Water Resource Impacts of the Kaikōura Earthquake

REGULATORY AND OTHER RESPONSES

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1. Introduction

The Flaxbourne Settlers' Association and Marlborough Research Centre, with support from the Ministry of Primary Industries, have been working to identify the changes, and quantify the potential impacts, of the 14 November 2016 Kaikōura Earthquake on the water resources of the Flaxbourne, Mirza and Waima/Ure catchments (Figure 1.1). The emphasis has been on changes to both the surface water and groundwater resources, and their interaction, and how these changes have impacted water availability, water use, water-related infrastructure, and hazards.

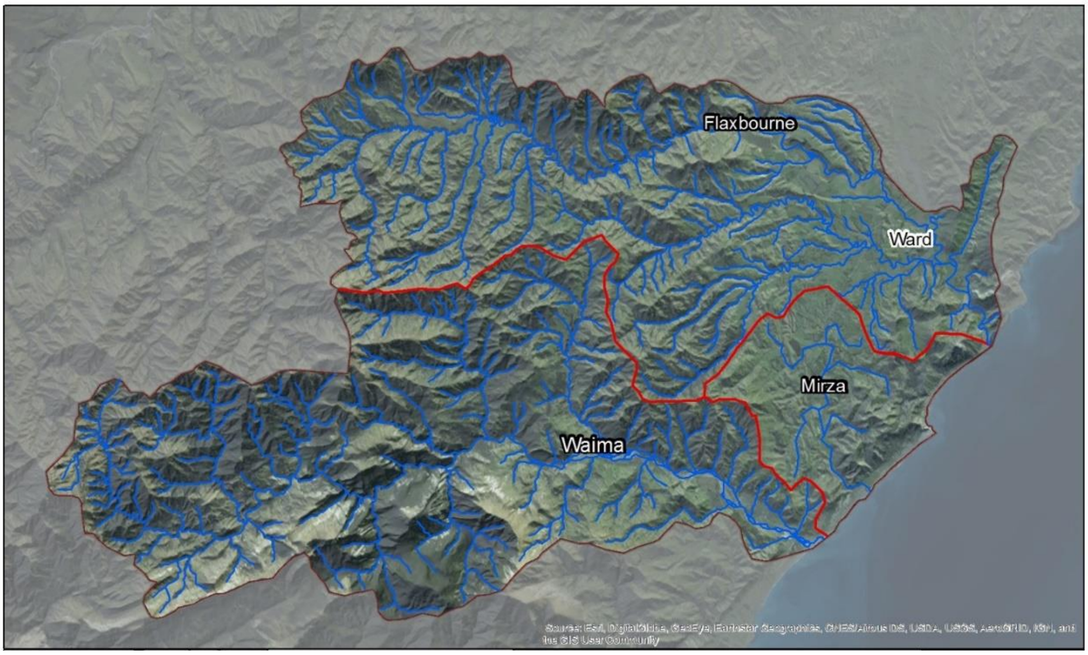

Figure 1.1: The Flaxbourne, Mirza and Waima/Ure catchments.

The wider Flaxbourne community relies heavily on the Flaxbourne and Waima/Ure Rivers for a diverse range of agricultural practices and land uses, including irrigation and stock water, and the domestic potable water supply for approximately 900 persons. The Flaxbourne-Waima area incorporates 25,000ha of farmland, 2600ha of potentially irrigatable land, and includes 154 rural properties that have been affected directly by the earthquake. Nationally significant infrastructure, including the State Highway and South Island Main Trunk Railway, and local roads and township facilities have also been affected.

The Kaikōura Earthquake caused dramatic changes to the landscape and waterways, including:

- Changed groundwater levels;
- Changed channel alignments (with implications for erosion, channel stability, sediment transport, the flood hazard etc.);
- Changes in channel gradient (with implications for erosion, channel stability, sediment transport, the flood hazard etc.);
- Changes in the alignment of the thalweg (i.e. dominant channel);
- Changes to groundwater conditions, both in specific bores and at a catchment level;
- Changes to surface water–groundwater interactions;
- Changes to water quality, through increased suspended sediment and bedload transport; and

- Changes to the flow regimes of rivers because of landslide-dammed lakes and exposed slopes in the upper catchments.

