Duncan Dam Water Use Plan

Lower Duncan River Mosquito Monitoring and Management Plan Development

Implementation Year 5

Reference: DDMMON-9

Study Period: 2014 –2015

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DDMMON#9: Lower Duncan River Mosquito Monitoring and Management Plan Development (Year 5)

Reference: Q9-9077

Prepared for BC Hydro

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Executive Summary

The Duncan Dam Water Use Plan (WUP) consultative process was initiated in 2001 with the objective of gaining stakeholder consensus on the operation of the Duncan Dam for a set period following the conclusion of the WUP process. To do so, several operating alternatives were evaluated against performance measures representing stakeholder interests. These performance measures integrated assumptions and knowledge of processes governing a particular interest into their interaction with operations of river and reservoir levels. The Duncan Dam WUP Consultative Committee (CC) was particularly interested in the effect that operations had on nuisance mosquito production in the Lower Duncan River floodplain.

Modelling has been used as an effective, and economical, tool in environmental management strategies. Linking floodplain hydrology with mosquito biology and species distribution allows for analysis of the effect that the Duncan Dam operation has on nuisance mosquito abundance in the Duncan-Lardeau floodplain, and subsequent improvements that can be made. In addition, this knowledge can be applied to treatment initiatives allowing for more sophisticated mosquito management protocols to be developed.

Larval abundance of different species and a range of environmental factors were recorded across a six year period (2009-2012 and 2014-2015) to better understand the dynamics of mosquito production on the floodplain. Environmental factors including temperature and water depth, as well as vegetation type, were found to be important variables explaining the distribution of larval mosquitoes. In particular, the presence of nuisance mosquitoes can be predicted by specific vegetation types with which they are associated, and provides improved knowledge of species distribution across the floodplain. The resulting data have been analyzed and combined with hydrological data and models within a GIS framework to produce a spatially-explicit predictive model, called the Nuisance Mosquito Performance Measure (NMPM). This evidence-based empirical tool predicts how operation of the Duncan Dam will influence production of nuisance mosquitoes on the Duncan-Lardeau floodplain.

The NMPM models productivity of mosquito larvae for the genus *Aedes*, which tends to be specialized for reproduction on floodplains and makes up most of the mosquitoes in the area. *Aedes vexans*, a species that is well-known to cause nuisance for humans and animals, makes up around half of the mosquitoes sampled during data collection. Due to its high abundance, this mosquito species is of primary concern for management on the floodplain.

Wetland vegetation is known to reflect local hydrological flooding regimes. Larval mosquitoes hatch and develop in shallow, impermanent aquatic habitats and areas of different classes of dominant vegetation contribute differentially to mosquito production. For example, our data show that areas where grasses make up the dominant vegetation produce much greater numbers of *Aedes* larvae. This empirical ecological information has been incorporated into the Nuisance Mosquito Performance Measure to provide informed predictions.

The current NMPM, based primarily on the 2D hydraulic model (Northwest Hydraulic Consultants Ltd. Project: DDMON #3), concludes that larval abundance increases with increased levels of dam discharge. The hydraulic model does not contain information pertaining to areas covered by wetland which may become inundated by flooding caused by discharge from the dam. We know from records of water levels taken at the thirteen sampling sites that there is a significant positive correlation between water level and dam discharge. An assumption of the NMPM model is that higher discharge increases the availability of mosquito larval habitat, and that this relationship is linear. However some mosquito larval habitat will be destroyed when flooding occurs due to scouring action or by reducing temperatures below those required for hatching.

Other ecological factors, including mosquito biology, are also considered in the model. The long-term data show very high numbers of larval mosquitoes directly after the freshet. A small proportion of eggs can hatch later in the season if flooding exceeds the original extent of wetted area from the spring freshet. These newly flooded areas will be expected to have higher larval production than those that were previously flooded by the spring freshet in the same season. *Aedes* eggs are also desiccation-resistant for many years and only hatch when wetted, therefore areas that are flooded during the freshet may still contain viable eggs that can hatch with subsequent flooding events.

Our long-term sampling results show that larval mosquito abundance is highest in the initial phase of the mosquito season, immediately following the spring freshet (Figure 12). The NMPM also predicts that nuisance mosquito productivity in the mid-season is higher than in the late season and that incremental changes in relative rates of larval productivity occur as dam outputs increase from 50 to 400 m^3/s (Figure 15). The greatest change in the rate of increase of mosquito productivity is predicted to be 7% which occurs over discharge rates of 300-325 m^3/s (Figure 16).

Executive Summary Appendix: DDMMON #9: Status of objectives, management questions, and hypotheses after Year 6

Objective	Year 6 (2014-2015) Status	Progress/Impediments WRT answering Management Question(s)
Refine the nuisance mosquito performance measure originally designed for the DDM WUP by improving the resolution of the flow-habitat flooding relationship and increasing the understanding of mosquito production drivers and migration in the lower Duncan River floodplain	Complete	Modelling work completed by Dr. Phelan. Migration not relevant to NMPM design for DDM WUP.
Provide meaningful recommendations towards improving the effectiveness of the current mosquito abatement program	Complete	The model identifies areas that are likely productive habitat for nuisance mosquitoes.
Provide meaningful recommendations towards identifying and addressing the potential threat of WNv	Complete	Very few WNv vector mosquitoes were discovered throughout the entire study, and the threat is low.

Management Hypothesis	Year 6 (2014-2015) Status	Progress/Impediments WRT answering Management Question(s)
Nuisance mosquito productivity is correlated to environmental and stochastic factors, such as precipitation and temperature, and to the frequency and amplitude of flooding.	Complete	Multiple regression analysis accounts for the relationship between environmental variables and larval productivity
Existing nuisance and WNv mosquito management programs on the Lower Duncan River can be improved through increased understanding of drivers of mosquito productivity.	Complete	Model can identify important wetted areas for nuisance mosquito habitats

Management Question(s)	Year 6 (2014-2015) Status	Progress/Impediments WRT answering Management Question(s)
How may discharges from the Duncan Dam affect production of *Aedes* mosquitoes through inundation of Low Bench areas in the Lower Duncan and Lardeau floodplains from May to September?	Complete – subject to validation in 2016	Model predicts a relationship between Dam discharge and mosquito production
Do groundwater variations in different areas at different dam discharge rates relate to flooding regimes, vegetation types and mosquito production?	Unknown, but not relevant	Model speaks to wetted areas. Links between discharge, vegetation, and mosquito abundances are discussed.

Management Question(s)	Year 6 (2014-2015) Status	Progress/Impediments WRT answering Management Question(s)
How widely do adult mosquitoes disperse from their breeding grounds and how significant is the Duncan Dam in creating adult mosquito nuisance to residents of the Lower Duncan Floodplain? Can we better predict the potential nuisance mosquito production associated with vegetation types?	Unknown and not measurable Complete	Adult dispersion measurements were not feasible. Larval abundances were used as proxy for adult mosquito nuisance. Grass is by far the most productive vegetation type in the floodplain.
Is the current Nuisance Mosquito Performance Measure effective at predicting the potential production of late outbreaks of nuisance mosquitoes related to Duncan Dam operations?	Complete – subject to validation in 2016	Yes. NMPM has been updated to include mid-, and late-season nuisance mosquito outbreaks.
Can we more accurately predict when outbreaks of nuisance mosquitoes are most likely to occur given particular environmental and climatic conditions?	Complete – subject to validation in 2016	Environmental and climatic data can be entered into model to predict where and when nuisance mosquitoes will hatch.
What can the current mosquito abatement program (managed by the Regional District of Central Kootenay, RDCK) do to improve its effectiveness based on the information collected in this program?	Complete	Prioritize treatment of low lying grass areas as these are the most productive habitat for nuisance mosquitoes. Plan the timing of treatments using thresholds to target specific species. Include mosquito identification in the program to enable focused treatment of target species, and to eliminate unnecessary treatments. Use species ecology and larval monitoring to ensure treatment applications are conducted at the optimal time to result in maximum effectiveness
Is the operation of the Duncan Dam linked to production of high competence WNv vector mosquitoes?	Complete	Low numbers of *Culex tarsalis* can be found in the floodplain in high water years, but this is not linked to Dam operations. There is very low risk of West Nile virus outbreaks.

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1.0 Introduction

1.1 Project Rationale

The Duncan Dam facility became fully operational in 1967. The dam is a storage reservoir for a drainage basin of 2,400 km^2 and the largest inflows occur in May and June as a result of snowmelt. The highest levels of precipitation are seen from July to October, or later. The dam is operated under the terms of the Columbia River Treaty and the Water Use Plan, which dictate reservoir storage requirements throughout the year to manage downstream flooding and power requirements for environmental and social values (BC Hydro 2005). The 45 km long Duncan Reservoir is contained by a 40 m high earth-fill dam wall and holds 1,727 million m^3 of storage with an average drawdown of 30 m. Due to the restrictions of the Water Use Plan (WUP), it is unusual for large volumes of water to be discharged from the dam between May and mid-July. Thus, there was uncertainty as to the degree of influence that discharges from the dam may have on mosquito production annually (Jackson *et al.* 2002). Upstream of the dam is the unregulated Lardeau River, which can contribute to flooding of the Lower Duncan River and Meadow Creek floodplain during May and June. Fluctuation in Kootenay Lake levels may also have an impact on mosquito production along the shores and in other areas of the floodplain.

The Duncan Dam WUP Consultative Committee was particularly interested in the effect that dam operations had on nuisance mosquito production in the Lower Duncan River floodplain. The WUP was approved with significant operational constraints to downstream flooding, which were assumed to minimise mosquito production. A monitoring program was recommended to test this assumption and provide recommendations for improved mosquito controls.

In addition to monitoring, advances in computer technology now allow for the development of sophisticated models to predict species distributions based on environmental variables. Data collected in the field can both inform the model and help to test model accuracy. Understanding mosquito distribution and abundance at the landscape level, and the underlying factors that affect mosquito presence, is an essential tool in developing appropriate mosquito management strategies, whether for vectors or nuisance mosquitoes.

The term 'nuisance mosquito' is broadly defined as mosquito species that are known to emerge in large numbers and are aggressive human biters, but are not known vectors of human diseases. The two major species that fall into this category on this floodplain are *Aedes sticticus* and *Aedes vexans*.

