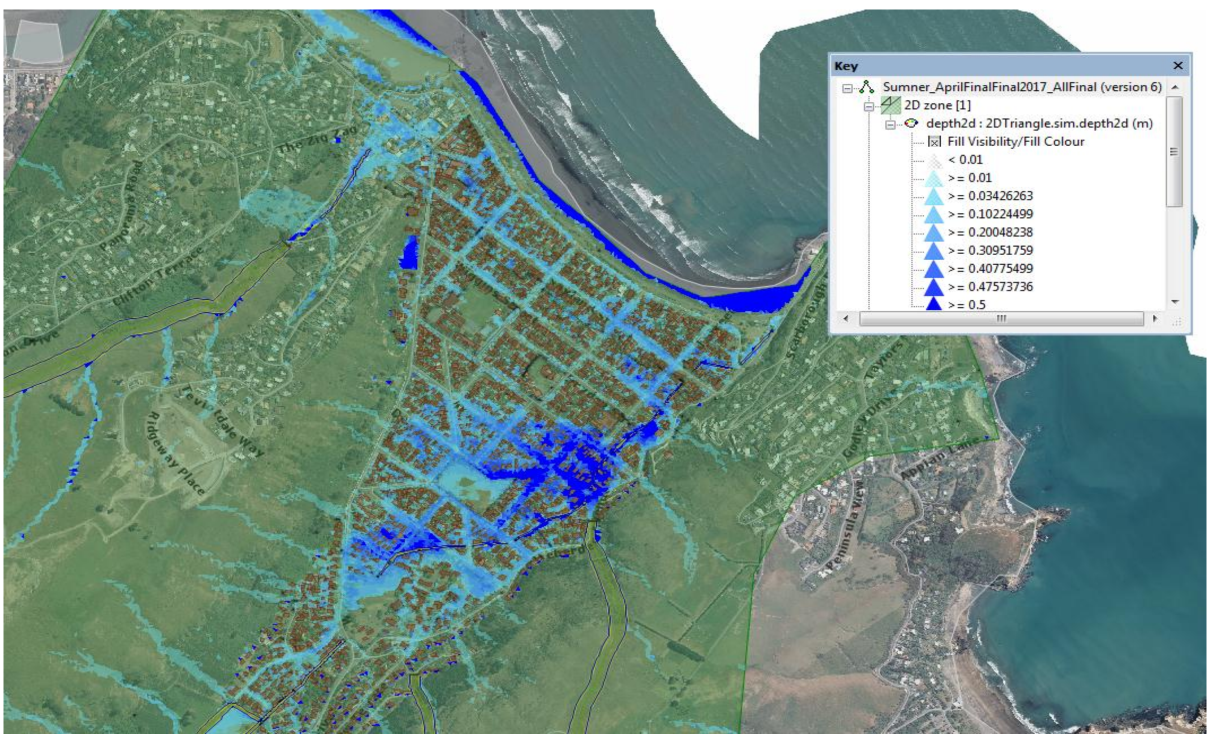

Fig. 4: Sumner post-quake storm water flooding

Since February 2011, around 15,000 earthquakes and earthquake-related aftershocks occurred in Sumner [1]. Of these, around 20 had a magnitude greater than six [1]. This means that Sumner's topography is also changing due to earthquakes. The storm water modelling scope also changes continually when a network faces ongoing earthquakes. Table 1 outlines key challenges that occurred during the storm water modelling when the network was continually changing due to ground movement.

Table 1. Storm water modelling and post-earthquake challenges

Earthquake effects/ challenges	**Comments/actions**
Continual changes in ground levels and LiDAR information	Unless there are major changes in ground levels small-scale earthquakes can be ignored. If the change in ground level is more than 0.05 m and if the changes are anticipated to cause notable effect on flooding it is highly recommended to do a ground level survey and update the storm water model accordingly.
Changes in river channels	In some cases, earthquakes may decrease or increase the cross section of an open channel. Some spot checks can be done to ascertain whether there are notable changes in open channel shapes or not. If there are significant changes then an engineering survey needs to be done to update the model.
What-if scenario modelling for immediate response	The model should be built with appropriate details so that what-if scenarios can be investigated easily with minimal effort. A storm water model with all the water channels and piping network will help to investigate different concept design options more accurately and efficiently. Model simulation run time needs to be kept within acceptable limit.
Calibration/validation	Once a model is calibrated, adding post-quake LiDAR information and post-quake survey file data should ensure the model is acceptable for use until validation is done with a post-quake flood event. Further calibration can be done once appropriate data and resources are available. Engineering judgement and decision makings are very important for a network which is changing continually due to earthquakes.
Modelling tools	An appropriate storm water modelling tool should be selected so that the model is able to take updated information easily and efficiently. The tool should be selected before any work is done on model building. Infoworks ICM was used for the Sumner model. The tool was found to be very powerful tool in that it could take new and updated information files in different formats (excel, CSV, .shp, and ASCII) easily and efficiently with minimal effort.

VIII. CONCLUSIONS

Christchurch's storm water network was significantly damaged due to earthquakes. The extent and severity of flooding in different parts of the network increased due to changes in topography and earthquake-associated land damage. The land-drainage recovery programme will take approximately 30 years to complete the land-drainage recovery programme and it is estimated to cost around NZ$1.2 billion.

Storm water modelling is key for the land-drainage recovery programme as the modelling tool can be used to understand the extent and severity of pre-quake and post-quake flooding. The tool can be used for concept design and optioneering for different projects. It is a challenge to keep storm water models current and up to date in the face of changes in ground levels and the condition of different storm water structures due to thousands of earthquake and earthquake-related aftershocks. It is very important to keep records of these rapid changes in the network and replicate these in the model so that the models can be used correctly to meet the changing needs of the stakeholders.

The Sumner storm water model was run with pre-earthquake and post-earthquake information to show the extent of changes in flooding in an area which currently faces recurring earthquakes and earthquake-related aftershocks. Modelling the storm water network in a single database platform in Infoworks ICM provided a huge advantage as the network can easily be changed and ground level information can also be updated quickly. Ongoing earthquake events created some unusual modelling challenges. An effective and efficient collaboration among hydraulic modellers, construction contractors and network operation engineers is important to keep the model current and up to date.

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