There is, however, considerable uncertainty over the magnitude and timeframe over which these changes may be experienced. Also, over time, the direction of these changes may change; first, as the environment adjusts to the effects of the earthquake, and then as these effects dissipate as environmental processes and conditions trend back towards the pre-earthquake situation.

This uncertainty is likely to be exacerbated should the predicted potential effects of climate change be experienced in the Flaxbourne, Mirza and Waima/Ure catchments.

While the effects of some of these changes were immediate, others will be experienced over the medium and longer-term. In the case of the longer-term effects, it is possible that these can be mitigated by a range of interventions and regulatory responses.

2. Increased Risks

The Kaikōura Earthquake increased several risks to the water resources, and consequently the community, of the Flaxbourne, Mirza or Waima/Ure catchments. These risks include:

- An elevated flood hazard caused by increased bed levels, and reduced channel capacity and gradient;
- The potential loss of productive valley floors from sediment aggradation and increased groundwater levels;
- An increased hazard to bridges and major infrastructure, from increased flood risk and gravel aggradation;
- Changes to the saline interface towards the coast, affecting water quality; and
- Issues relating to resource consent compliance from significant changes to the environment.

Several of these risks will be affected by the landslides, the landslide-dammed lakes, and the large volume of material which has been mobilised in the upper catchments. This debris will be transported downstream over time resulting in reduced channel gradients, aggradation, and reduced channel cross-sectional area. This will exacerbate the existing flood hazard to the valley floors; some of the most productive, versatile, and valuable land in these catchments.

These risks, and the increased uncertainty caused by the potential effects of climate change, can be mitigated through a range of options; from the development of new planning rules, through to physical interventions e.g. gravel extraction, channel works, well relocation, water storage etc.

3. Recommendations

The following provides a preliminary discussion of some of the effects of the Kaikōura Earthquake and potential regulatory and other responses that could help mitigate the adverse effects on the Flaxbourne Community. Proactive adaptations and management to mitigate the potential adverse effects of the earthquake will strengthen the security and resilience of the wider Flaxbourne community.

The principle effects of the Kaikōura Earthquake relate to:

- Channel stability and dynamics;
- Water supply and water quality; and

- Surface water-groundwater interactions.

These, their various drivers and controls, and possible responses to mitigate adverse effects, are discussed below.

3.1. Gravel monitoring and management

Many of the risks identified are either related to, or exacerbated by, the movement of sediment down the various rivers and stream. While the potential effects of this sediment are relatively easy to predict, the rate of change is more problematic. This is because sediment transport, and particularly the transport of coarse material, is essentially random in both time and space. The rate of sediment transport is controlled largely by the frequency, magnitude and duration of floods large enough, and with sufficient energy, to erode and transport material. The frequency, magnitude and duration of floods is impossible to predict. This uncertainty is exacerbated by the predicted effects of climate change.

Despite this uncertainty, monitoring river channels and aggradation (or degradation) of the beds is essential to both manage, and then mitigate, a range of risks.

The traditional approach to quantifying channel change, and therefore changes in mean bed levels (MBLs) or sediment volume in a particular reach, has relied on the measurement of cross-sections. While cross-sections are vertically precise i.e. the elevation of point is defined accurately, they invariably provide sparse sampling of the channel morphology longitudinally. For example, cross-sections may be hundreds of metres apart, even for the rivers in the Flaxbourne area. This methodology for quantifying channel change also requires the application of two-dimensional data (i.e. surveyed cross-sections) to the three-dimensional domain (i.e. a channel reach). This leads to considerable uncertainty that is then propagated into hydraulic, eco-hydraulic and morpho-dynamic related phenomena.

The past decade has seen the development of ‘next generation’ terrain models, based on high-resolution point cloud datasets generated by ground-based or mobile laser scanning and photogrammetric modelling. Systems providing point densities of >100pts/m^2 can provide measurements with a vertical and horizontal accuracy and precision at the centimetre scale.

These data can then be used to:

- Model three-dimensional morphology;
- Quantify the spatial pattern of surface sediment cover; and
- Create numerical models of sediment transport and morphodynamics.