1.2 Summary of Previous Work (Year 1-4)

In 2001, a consultative process began between BC Hydro and the Duncan Dam WUP CC. The committee wished to identify and minimize any contribution that dam operations were having on the production of nuisance mosquitoes in the local area downstream of the dam. Initial surveys of mosquito habitat in the Lower Duncan Dam Floodplain were conducted during the WUP process to inform the development of the initial Mosquito Performance Measure. Data on flooding regime, vegetation type and the distribution of mosquito breeding habitat were collected. There was an additional focus on the spatial distribution of mosquito species across the floodplain, and temporally throughout the season, to look for correlation between these factors and mosquito species identity. Results indicated that the major nuisance mosquitoes in the region (*Aedes* spp.) were most often found in open grasslands, whereas species present in wetland environments, such as swamps and fens, were less likely to be species of concern to humans. Additionally, there was clear temporal variation across the season in terms of which mosquito species were present at any given time. The initial Performance Measure concluded that while dam operations could be altered to reduce nuisance mosquito presence, mosquito numbers were highest immediately following the freshet period and before dam discharges had occurred.

At the conclusion of the WUP process, a monitoring program was recommended, which has been implemented since 2008. Data from the monitoring effort have been used to generate a new Nuisance Mosquito Performance Measure (NMPM) regarding mosquito production. The results of sampling effort across all years are shown in Table 1. Thirteen sites were selected across the floodplain and these were sampled for larvae six times across the mosquito season. CDC light traps were used to capture adult mosquitoes. Even though 2009 was a dry year with low incidence of nuisance mosquitoes, ten different species of mosquitoes were identified from both collection methods. Similarly to the 2002 study, *Aedes* and *Culiseta* spp. tended to be high in abundance in June but species composition switched to primarily *Anopheles* spp. in August. Discharge rates from the Duncan Dam did not affect species composition or mosquito abundance in 2009.

The same sampling regime was repeated in 2010, which was another dry year. However, higher discharges than 2009 resulted in two flood events later in the 2010 season. Following these floods, larvae of the *Aedes* genus, most notably the nuisance mosquito *Aedes vexans*, were found in mid-August and September (Figure 1). This indicated that hatching could occur later in the season. Once again, the data collected in 2010 displayed clear relationships between genera and habitat type, as well as temporal distribution across the season. However, a full picture of species distribution in the floodplain would only be possible during a high water year.

This occurred in 2011, with high levels of snow pack leading to a high freshet and increased discharge rates from the Duncan Dam later in the season. A reduced monitoring plan was conducted with three sampling events across the season. There were very high levels of nuisance mosquitoes in 2011 as well as the presence of West Nile virus vectors, *Culex tarsalis* and *Culiseta inornata*, across the floodplain on multiple sampling occasions. As a result of this, a West Nile virus response plan was recommended to ensure preparedness following a potential outbreak of West Nile virus in the future. Additionally, there was evidence of a minor second hatch of *Aedes* later in the season (Figure 1) when water levels, as a result of discharge from the Duncan Dam, went above the level reached by the freshet earlier that year.

Table 1: Sampling effort of adult traps and larvae dip sampling across six years, 2009-2012, 2014, and the freshet period of 2015. In 2014, sampling effort was increased to include specific areas for vegetation mapping, as well as routine sampling at the same 13 sites used in previous years. In 2015, a subset of sites were sampled during the freshet in early June.

Year	Adult Traps Set	Adults Collected	Dip Samples	Larvae Collected
2009	40	77	1450	3174
2010	49	68	1660	3142
2011	25	222	1800	4577
2012	81	11335	3780	3688
2014 routine sampling	29	216	2700	6597
2014 vegetation specific sampling	-	-	2210	8377
2015 freshet sampling	-	-	390	3204
Total	**224**	**11918**	**13990**	**32759**

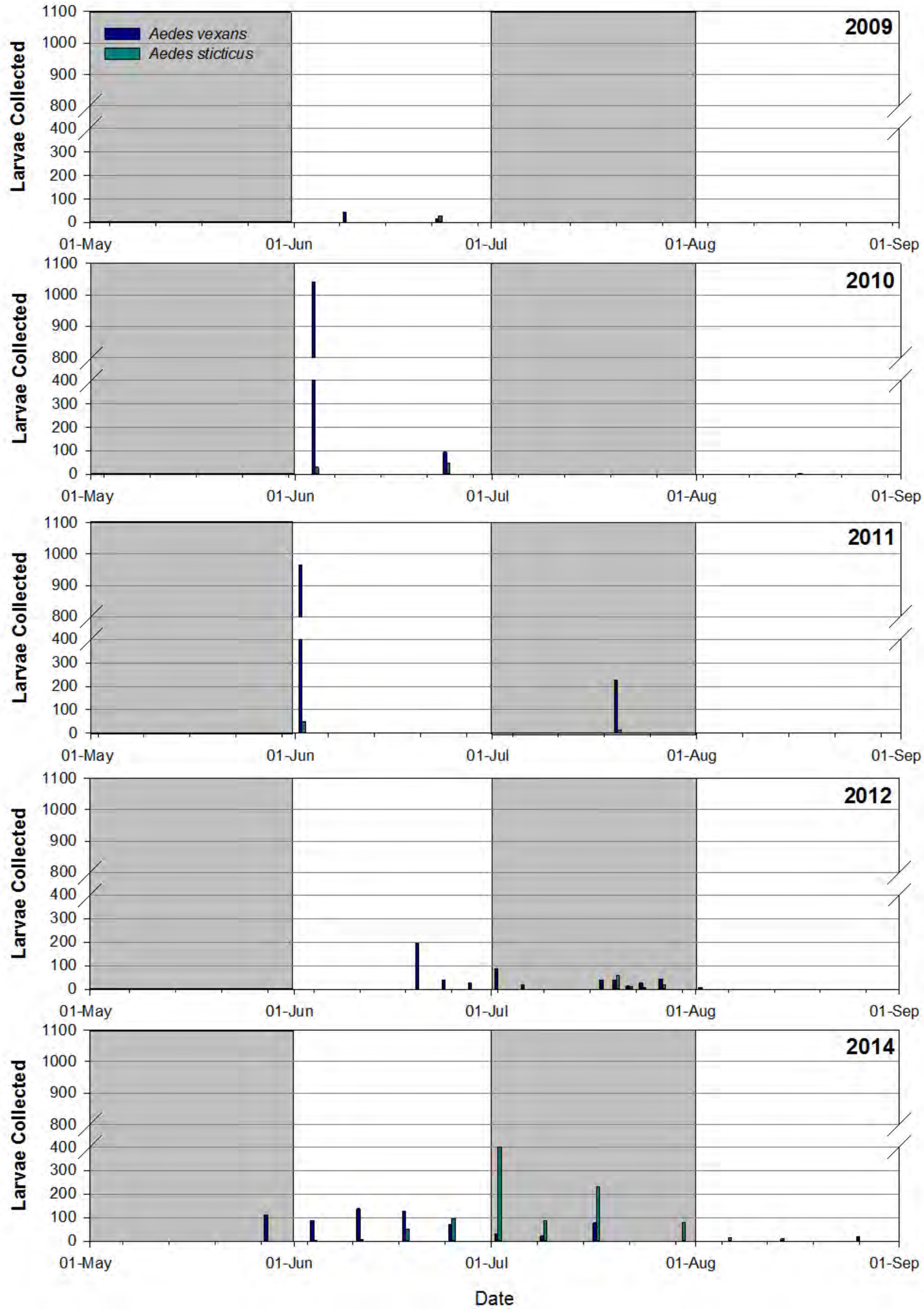


Figure 1: Summary of *Aedes vexans* and *Aedes sticticus* larval collections 2009-2014.

Sampling in 2012 used adult traps with baited with carbon dioxide to improve their efficacy and this proved effective as counts were much higher than they had been (Table 1). Increased sampling efforts identified 22 species across the season. Water levels were remarkably high, resulting in an extreme freshet, which was followed by high (but necessary, as the dam had reached full pool) discharge levels later in the season. When discharge levels go above the level already reached by the freshet, a second hatch of *Aedes* species will occur in newly flooded areas. Vegetation type can be a strong predictor of mosquito species (Figure 2).