There are also significant advantages of these remote sensing techniques with regard to health and safety, particularly when compared to the risks inherent with working in and around water.

Consequently, a number of regional councils have been exploring, and subsequently adopting, the use of this new technology for monitoring rivers, particularly larger rivers, in their regions e.g. the Otago, Hawkes Bay and Canterbury Regional Councils. These councils have used, either directly or through consultants, software to study bed level change using high resolution topographic data; derived from either LiDAR or SfM photogrammetry.

Data acquisition

There are a number of providers of high-resolution topographic survey in New Zealand, and this number is expanding rapidly. These systems are deployed either by helicopter or drone, and development of these systems is happening at a rapid rate.

Survey grade sensors, such as the Riegl VUX line, are typically heavier and best deployed using a helicopter. Surveys therefore have greater mobilisation costs and are best suited to larger applications e.g. all rivers in the Flaxbourne area and Marlborough. Typical costs are about $1850/hr for the helicopter, with slightly lower costs for deployment to the site. For example, a survey of a 10km reach of the Ashley River would take about 1 hour, with another 30-mins to ferry the helicopter from Christchurch. The total helicopter cost would therefore be about $3,000. Georectification, QA/QC of the LiDAR, plus classification would probably cost another $3-5k, depending on what exactly was required. The cost of surveying the Waima/Ure River from Blue Mountain to the coast (10km) would likely be very similar to that for the Ashley River.

Flying at 90knots (170k/h), at a height of 300m, would generate a swath of topographic data 380m wide on the ground. These parameters would generate >80pts/m² which is more than required to generate high quality terrain data. Surveying of the rivers in the Flaxbourne area and Marlborough, would probably only require 1-2 swaths, dramatically reducing the survey time down to less than an hour for each river system.

The major constraint with LiDAR technology at present is getting data for the riverbed beneath the water surface. LiDAR only penetrates about 10cm below the water surface. This would not be a constraint for most rivers if the LiDAR was acquired during periods of low flow. Under these conditions, the thalweg occupies only a very small percentage of the active channel and so any 'missing data' represents only a small proportion of the total river channel. In the Waima/Ure and Flaxbourne catchments, at the end of summer, the lower reaches of the channels, those of most interest, are dry. This limitation of LiDAR would therefore not be a constraint.

The potential significance of this current constraint is likely to reduce significantly over even the short term, with the advent of accessible, high resolution bathymetry (green) LiDAR. The University of Canterbury, for example, are running trials with a new system (the Riegl 840G) later this year. This technology has the potential to acquire bed elevations down to two secchi depths (i.e. the depth to which a secchi disk can be seen). This would cover most rivers in the Marlborough Region under low flow conditions.

Data processing

There are an existing range of tools for processing high-resolution LiDAR to produce accurate terrain models (DEMs) and to analysis change in river channels. For example, Geomorphic Change Detection (GCD) toolkit (see references) is designed to quantify 3D morphological change from DEM timeseries accounting for data uncertainties. This package, which is in the public domain, has been used by US Army Corp Engineers, UK Environment Agency, Scottish Environment Protection Agency, ECan, HBRC, and ORC to assess bed level change, storage and river channel morphodynamics.

The GCD software was developed primarily for topographic change detection in rivers, but works for simple, raster-based change detection of any two surfaces. The volumetric change in storage is calculated from the difference in surface elevations from digital elevation models (DEMs) derived from repeat topographic surveys.

A number of regional councils and other organisations have developed an in-house capability with these tools, although expertise can also be provided through external consultants.

A key advance from the move to LiDAR-based surveys is the ability to also extract information on bed material grain size; which is not available currently through any other means than direct sampling. There are a range of tools for processing high-resolution LiDAR to produce accurate characterisation of the material comprising the active channel. For example, the Topographic Analysis Toolkit (TAT) and ToPCAT (Topographic Point Cloud Analysis Toolkit) are designed for modelling surface roughness and grain size from dense LiDAR/photogrammetric data.

This information, when used in conjunction with that from the GCD, would allow the extraction of material from the bed of a river to be targeted to particular areas that have certain size material. This could be a very efficient means for maximising the efficiency and effectiveness of the extraction of material from specific reaches.

Recommendation

Because of the potential effect of changes in the riverbeds of the Flaxbourne area, it is recommended that:

- Regular topographic surveys of the channels of at least the Waima/Ure and Flaxbourne Rivers be initiated. These should be undertaken at an interval not exceeding five years, and after every major flood event;
- Regular topographic surveys of the channels at least the Waima/Ure and Flaxbourne Rivers be included in MDC's Long-Term Plan;
- MDC explore, and ideally adopt, LiDAR and terrain analysis tools (e.g. GCD, TAT and ToPCAT toolkits) to quantify channel and geomorphic change; and
- Given the significance of channel dynamics, and aggradation and degradation of the riverbeds, to the security of nationally important infrastructure, Waka Kotahi (NZ) Transport Agency and KiwiRail be approached to support ongoing monitoring.

3.2. Channel alignment

River channels reflect the interaction of the flow regime with the physical characteristics of the catchment. Because of the significant changes to characteristics of these catchments, particularly the percentage of bare ground, sediment supply and channel gradient, the channels of the Waima/Ure and Flaxbourne Rivers are expected to be more dynamic for a number of years. Greater changes than previously experienced are expected at both the reach and temporal scales.

The scale, rate and location of these changes are likely to be problematic for adjacent landowners, the owners of major infrastructure (Waka Kotahi and KiwiRail) and catchment management agencies. The scale and potential effect of these changes could, however, be mitigated by active and flexible channel management.

Possible responses

To recognise the increased dynamics of the stream channels:

- Regular topographic surveys of the Waima/Ure and Flaxbourne Rivers should be implemented, as discussed above;
- Riparian management, and particularly planting, should be encouraged; although the use of willows and other invasive species should be discouraged. The aim should be to encourage the stream to remain within its active bed, while minimising bank erosion;
- The possibility of reducing the regulatory demands for the removal of willows from within riverbeds and adjacent to the banks should be explored; particularly with respect to the Flaxbourne River where willows are currently choking the channel. This problem is likely to be exacerbated in the future. Consideration should be given to allowing machinery to access the river to assist with removal when this can be achieved efficiently and effectively; and
- Large woody debris is particularly problematic with regard to the security of bridges and other infrastructure managed by Waka Kotahi and KiwiRail. Consideration should be given as to how the potential impact of large woody debris can be mitigated.

3.3. Channel gradient

Differential uplift of the landscape as a result of the Kaikōura Earthquake has resulted in significant changes to the channel gradient of the Waima/Ure and Flaxbourne Rivers. This has had a significant effect on the bed shear stress and therefore sediment transport capacity. When combined with existing topographic constrictions, this will lead to the deposition of sediment and the aggradation of the riverbed. The reduction in channel capacity will lead to lateral erosion, an increased flood hazard, and reduced freeboard under bridges.

Possible responses

To mitigate the reduced channel gradient, and bed aggradation:

- Regular topographic surveys of the Waima/Ure and Flaxbourne Rivers should be implemented, as discussed above;
- The changes to the sediment transport regimes within the various catchments should be quantified. Reaches particularly prone to aggradation, and where aggradation poses a significant risk to infrastructure, should be identified;
- Ongoing monitoring of bed levels and channel form and character of these key reaches should be undertaken on a regular e.g. 5-yearly, basis and after every major flood event; and
- Once these critical reaches have been identified, the extraction of gravel should become a 'permitted activity' until the period of channel instability has ended.

3.4. Flood hazard

As a result of changes to both the runoff regime (volume and timing) and hydraulic efficiency of the various stream channels, the flood risk to land adjacent to the various rivers and streams has increased since the earthquake.

The current flood hazard within the Flaxbourne District has been quantified by the Project through rain-on-grid computational hydraulic models. Although uncalibrated at this time, the results from these models provide a clear indication of areas exposed to a greater flood hazard.