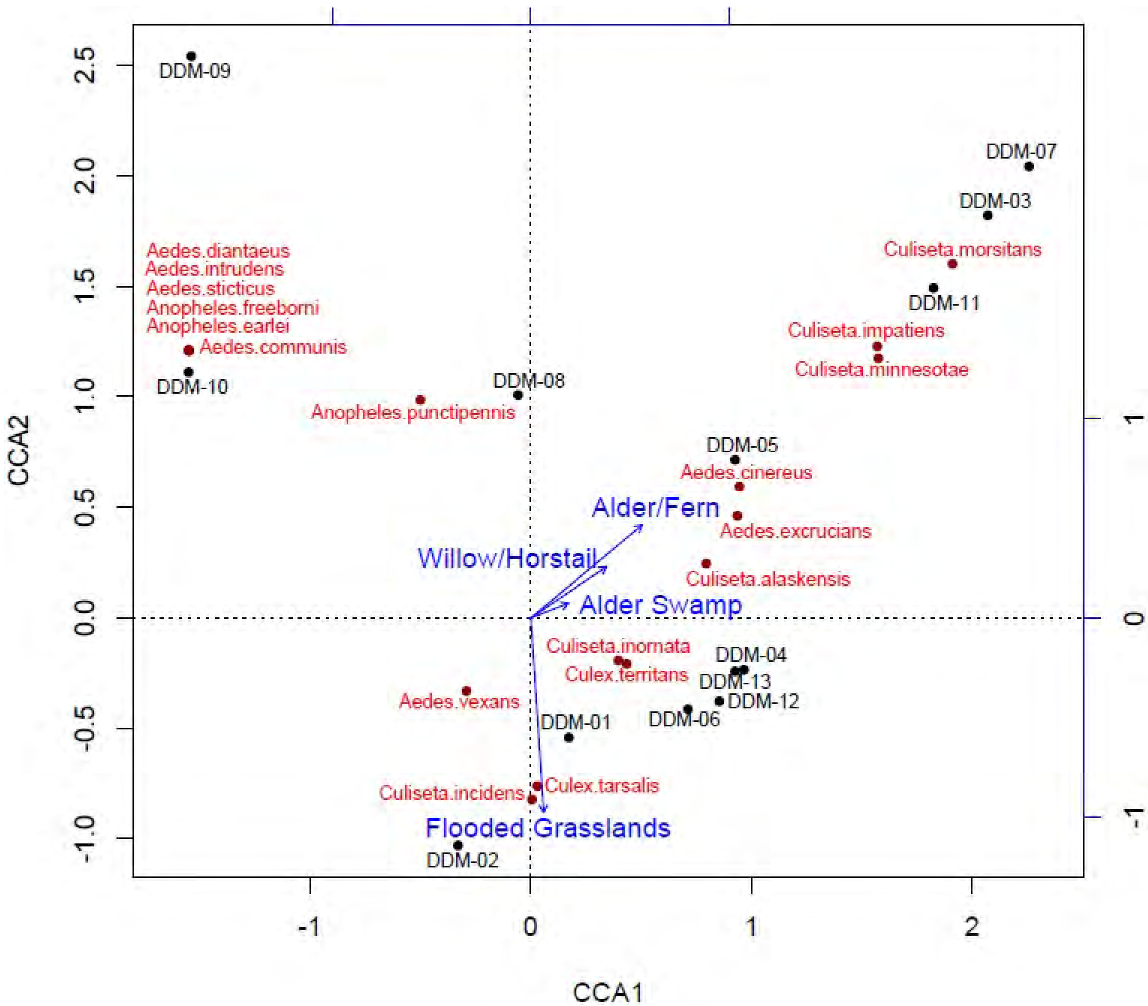


Figure 2: Canonical Correspondence Analysis of the vegetation and species identified from each site in 2011 and 2012.

Aedes vexans are commonly located in grasslands (Figure 2), and *Aedes sticticus*, another nuisance species, is closely associated with cottonwoods. The combined data from six years is now an extensive data set which shows strong trends between vegetation type and species identity. There are also species specific differences across the mosquito season with some, such as *Aedes sticticus*, appearing early in the season, and others, such as *Culiseta minnesotae*, emerging later on (Figure 3).

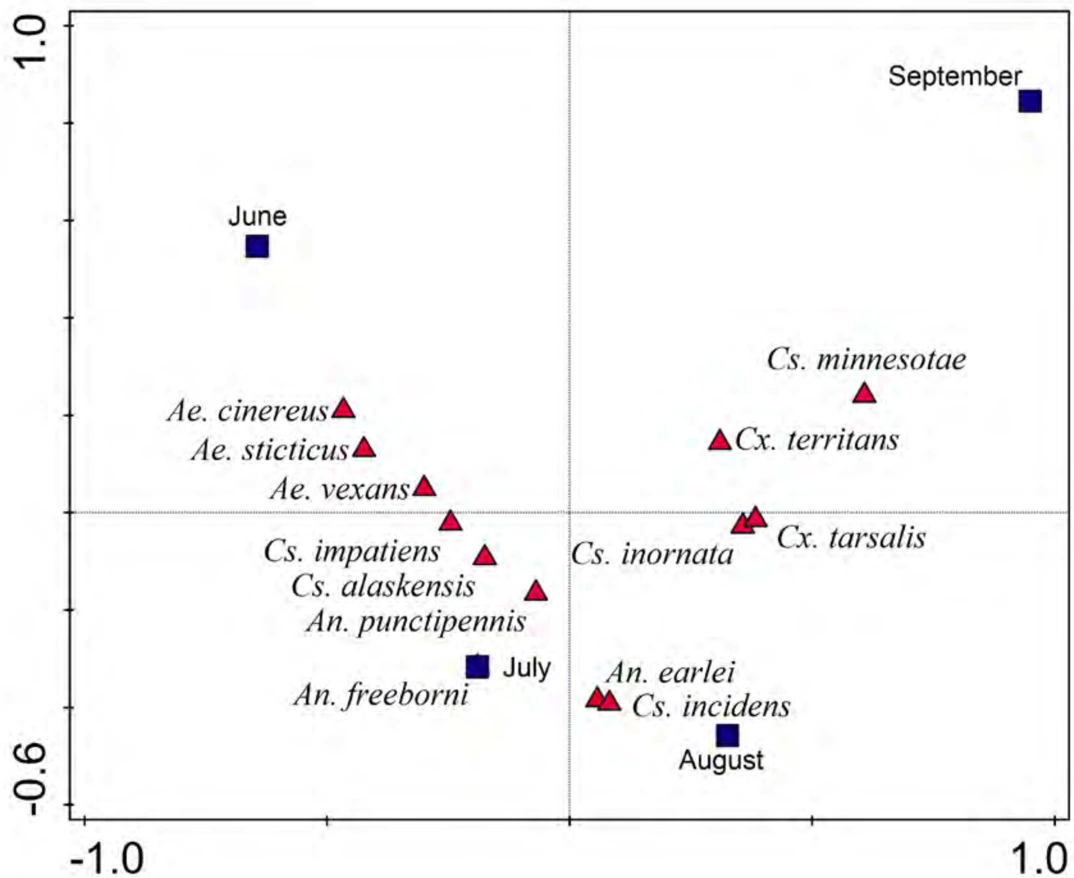


Figure 3. Canonical Correspondence Analysis of species distribution across the year from data collected in 2011 and 2012.

In addition to vegetation type and seasonal variation, other factors can interact to affect mosquito distribution and this variation needs to be taken into account in the analysis. A numerical model, based on this rich dataset, can determine the relationship between flood regimes, vegetation type, temperature, and species identity. This will allow for predictions of mosquito abundance depending on environmental conditions and will help inform management decisions.

1.3 Approach to the Nuisance Mosquito Performance Measure

The Nuisance Mosquito Performance Measure (NMPM) reported here is based on ecological data that were collected from the Duncan-Lardeau floodplain between 2009 and 2014. These data are reported in the annual reports from 2009-2012, which are summarized above. Aquatic sites with the potential to produce mosquitoes were systematically sampled for mosquito larvae, and water depth and water temperature were recorded at each sampling event. Multiple sampling events were conducted across the season of mosquito production. Larvae were collected during sampling, counted and identified to species using morphological characteristics. Vegetation was categorized and mapped across the lower Duncan floodplain using satellite imagery and were ground-truthed by Brenda Herbison. Full details can be found in the Materials and Methodology section (page 7).

A Performance Measure provides quantitative evaluation of one or more aspects of an organization's products or procedures. This report details a Performance Measure concerned with dam operations and the production of nuisance mosquitoes downstream of the Duncan Dam in the southern interior of BC. The computer files and software that accompany this document are an analytical tool that uses site-specific data to assess how dam discharge affects production of nuisance mosquitoes on the Duncan-Lardeau floodplain.

The Nuisance Mosquito Performance Measure (NMPM) is based on statistical associations between levels of environmental variables and larval abundance of nuisance species at different times. These statistical associations were used within a Geographic Information System (GIS), in conjunction with a 2D hydraulic model, to predict how mosquito production will respond to various dam discharge scenarios. The NMPM is generated using a software tool within the R environment for statistical computing and graphics. Levels of variables for different environmental and discharge scenarios are entered into the software tool and indices of relative mosquito production are generated. These predictions are informed by statistical associations between observed abundance of mosquito larvae and the various environmental factors relevant to production of larval mosquitoes, particularly the availability of water for mosquito habitats.

2.0 Materials and Methodology

To develop the Nuisance Mosquito Performance Measure, the following tasks were undertaken:

1. Larval sampling was extended in 2014 to measure effects of vegetation types on larval abundances;
2. Environmental and Operations data were collected to control for temperature and flow effects on mosquito production observed in the vegetation sampling;
3. Model Development - The NMPM makes use of three broad modelling processes (Figure 4):
    i. statistical analyses
    ii. a 2D hydraulic model of channel flow and flooding
    iii. GIS implementation that puts predictions from processes i and ii into a spatially-explicit and ecological context.

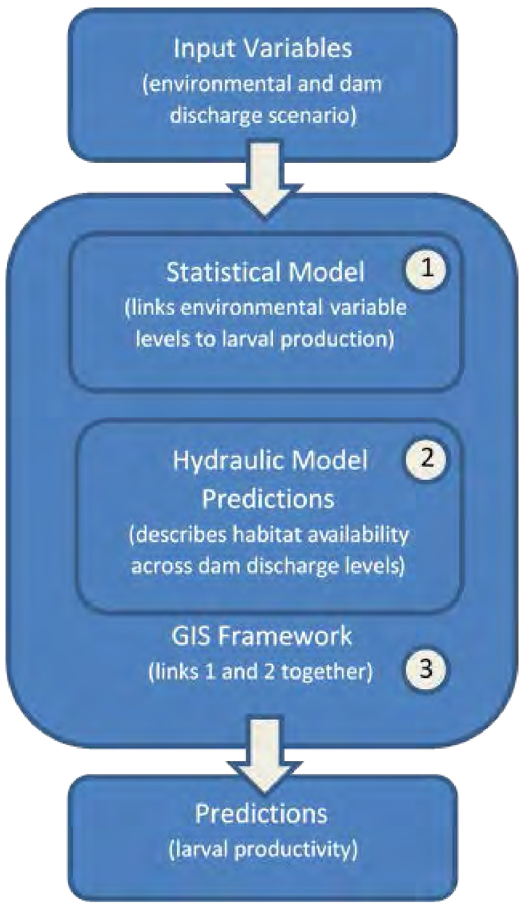


Figure 4: Flowchart of the Nuisance Mosquito Performance Measure modelling process

2.1 Larval Sampling

The NMPM was developed and parameterized using data specific to the production of larval mosquitoes in the Duncan-Lardeau floodplain. Sampling measured both abundance of larval mosquitoes and levels of environmental variables known to influence mosquito production. Data were collected during the season of mosquito production (spring through early fall) across multiple years. Mosquito sampling consisted primarily of systematically collecting, counting and identifying larval mosquitoes to species. Larvae were captured with a 500mL long handled dip sampler, using a standard dipping method described in the Municipal Mosquito Control Guidelines (Ellis 2004). Each sample consisted of ten dips pooled from a single site. Prior to 2012, samples were replicated five times. Data were collected in two major, distinct sampling regimes.