Possible responses

To mitigate the increased flood hazard, the results of the computational hydraulic modelling should be:

- Updated regularly using the improved topographic survey information of the Waima/Ure and Flaxbourne Rivers discussed above;
- Calibrated following any large flood event in either the Flaxbourn or Waima/Ure catchments;
- Included in MDC's digital land use database;
- Made widely available to the Flaxbourne Community; and
- Be considered when making decisions with the potential to be affected by flooding.

3.5. Landslide dams

Several of the risks to the Flaxbourne Community are related to the landslides, the landslide-dammed lakes, and the large volume of material which has been mobilised in the upper catchment. This debris will be transported downstream over time resulting in reduced channel gradients, aggradation, and reduced channel cross-sectional area. This, when combined with the increased runoff from these slopes, will exacerbate the flood hazard of the valley floors; some of the most productive, versatile, and valuable land in these catchments.

Possible responses

To mitigate the potential effects of the large number of landslides through the catchments:

- The landslides, and particularly the landslide dammed lakes, should be monitored;
- Planting of these slopes, particularly the foot-slopes adjacent to any water channel, should be encouraged and supported. This will limit the amount of debris that enters the channels and is transported downstream where it can cause significant, in terms of both scale and extent, adverse effects; and
- Monitoring and quantification of the effects of sediment from these sources should be undertaken using the regular topographic surveys of the Waima/Ure and Flaxbourne Rivers discussed above.

3.6. Flow regimes

A comprehensive coverage of low flow gaugings over the past three summers undertaken as part of the Project, has identified that the Kaikōura Earthquake caused significant changes to the runoff processes, and consequently the timing and volume of water, from many of the slopes throughout the Flaxbourne District. It also caused significant changes to the surface water-groundwater interactions, particularly the location and rate of conductance through the beds of some of the rivers. As a result, it is likely that the flow regimes, and various flow statistics used in water resource management, have also changed; although this is difficult to quantify given the variability of rainfall and other climatic parameters. Despite this, it is likely that the earthquake has caused changes to the flow regimes and descriptive statistics of flow in these catchments. This will create considerable uncertainty over the short to medium term. This uncertainty will be exacerbated by the effects of predicted climate change.

There is no robust relationship between flows at any of the sites within the Waima/Ure catchment and the flow recorder in the Flaxbourne at Corrie Downs. Management of the surface water resource in the Waima/Ure catchment therefore requires the installation of a permanent flow recorder, most likely at Blue Mountain where the total flow is confined by a bedrock channel. A temporary flow recorder has recently been installed at this location by MDC who are exploring options for a permanent recorder;

There has been a shift in the relationship developed previously by MDC between flows at Blue Mountain and at SH1. This has significant water resource implications. There is now a significantly greater loss of surface flow to groundwater than prior to the Kaikōura Earthquake;

The reduction in surface flow in the lower Waima/Ure catchment has implications for the management and maintenance of surface flows, and the connectivity between surface water and groundwater. This has implications for both surface water and groundwater abstraction.

Possible responses

So that any potential effects of the earthquake on the flow regimes can be placed in context, it is important to:

- Review the available hydrometric data, including rainfall, river flow (and level) and groundwater so that the dynamics of the hydrological system since the earthquake can be placed in a longer-term context;
- Continue to increase the number of low flow gaugings, to better quantify the quantum of water either gained or lost from these reaches. This is essential since the effects of the earthquake on these processes may dissipate or change over time. MDC are continuing the low flow investigation; and
- Ensure that there are flow monitoring sites on the major rivers i.e. Flaxbourne and Waima/Ure. A temporary flow recorder has been installed by MDC on the Waima/Ure River at Blue Mountain. MDC

are now investigating options for a permanent flow recorder; most likely at Blue Mountain or a similar location.

3.7. Water quality

The increase in bare ground and slope runoff has resulted in higher suspended sediment loads in the various rivers and streams during freshes and flood events. This has reduced water quality, and habitat quality where there is deposition of fine sediment. Higher suspended sediment concentrations also have implications for the efficiency and security of pumps and pipes.

Because of this, the Project has supported MDC with installing a water quality sonde, including a turbidity sensor, in the Flaxbourne River at Corrie Downs. This allows changes in turbidity to be related to flow and the effects of suspended sediment on water quality to be better defined.