The first larval sampling regime occurred in the years 2009, 2010, 2011, 2012, and 2014. The aim of this sampling was to evaluate the relationship between the productivity of various larval habitats and levels of environmental factors, including dam discharge, through time. Larval counts were collected from 13 fixed locations on the floodplain. These sites are labeled with the designation DDM in Figure 10. For 2009 through 2011, larvae were sampled at each site on two to four sampling occasions across the mosquito season. In 2012 and 2014 sampling was far more intensive, occurring every four days in 2012 and once per week in 2014 (for 24 and 17 sampling events respectively).

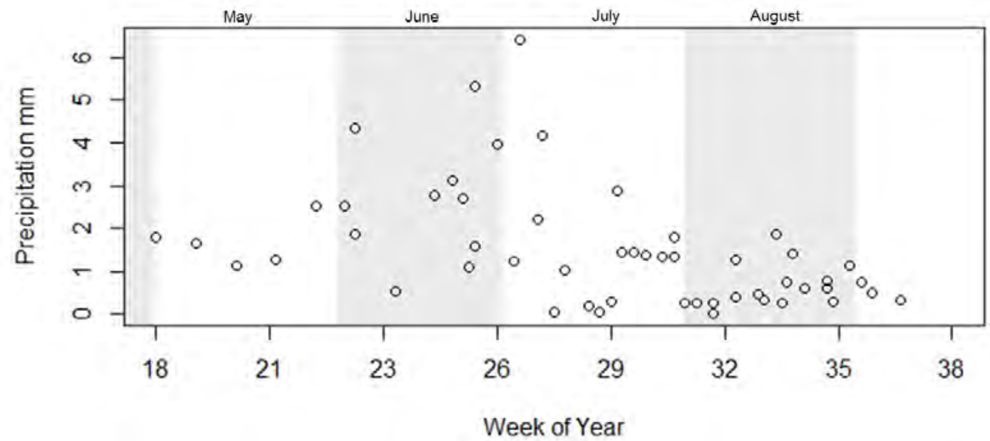
In 2014, a second, and more spatially intense, larval sampling regime was conducted, in addition to the sampling described above. Ninety samples were collected three times over the 2014 larval season, covering six dominant vegetation classes identified on the floodplain. For each sampling event, 15 samples were collected from within each of the six dominant vegetation classes on the floodplain (three events x six vegetation classes x 15 samples = 270 samples total). Sampling locations are shown in Figure 10. Samples were collected using a standard dip cup method and each sample consisted of ten dips. Each of the three sampling events over the season took two or three days to complete. The first event occurred from May 30-June 3 (a few cottonwood samples were collected a week earlier on May 23), the second July 23-25, and the third August 8-10. Larval sampling was also conducted in June 2015 at all 13 sites, as well as ten additional grassland and cottonwood sites.

The larvae in each sample were counted and collected for later identification to species level. Late-instar larvae were immediately preserved in alcohol for identification. Early instars cannot be identified to species, therefore early instars were kept alive and reared into adult mosquitoes, which are more easily identified. Mortality during rearing is variable, and dependent on ambient temperatures and the density of larvae in the rearing vials, among other factors. To account for this mortality, the proportion of each identified species that made up a sample was multiplied by the original larval count for that sample, thus providing a reliable measure of species counts per sample.

2.2 Environmental Data

Data on environmental variables were gathered in the following ways. Water depth was measured at each sampling event from a fixed rebar post at a set location for each of the 13 sites. At six of these sites, water temperature was recorded using data loggers (StowAway TidbiT model, Onset, Bourne, MA, USA) which were affixed to the base of the rebar posts throughout each sampling season 2009, 2010, 2012, and 2014 (sites labeled DDM-1, 4, 6, 7, 9, 10). Local air temperature and precipitation data from the Duncan Lake Dam weather station were provided via the Environment Canada Website (www.climate.weather.gc.ca). Daily mean levels of water discharge from the Duncan Dam were provided by BC Hydro. Finally, a local consultant, Brenda Herbison (who specializes in vegetation), categorized and mapped the vegetation of the entire floodplain area (Figure 7).

a)



b)

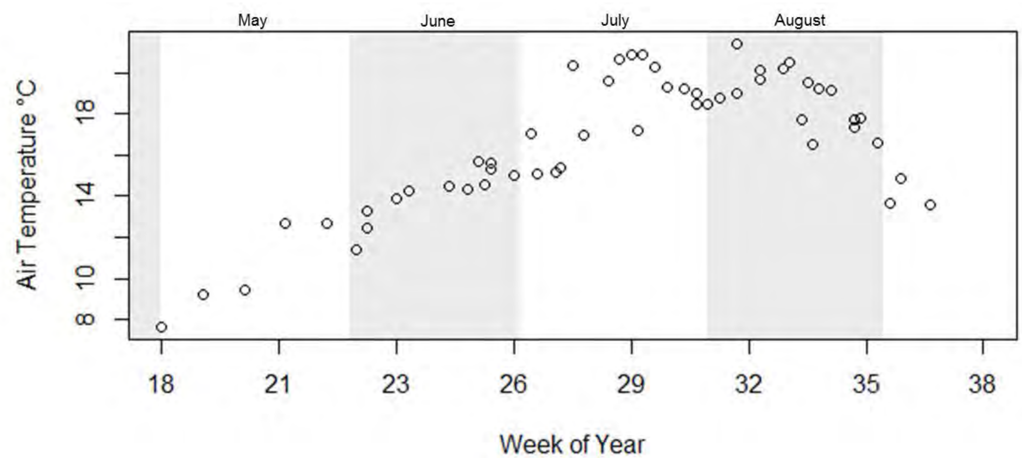


Figure 5. Week number and the associated temperature (a) and precipitation (b). Months are indicated with grey shading.

Trends for precipitation and air temperature differed across months. Precipitation is highest in June and July and reduces in August (Figure 5a). Air temperatures rise from May to mid July and then level off until mid-August after which they rapidly decrease (Figure 5b). Interaction terms between the environmental variables and time of season were included in the model. Water temperature tended to be very low, likely owing to the depth placement of the data recorders. For this reason, mosquito habitat was modelled using a wetted-edge model as larvae will only occupy the warmer, shallower edges of pools (Appendix IV).

Discharge and Seasonality

Annual volumes of discharge from the Duncan Dam follow a broadly similar pattern. Discharge during the six-year study period are shown in Figure 6. During the early season, discharge levels do not exceed 130 m^3/s, as the freshet is ongoing during this time. The mid-season period historically sees the highest levels of discharge, with peaks in excess of 300 m^3/s in very high water years such as 2012, shown in blue. In the late season, discharge generally levels off below 200 m^3/s.

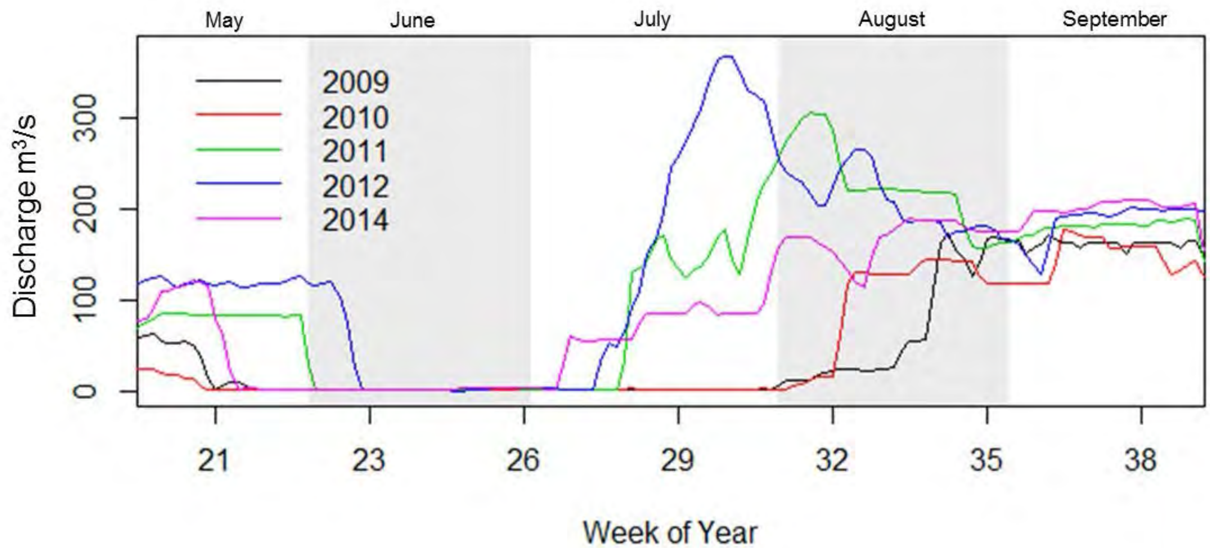


Figure 6: Discharge of the Duncan Dam over five years during the productive mosquito season, showing early, middle, and late divisions.

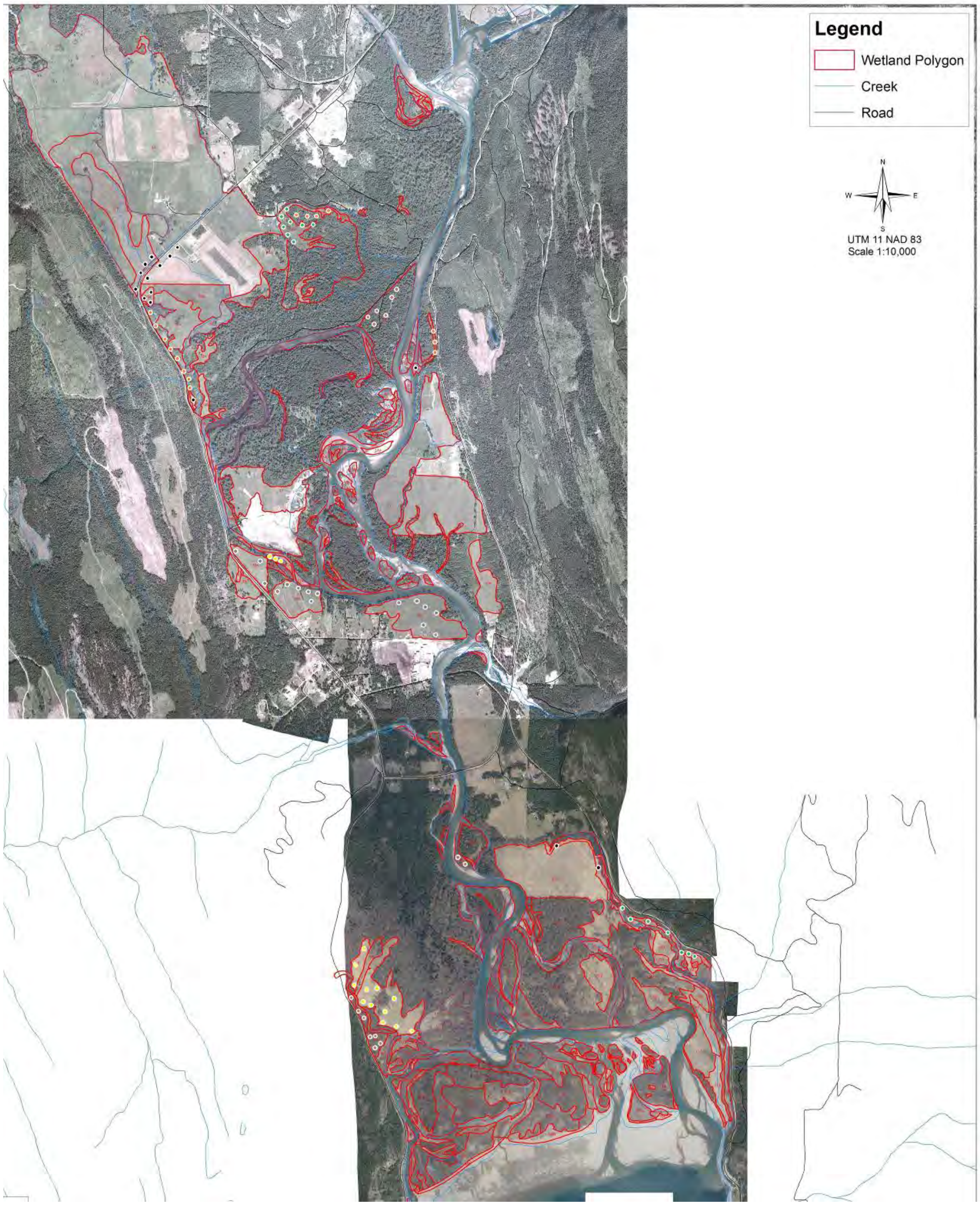


Figure 7: Vegetation polygons of the Duncan Floodplain from B. Herbison

2.3 Modelling Process

All statistical analyses were conducted using R version 3.1.0, Spring Dance (R Core Team 2014). Multiple R packages for GIS and graphing were used, including ggmap, ggplot2, raster, and rgdal. Vegetation classification maps and outputs from the 2D hydraulic model were processed with ArcGIS 10.0. Those data were rasterized and subsequent processing and analyses were conducted within the R software environment for statistical computing and graphics. Appendix II provides instructions for using the NMPM calculator.

i. Statistical Analyses

Analyses consisted primarily of fitting multiple regression models. The measured response variable consisted of larval counts. These count data had a strong positive skew with a large proportion of zero counts, which is consistent with a negative binomial frequency distribution with a low mean. Figure 8 below shows observed values alongside a simulated negative binomial distribution with the same sample size and mean. The two distributions are very similar and a negative binomial distribution is appropriate for describing this data set.

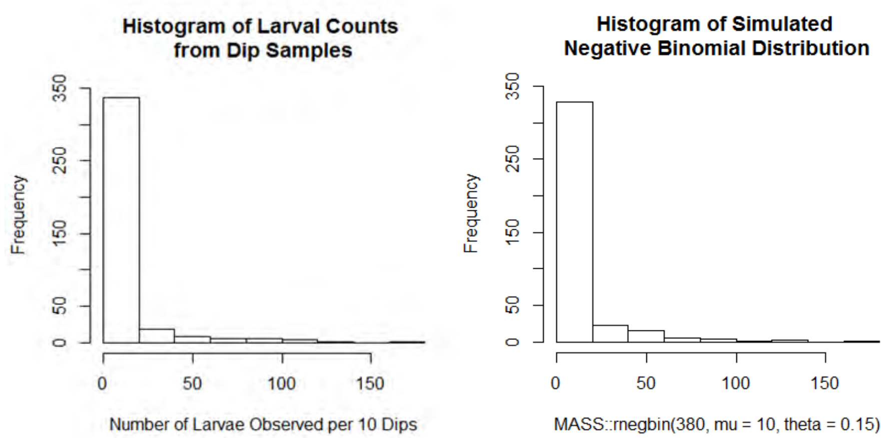


Figure 8: Histograms of observed and simulated count data. The panel on the left shows the frequency distribution of the observed counts per 10 dip sample. For the observed data, the number of observations was 379 and the mean observed count is 9.77 larvae. The right panel shows a simulated negative distribution for a sample size of 380 with a mean of 10 and a shape parameter of 0.15.

Larval abundance data were analyzed using generalized linear mixed models (GLMMs). When feasible, it is best to model such data using generalized linear modelling methods that have been developed to handle a negative binomial distribution (Bolker et al. 2009). Further, a mixed methods approach was needed to account for non-independence among observations. Larval counts were taken repeatedly from each of the same 13 long-term sampling sites and consequently observations were nested within sites. Additionally, on some dates five replicate samples were collected, and these replicates were nested within sites.

Count data for all mosquito species were fitted using the R package glmmADMB, which handles negative binomial data and mixed methods (Fournier et al. 2012). For analyses that used data from the 13 long-term sampling sites, site was included in models as a random factor. Where appropriate, replicate was also included as a random factor. An information theoretic approach was used to identify the best models from various candidate models (Johnson &

Omland 2004). The importance of a zero-inflation term was evaluated by comparing full zero-inflated and full non-zero-inflated models by way of an F-ratio test.

Environmental Variables and Seasonality

Two separate multiple regression models were used to estimate larval productivity. One model simply predicted larval abundance as a function of dominant vegetation at the habitat location. The second model used environmental variables and season to model productivity. For each cell within the GIS framework, estimates from the two models were averaged.

Time of season was divided into three categories - early, mid, and late mosquito-producing seasons. Early-season corresponds to the period before June 29th (180th day of the year in non-leap years), mid-season is the period between June 29th and August 8th (180th and the 220th days in non-leap years), and late-season refers to the season after August 8th (220th day). For environmental variables, larval abundances were estimated as a function of average air temperature over the preceding 10 days, average precipitation over the preceding 10 days, and time of season (mid and late periods of larval productivity). Additionally, interaction terms between time of season and the two environmental variables (temperature and precipitation) were included. Figures 5a and 5b show the relationship between environmental data and the day of the year.

ii. 2D Hydraulic Model

In addition to monitoring mosquito production and development of the NMPM model, the DDM WUP also led to development of a comprehensive 2D hydraulic model for the Lower Duncan River. The model was developed to better describe availability and dynamics of fish habitat in the area in order to improve BC Hydro's performance measures. This model provides a tool for predicting the extent of wetted area around the Lower Duncan under different flow regimes from the Duncan Dam operations.

BC Hydro's hydrotech department have used this site-specific hydraulic model to provide predictions of wetted area on the floodplain under discharge scenarios ranging from 25 to 400 m^3/s. Area and location of these predicted wetted areas were provided in GIS files. These predictions reflect model equilibrium and represent expected wetted areas after dam discharge is constant for a substantial duration. Figure 9 shows the relationship between level of discharge and predicted area of inundation.

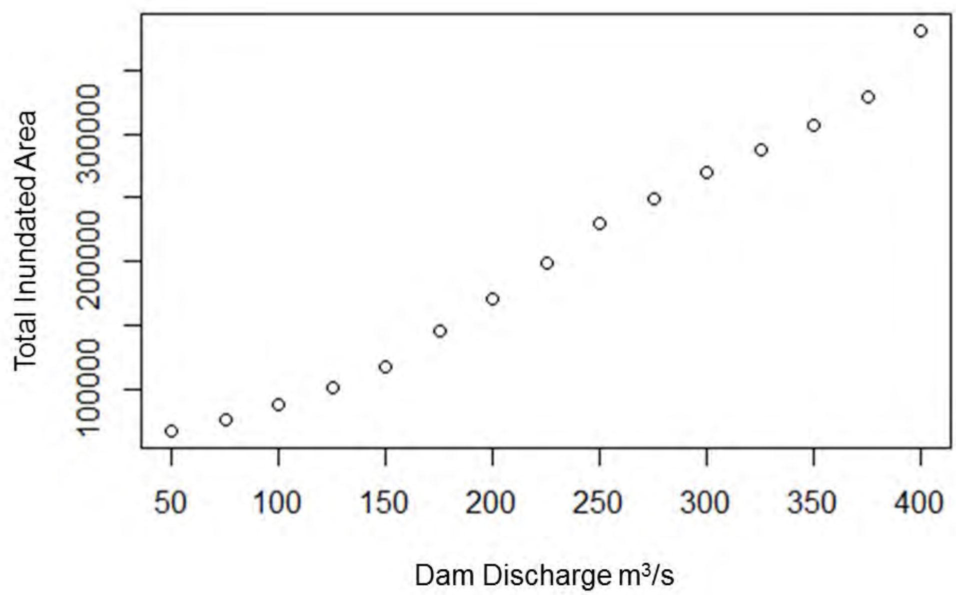


Figure 9: Dam discharge in m^3/s plotted against predicted area of inundation from the 2-D hydraulic model.

In addition to predictions from the sophisticated hydraulic model, statistical associations between dam discharge levels and water depths at the 13 long-term larval mosquito sampling sites provided useful information about how dam discharge affected larval habitat availability across the floodplain.

Figure 10 shows the extent of predicted inundation under the highest discharge scenario (400 m^3/s) from the hydraulic model and the locations of the 13 long-term sampling sites; 12 of the 13 sites lie outside of the predicted wetted area. Both predictions from the hydraulic model and statistical association between dam discharge and water depth at the 13 sampling sites were used to inform predictions of larval productivity within a GIS framework.