Possible responses

So that the potential impact of suspended sediment on water resources and the environment can be quantified:

- Monitoring of turbidity by MDC should continue in the Flaxbourne River;
- Monitoring of suspended sediment should be undertaken in the Waima/Ure River;
- Suspended sediment samples should be obtained under a range of conditions to develop a sediment rating curve for at least the Flaxbourne River; and
- The suspended sediment regime should be investigated, the principle controls identified, and how this varies through time should be quantified.

3.8. Security of water supplies

The Kaikōura Earthquake has affected the security of existing water supplies from rivers and streams; both agricultural and domestic supplies, including the community water supply for Ward. There are risks to:

- Water quality, from increased suspended sediment; and
- Water quantity, caused by changes in the flow regimes of rivers, groundwater levels, surface water-groundwater interactions, and topography.

Because of this, the Project has supported the Ward Community improve measurement of both water levels and abstraction from the water supply bore. These data will assist the community to manage the water supply so as to minimise and mitigate the risk inherent in the current system.

The Project also supported the investigation of an alternative water source, with the aim of developing a more resilient and sustainable long-term water supply. This, however, was unsuccessful despite promising indications early in the process.

Possible responses

So that the potential risk to water supplies can be mitigated:

- The levels, behaviour, and yield from the Ward community bores should continue to be measured and quantified. The installation of additional monitoring of the system at key locations is being investigated currently;
- Options for water storage to improve the resilience and sustainability of the Ward Community Water Supply should be considered and developed;

- Data available from other water supplies should be reviewed;
- Greater flexibility should be permitted regarding existing resource consent conditions;
- The current uncertainty should be recognised in any new water permits; and
- Support should be provided for 'out of river' water storage schemes and water harvesting.

3.9. Groundwater conditions

MDC's only groundwater monitoring bore within the Flaxbourne, Mirza and Waima/Ure catchments was damaged severely during the earthquake. As a result, there are no data to correlate pre- and post-event conditions, and to identify any changes to groundwater levels or water chemistry. The results of a community survey undertaken by this Project, however, indicate that any groundwater effects are likely to be site specific, and deriving a broader-scale groundwater response model may be difficult.

Significant geodetic changes within the Flaxbourne, Mirza or Waima/Ure catchments could have impacted the physical form and hydraulic properties of the aquifers, and zones of recharge and discharge; including several new springs. Issues with groundwater turbidity were also noted within the wider Marlborough Region, however, the extent of these has not been documented and there are no data specific to the Flaxbourne, Mirza or Waima/Ure catchments.

All known groundwater in the Flaxbourne catchment is restricted to the shallow alluvial gravel deposits associated with the Flaxbourne River; or its tributaries Tachalls and Needles Creeks. Therefore, Needles Creek and the adjacent groundwater are hydraulically connected and considered as one water resource.

A trigger level of 22.8m asml was set previously for the Needles Creek monitoring well. This corresponded to when surface flow ceased in Needles Creek. However, it is likely that the previous monitoring well experienced vertical uplift of 1.6–1.64m during the earthquake. Water levels recorded in the new monitoring well are significantly different to those recorded before the earthquake.

MDC has installed a new Needles Creek monitoring bore and developed a preliminary trigger to mimic the previous criteria i.e. cessation of surface flow in Needles Creek. Since surface flow was still observed during the lowest recorded water level of 24.43m, the new trigger level is likely to be lower than the previous value.

Possible responses

The Needles Creek monitoring bore is a critical water resource management tool, therefore:

- The new trigger should be formalised as quickly as possible;
- A new trigger level should be established following low flow gaugings to identify any changes to the flow regime in the wider Flaxbourne catchment; and
- Until a new robust trigger has been formally adopted, greater flexibility should be permitted regarding existing resource consent conditions.

3.10. Surface water-groundwater interactions

Results from a comprehensive suite of low flow gaugings undertaken by the Project and MDC have several implications for water resources in the Flaxbourne and Waima/Ure catchments, and water resource management. These include:

- A shift in the previously developed relationship between flows at Blue Mountain and at SH1; and
- Significantly less surface flow at SH1 relative to Blue Mountain since the Kaikōura Earthquake.