Limitations of the 2D Hydraulic Model

The outputs of the 2D hydraulic model provided predicted wetted area for different dam discharge levels. The hydraulic model was originally developed to improve estimates of channelized fish habitats. Such habitats differ from those of larval mosquitoes in that they are generally connected directly to main water channels, they often experience flow, and they are typically deeper than is required to create adequate nursery conditions for mosquitoes. Consequently, the predicted overlap between predicted wetted area from the hydraulic model only intersects with the vegetation polygons in areas immediately around main channels.

The hydraulic model predictions effectively divide the Duncan-Lardeau floodplain into two distinct categories - inundated and non-inundated. However, water levels at the 13 long-term sampling sites were correlated with dam discharge and level of the Duncan River (Culex Environmental report, 2012), indicating that the hydraulic model may not be informative enough (Figure 9; 10; 11/Table 2). Further, this dichotomy does not provide a useful means of accounting for mosquito production outside the predicted wetted area, which includes the majority of the floodplain.

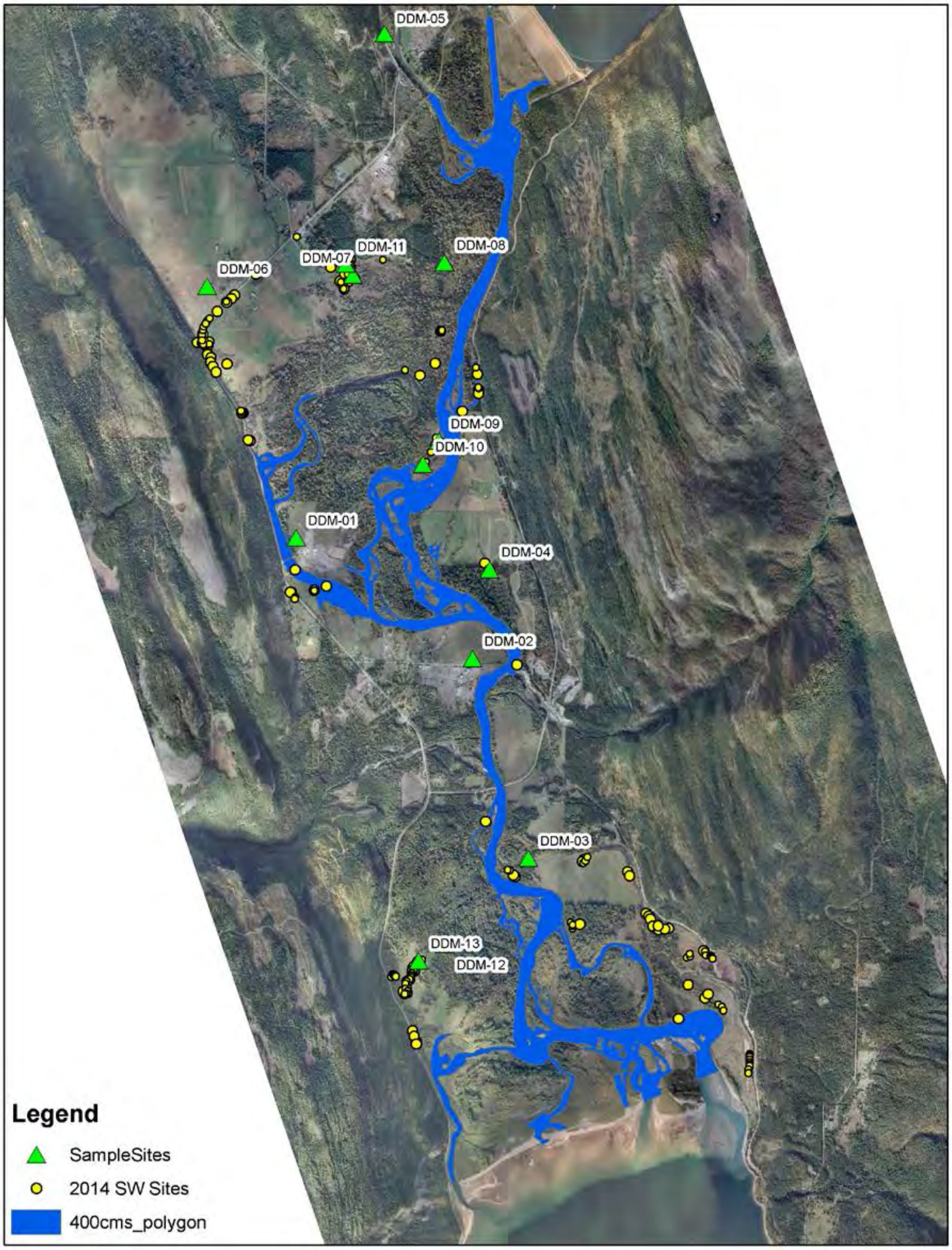


Figure 10: Predicted inundated area under the highest discharge scenario (400 m^3/s) from the 2D hydraulic model and the locations of the 13 long-term sampling sites.

The Wetted Edge Model: Predicting Mosquito Habitat in Non-Inundated Areas

Since mosquito production is known to occur across the entire floodplain, a method was needed to estimate availability of aquatic larval habitat beyond the immediate area around the channels of the Lower Duncan River. Accounting for productivity of this non-channelized area was important because it makes up most of the floodplain. To address this issue, availability of larval habitat in non-inundated areas was assumed to change in proportion to the observed relationship between dam discharge and water depth measured at the 13 long-term sampling sites (Figure 11); that is, higher discharge levels were assumed to increase the amount of larval habitat in areas outside the narrow wetted area predicted by the 2D model.

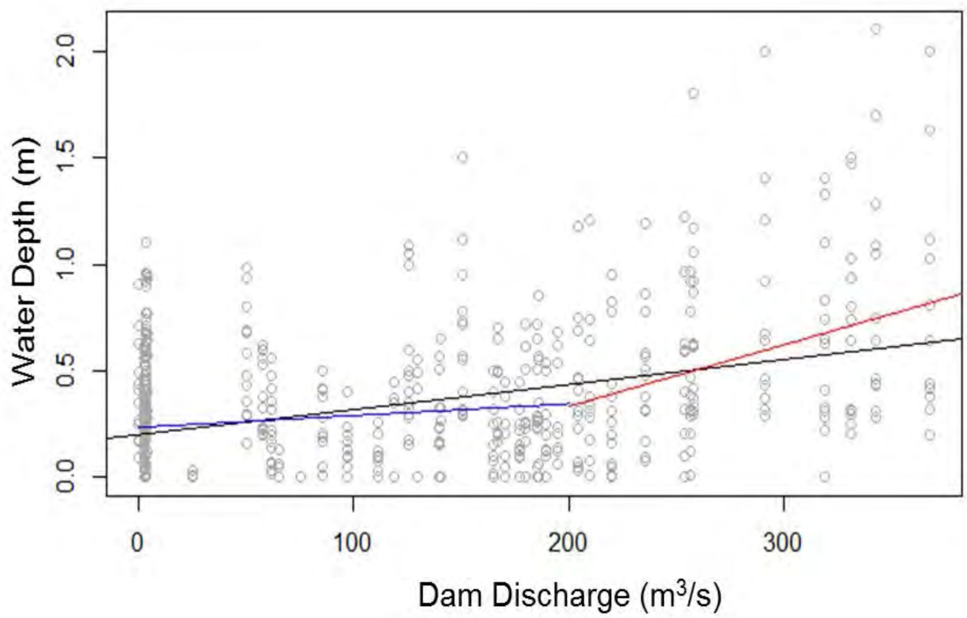


Figure 11: The relationship between discharge from the Duncan Dam (m^3/s) and water depth (m) at all 13 long-term larval sampling sites with a fitted regression line (black). The blue line indicates regression analysis below 200 m^3/s and the red line is the regression analysis above 200 m^3/s. See Table 2 for statistical output from the regression model(s).

Table 2: Statistical output from three regression analyses on the relationship between discharge from the Duncan Dam and water depth at each of the 13 larval sampling sites.

Model	Mean intercept	Slope	p value
Overall discharge regression model (Figure 9)	0.201	0.001	<0.0001
Discharge rates ≤ 200 m^3/s only	0.2353	0.0006	<0.0001
Discharge rates >200 m^3/s only	-0.245	0.0029	<0.0001

The Pearson correlation coefficient between dam discharge and water depth at the sites was used to predict how habitat availability changed with discharge across the non-inundated region (Figure 11/Table 2). Different coefficient values were assigned to each vegetation class, depending on the observed relationships between dam discharge and depth at the sampling sites within each vegetation class (Table 3). These coefficients were used to adjust productivity in response to discharge. This adjustment modelled the change in percent area of viable mosquito habitat for the non-inundated area of the floodplain. These percent-habitat coefficients were adjusted by a coefficient *k* to make them ecologically realistic and align estimates of productivity with the scale of estimates for the inundated area of the floodplain.

Table 3: Mean Pearson correlation coefficient *r* and regression coefficient *β* for dam discharge level and water depth in each vegetation class. Data are for 13 long-term sampling sites and means are for each vegetation class across one or more sites.

Vegetation class	Mean *r*	Mean *β*	Number of sites
GRAS	0.389	0.001076967	3
ALDR	0.478	0.0015188	2
SEDG	-0.253	0.0004653	1
CATL	0.447	0.0003628	1
HORS	0.406	0.0006743	2
COTT	0.675	0.0023631	2

Larval mosquitoes tend to occupy the shallow margins of lakes, ponds, and pools where there is safe refuge from predators and the water temperature is relatively high compared to the middle of large, deep water bodies. Consequently, basing estimates of larval habitat on wetted area tends to over-estimate actual habitat availability. For this reason, habitat is modelled as a function of the circular perimeter of the wetted areas predicted by the hydrological model and vegetation polygons.

iii. Spatial Component: GIS

Predictions for the NMPM were produced using spatial information, and therefore demand a GIS framework. This framework ties the statistical and hydraulic components of the mosquito-production system together.

As illustrated in Figure 4, results of the statistical and hydraulic modelling processes are used together within the GIS framework to generate predictions. The statistical modelling produced regression coefficients that estimated how production of larval nuisance mosquitoes changed with levels of different environmental predictor variables including time of season, air temperature, precipitation, and dominant vegetation. These coefficients estimated mosquito production for a given location on the Duncan-Lardeau floodplain according to levels of the predictor variables for each location.

Six dominant vegetation classes were mapped across the floodplain (Figure 17). These vegetation classes represented a consolidation of 24 vegetation associations identified in the 2012 classification of vegetation on the floodplain. In the R code and data objects, these classes are named for the common names of dominant plant species. The classes are named: ALDR for alder, COTT for cottonwood, CATL for cattail, GRAS for grass, HORS for horsetail, and SEDG for sedge. The combined areas of these six vegetation classes make up about 75% of the floodplain. For purposes of the NMPM they were assumed to be the total extent of potential larval mosquito habitat on the floodplain. The predicted extent of realized mosquito habitat is provided by estimates of wetted area available for larval habitats within each of the vegetation class.

2.4 The Nuisance Mosquito Performance Measure

The NMPM provides an index of larval productivity for the floodplain. This index is a relative measure of productivity and is not intended to predict mosquito population size. Recall that the regression coefficients used to model larval productivity relate environmental predictors to the number of larval *Aedes* mosquitoes in one sample (10 dips). Data are not available to translate hydrological conditions on the floodplain to the total number of potential sampling units (i.e., dips), therefore the NMPM cannot accurately estimate larval population size; instead it provides an index that is proportional to the expected population size across the floodplain.

The NMPM index is calculated by summing predicted larval abundances of *Aedes* larvae in both the inundated and non-inundated areas. These predictions are generated by multiplying the regression coefficients of each predictor variable by the level of that predictor for each cell (pixel) on the floodplain and summing the productivity of all those points across the total estimated area of larval habitat. More formally:

$$P_{tot} = \left\{ \begin{array}{c} (1-E)\sum_{v=1}^{N}(p_{vu}\frac{\sum_{i=1_u}^{Nu} I+\beta_f X_{fi}}{Nu} + p_{vn}\frac{kc_v\sum_{i=1_n}^{Nn} I+\beta_f X_{fi}}{Nn}) \\ + \\ E3\sum_{v=1}^{N}(p_{vu}\frac{\sum_{i=1_u}^{Nu} I+\beta_f X_{fi}}{Nu} + p_{vn}\frac{kc_v\sum_{i=1_n}^{Nn} I+\beta_f X_{fi}}{Nn}) \end{array} \right\} \quad \text{Eq.1}$$

(Note that the upper and lower terms on the right are identical except for the coefficients at their beginnings)

Table 4: Definitions of terms for Equation 1. Interactions terms were included for time of season by air temperature and time of season by precipitation.

P_{tot}	**Total larval productivity**
E	Proportion of the floodplain where late season flooding has exceeded flooding levels from the spring freshet
v	Vegetation class
f	Environmental factor (including vegetation class)
i	An individual cell in an area that has already been flooded once in the spring freshet
j	A cell that has not been flooded yet this season
β	Regression coefficient for each environmental variable
k	Weighting coefficient that adjusts predicted productivity outside of the inundated area to a sensible level
u	Indicates cells that fall within the predicted inundated area from the 2D hydraulic model
n	Indicates cells that fall outside the predicted inundated area
c	A coefficient that relates the amount of potential larval habitat outside the predicted inundated area to dam discharge for each vegetation class
p	Circular perimeter of wetted area
X	Random variable (e.g. precipitation, vegetation class or time of season)

The exceedance term *E* accounts an important effect of flood dynamics on hatching of *Aedes* larvae from eggs. An area that is re-flooded produces far fewer mosquitoes than an area that is being flooded for the first time in a season. This is because most, but not all, eggs hatched during the initial flooding (this is one reason why there are so many mosquitoes in the spring). *E* is calculated by comparing water levels of both the spring freshet and late season flooding. *E* = *H*/*R*, where *H* is the high water level of the Duncan River below Lardeau during spring freshet. Based on previous years, this level is typically ~3 m, and this is the default level included in the NMPM. However, the level of this model parameter may be changed easily to reflect the observed level of the year under consideration. *R* is the predicted level of the river later in the season as a function of dam discharge level. Predictions for this value are from a regression of river level against discharge for all years for which such data were available. The resulting predictive equation is approximately R = 1.45 + 0.005×discharge level (m^3/s). Based on data collected from 2009-2012, larval productivity in areas which had not been flooded previously in a season were assumed to be three times greater than areas that had been flooded once before (Gjullin et al 1950: Gillett, 1955 and Vitek and Livdahl, 2009).

The value of c_v is the Pearson correlation coefficient for the relationship between dam-discharge and water depth at the 13 long-term sampling sites, averaged within vegetation classes (Table 3).

3.0 Results

3.1 Seasonal variation in larval abundance

Although early season productivity cannot be predicted by the NMPM due to the lack of dam discharge at this time, the long-term data show that mosquito abundances are considerably higher immediately following the freshet than at any other time of the year (Figure 12).

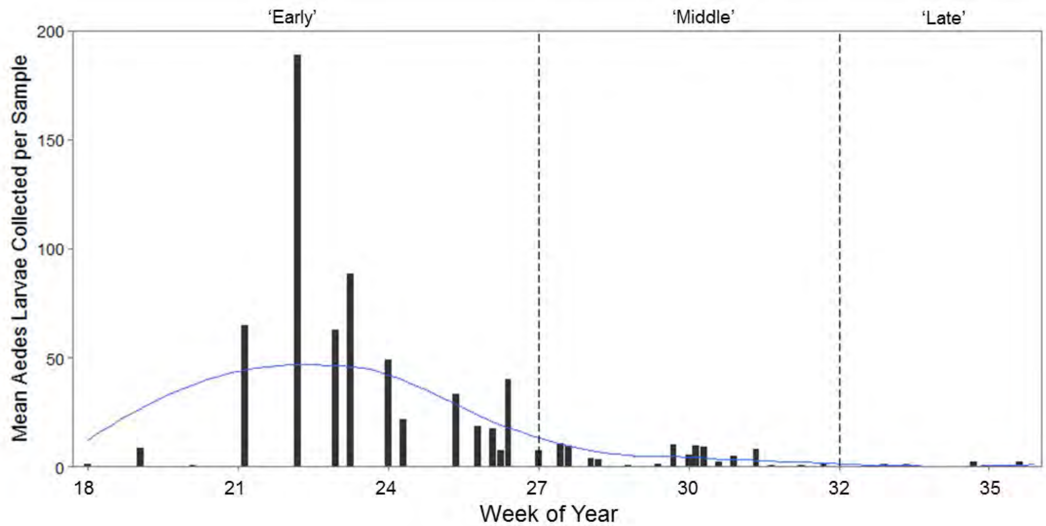


Figure 12: *Aedes* mosquito production across the early, middle and late periods of the season using data combined from all sampling years (2009-2015). Vertical dashed lines indicate the between-period boundaries.

3.2 Vegetation classes and environmental variables

For the regression models, the effects of time during the season, temperature, and precipitation on larval abundance were modeled separately from the effects of local dominant vegetation. This is because different sampling designs and data sets spoke to each relationship (see the larval sampling section of the Materials and Methodology on page 7). Coefficients from each analysis were used within the GIS framework to predict floodplain-wide larval production. Predictive coefficients for environmental variables and vegetation variables are shown in Tables 5 and 6. The large amount of grass and high productivity of this vegetation type contributes up to 97% of total nuisance mosquito productivity (Table 6).

Table 5. Regression coefficients for predictive variables (back-transformed from log link).

Predictive variable	Regression Coefficient
Environmental model intercept	8.84454
Early time of season	1.00000
Mid time of season	0.35187
Late time of season	0.01987
Recent temperature	0.90511
Recent precipitation	1.06046
Vegetation model intercept	20.71794

Table 6. Regression coefficients of the six vegetation classes used to predict mosquito abundance. The circumference of the total area is multiplied by each respective coefficient to give the percent contribution of each vegetation type to the mosquito productivity prediction. This value will vary depending on the degree of inundation of the floodplain and the differences between wetted areas predicted within and outside of the 2D hydraulic model.

	Vegetation Classes	Coefficient	Circumference of Total Area	Circumference x Coefficient	Percent of Vegetation Production
1	**ALDR**	1.00000	3225.55	3225.55	**0.56**
2	**CATL**	2.12884	1536.68	3271.35	**0.56**
3	**COTT**	1.54825	4429.79	6858.45	**1.18**
4	**GRAS**	85.83373	6555.04	562643.17	**97.04**
5	**HORS**	0.53411	2470.94	1319.75	**0.23**
6	**SEDG**	0.87723	2855.51	2504.94	**0.43**

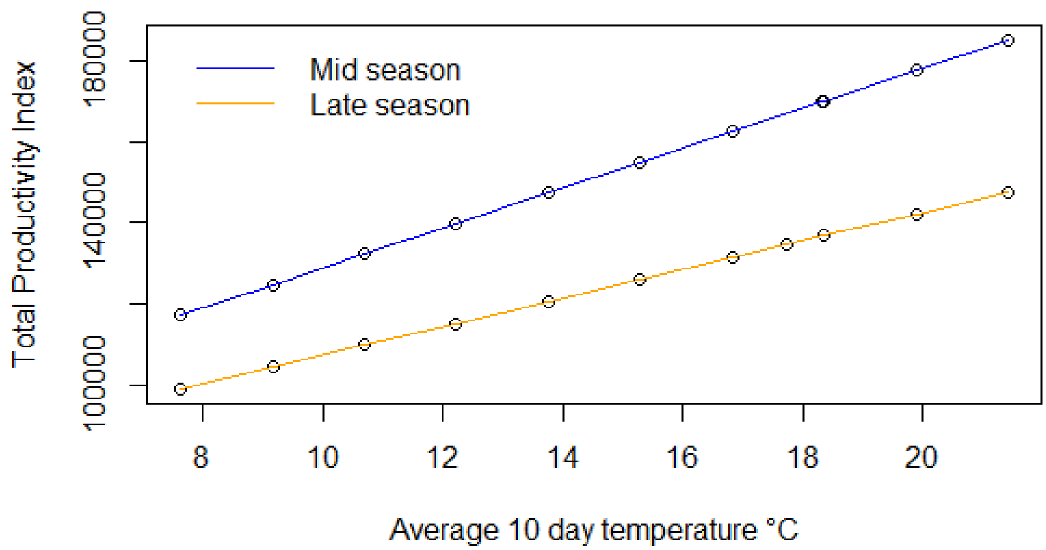


Figure 13. Predicted larval productivity across the observed range of mean air temperatures. Air temperatures are averages for the preceding 10 days, which corresponds to the development time of mosquito larvae. Dam discharge level was held constant at 400 m^3/s, with k at 0.112.