A greater proportion of the flow at Blue Mountain is now 'lost' upstream of the SH1 Bridge. This change does not appear to exist, at least to the same level, between the Blue Mountain and the Ure Road Bridge. The apparent change in the proportion of surface flow 'lost' to the underlying gravel appears to be the result of changes to the connectivity between surface water and groundwater between the Ure Road Bridge and SH1.

This change in river behaviour is consistent with the differential uplift that resulted from the Kaikōura Earthquake. Uplift at the coast reduced the channel gradient and provided a greater volume of porous gravel above sea level. This has facilitated both greater storage and greater underflow i.e. flow through the gravel.

This means that at present the unconfined aquifer beneath, and adjacent to, the lower river now contains more water than prior to the Kaikōura Earthquake. This additional groundwater storage, however, is likely to decrease over time as the bed level and long profile of the Waima/Ure River adjust back to their pre-earthquake configurations.

The longer-term effects of the changes caused by the Kaikōura Earthquake are currently difficult to predict, certainly the timeframe of any future changes. Over time, it is likely that the Waima/Ure River will downcut through the uplifted gravel to attain grade, and a long-profile, similar to those before the Kaikōura Earthquake. Once this has occurred, it is likely that the surface water and groundwater dynamics, and their interaction, will be similar to those before the earthquake. The speed of downcutting will be controlled by the frequency, magnitude and duration of flood events. Since floods are essentially random in time, any future changes in the lower Waima/Ure catchment are difficult to predict at this time.

The current reduction in surface flow in the lower Waima/Ure catchment has implications for the management and maintenance of surface flows, and the connectivity between surface water and groundwater. This has implications for both surface water and groundwater abstraction.

Possible responses

Given the significance of any shift in the location and behaviour of surface water-groundwater interactions, it is recommended that:

- Changes in the flow regime between Blue Mountain and SH1 should be investigated further;
- Regular high-resolution LiDAR surveys between SH1 and the coast, as discussed above, be considered to monitor bed level changes; and
- The implications of the changes in bed level for both the shallow unconfined aquifer and surface water–groundwater interactions in the lower Waima/Ure catchment be investigated.

3.11. Saline interface

The geomorphic evolution of the Flaxbourne and Waima/Ure catchments, and particularly the transport of sediment from the mountains to the coast, has resulted in a thick wedge of alluvial sediment connecting the lower valleys to the coast. The sediment contains both confined and semi-confined aquifers which are hydraulically connected to both the rivers and the coast. Consequently, the aquifers have a saline interface between the fresh and seawater.

During the Kaikōura Earthquake, the area experienced a general trend of vertical uplift ranging from 1-3m, but with significantly greater uplift towards the coast. Increased relative uplift experienced at the coast has reduced the channel gradient in the lower reaches of each catchment. The lowered gradient over these reaches has the potential to change the existing dynamics of the saline interface at the coast. While the uplift may have increased the depth to the interface, the reduced gradient could lead to any saltwater intrusion extending further inland, affecting water quality.

Because of the sensitive balance of the saline interface, abstraction of water from the aquifer can have a significant effect on both the depth and lateral extent of the interface. This may represent an increased risk of groundwater contamination, at least over the short to medium term.

Over time, it is likely that the Waima/Ure River will erode through the uplifted gravel and attain conditions similar to those before the Kaikōura Earthquake, as discussed above. Once this has occurred, it is likely that the surface water and groundwater dynamics, and the position and dynamics of the saline interface will also be similar to those before the earthquake.

Possible responses

Given the significance of any shift in the position of the saline interface, it is recommended that:

- A new monitoring well be installed adjacent to the coast to measure the position and dynamics of the saline interface. The Project team has been in discussion with Flaxbourne Community Irrigation Ltd. to support and facilitate monitoring of the saline interface;
- The interactions between surface water, groundwater and the saline interface be investigated, and where possible quantified; and
- The implications of the nature and dynamics of the saline interface for sustainable water resource management and use be assessed.

3.12. Infrastructure resilience

Both SH1 and the SIMT railway pass through the Flaxbourne and Waima/Ure catchments. These nationally important transport networks were affected severely by the Kaikōura Earthquake, and the bridges and culverts will be affected by ongoing landscape changes. These networks are also prone to both the existing and future flood hazard affecting the area.

Possible responses

To mitigate the risk to nationally significant infrastructure, it is important that Waka Kotahi NZ Transport Agency and KiwiRail are:

- Made aware of the flood hazard and other information developed during this project;
- Involved in the proposed regular topographic survey of the river channels recommended above;
- Involved in discussions and decisions regarding gravel management; and
- Involved in discussions regarding ongoing channel management.

3.13. Lake Elterwater

Lake Elterwater is the largest surface water body in the Flaxbourne-Mirza-Waima (Ure) area and has high ecological significance. It is a highly dynamic system; unique in the sense that it functions as both a lake and wetland environment depending on conditions. The lake possesses a distinctive hydrological regime because of its seasonal fluctuation in water level combined with warm temperatures.

Differential uplift during the Kaikōura Earthquake raised the southern end of Lake Elterwater relative to the northern end. Given the significance of Lake Elterwater, the Project has quantified the effect of the earthquake on surface area, depth and water storage. The ‘tilting’ has increased the potential volume of the lake below the invert of the outlet channel by 78,177m^3 (~16.5%) and its maximum surface area by 24,094m^2 (~4.3%).

While flow into Lake Elterwater is unlikely to have changed because of the earthquake, the increase in potential surface area, depth and volume of water will impact the aquatic habitat i.e. the area of wetland will increase slightly. Since the lake can hold more water, the water level will also decrease more slowly during summer. Overall, there is likely to be a slightly greater area of wetland habitat and wetland conditions are likely to persist for longer periods. It is also possible that flow downstream of Lake Elterwater into the Flaxbourne River will be moderated and attenuated.

Because of the significance of Lake Elterwater, MDC, with support from the Flaxbourne Settlers' Association and the Ministry of Primary Industries, have installed, additional environmental monitoring. This includes:

- The installation of a continuous lake level recorder. This has been installed at close as possible to the deepest area of the lake to provide a water level record over almost the full range of levels likely to be experienced; and
- An automated climate station to collect high-resolution data relating to a wide range of parameters; including rainfall, temperature, humidity and wind. This data will fill the significant gap in available climate information that exists between Lake Grassmere and Ward.

MDC also anticipate that when Lake Elterwater is discharging to the Flaxbourne River, flow measurements will be undertaken at the outlet from the lake. Over time, these will allow the development of a flow rating. When these data are combined with the lake level record, it will be possible to develop a water balance for Lake Elterwater that quantifies, for the first time, inflows, outflows and changes in storage.

Because of the significance of Lake Elterwater and its wetland habitat, Marlborough District Council are considering including information relating to the lake in its State of the Environment reporting.

The above actions and strategy will ensure that high quality environmental data and information are collected for Lake Elterwater, and that its condition is monitored on an ongoing basis.

Possible responses

Given the significance of Lake Elterwater to the Flaxbourne District, it is recommended that:

- Climate and hydrometric data collected by MDC at Lake Elterwater be made available on their website;
- An outflow rating be developed, and a continuous outflow record be established;
- A water balance be developed and monitored for Lake Elterwater; and
- Information and data relating to Lake Elterwater be presented by MDC in its State of the Environment reporting.

4. Conclusions

While the effects of some of the changes caused by the Kaikōura Earthquake were immediate, others are likely to be experienced over the longer-term. In the case of the longer-term effects, it is possible that these can be mitigated by a range of options. Options could include regulatory responses, such as the development of new planning rules, through to physical interventions e.g. gravel extraction, channel works, well relocation, water storage etc.

Decisions regarding the preferred and most cost-effective and efficient interventions will involve ongoing discussion between the Flaxbourne Community and Marlborough District Council.

5. References

Geomorphic Change Detection (GCD) Toolkit: http://gcd.riverscapes.xyz

Topographic Analysis Toolkit (TAT) and ToPCAT (Topographic Point Cloud Analysis Toolkit: http://tat.riverscapes.xyz

www.wsp.com/nz