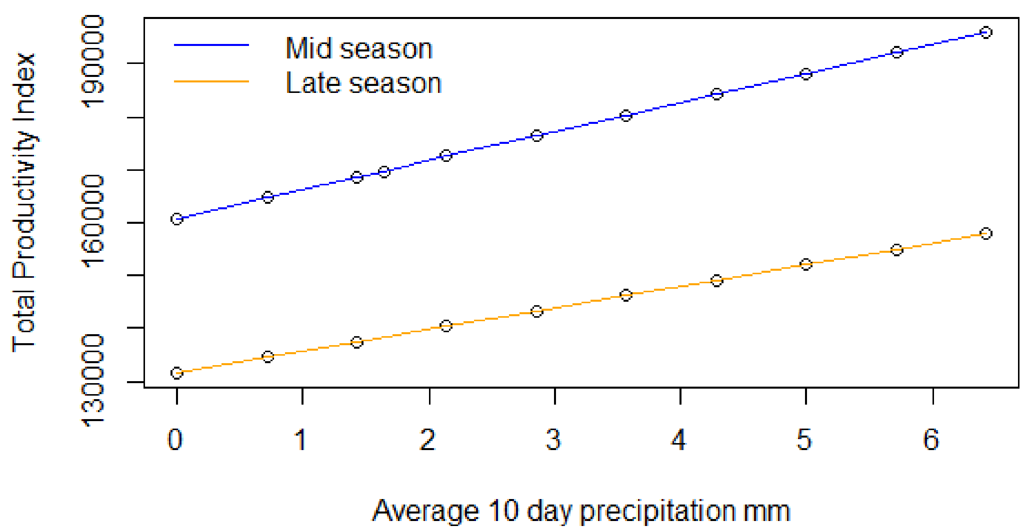


Figure 14. Predicted larval productivity across the observed range of mean precipitation levels. Precipitation values are averages for the preceding 10 days, which corresponds to the development time of mosquito larvae. Dam discharge level was held contstant at 400 m^3/s with k at 0.112, and air temperature corresponds to the seasonal average (18.32 and 17.74°C for mid and late season respectively).

3.2 Predicted Mosquito Productivity

Based on the 2D hydraulic model and the assumptions incorporated into the NMPM, there was a positive relationship between levels of dam discharge and the predicted productivity of larval *Aedes* mosquitoes. Figure 15 shows the predicted levels of larval abundance, reported as an index, across different discharge levels in the mid and late season. The early season is not reported on this chart as discharge does not occur during this time and therefore habitat availability could not be accurately predicted as this is closely linked with discharge levels via the hydraulic model (Figure 6). Predicted mosquito productivity increases with temperature (Figure 13). Total productivity is higher in the mid-season than the late-season and the relative effect of air temperature is slightly greater in the mid-season, indicated by the increased slope. Precipitation is associated with higher mosquito productivity, independent of predicted habitat area (Figure 14). The effect of increased precipitation on productivity is higher in the mid-season than the late-season, as seen in the slight difference between the slopes of the blue and orange lines in Figure 14.

The NMPM also predicts that nuisance mosquito productivity in the mid-season is higher than in the late season and that incremental changes in relative rates of larval productivity occur as dam outputs increase from 50 to 400 m^3/s (Figure 15). Arrows “a” and “b” indicate the beginning of a large increase in mosquito productivity as discharge increases through to the next 25 m3/s measurement. The greatest change in the rate of increase of mosquito productivity is predicted to be 7% which occurs over discharge rates of 300-325 m^3/s. (Figure 16).

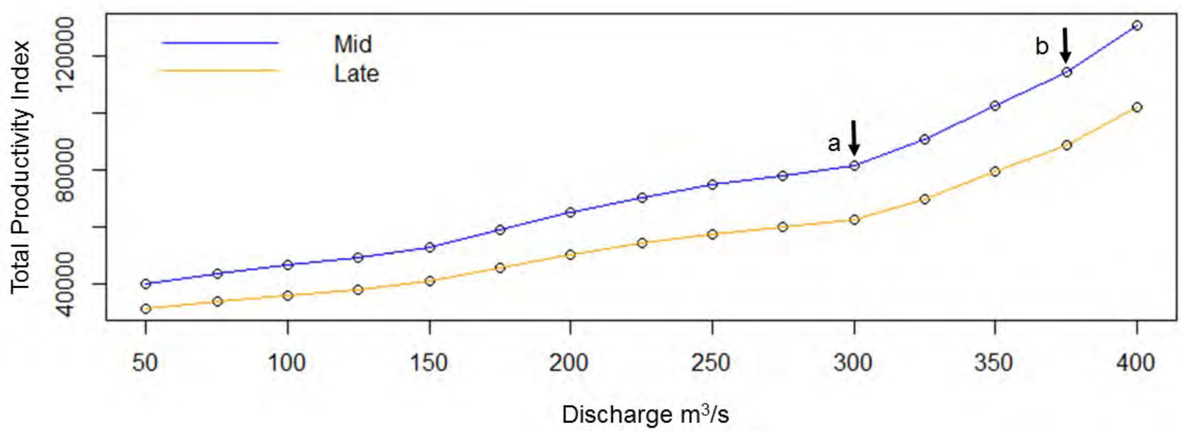


Figure 15: The predicted effect of mean daily discharge from the Duncan dam on an index of total productivity of larval *Aedes* mosquitoes on the Duncan-Lardeau floodplain. The total productivity index is reported across the mid (blue) and late (orange) season. Environmental parameter values are set at the default for each discharge level and time of season, and *k* was 0.01 (Table A2).

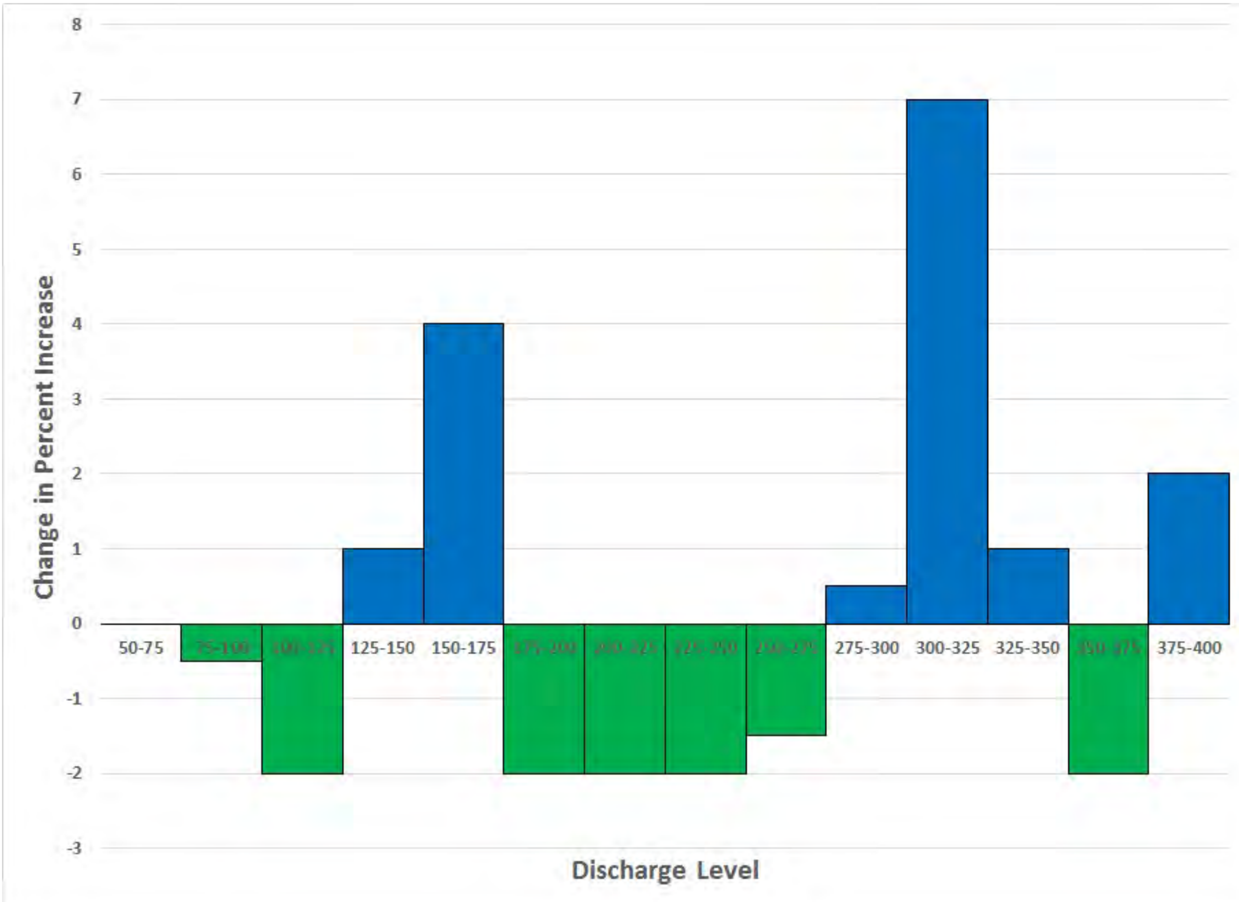


Figure 16. Difference in percentage change in late-season productivity across discharge levels from 50 to 400 m^3/s in 25 m^3/s increments during late season.

3.3 Relative distribution of mosquito productivity across the floodplain

Levels of larval production are predicted for each cell in the vegetation polygons on the floodplain. Figures 18 to 26 show relative levels of productivity for different discharge scenarios across the early, mid and late seasons. At any time in the season, a discharge rate of 75 m^3/s does not cause inundation of the floodplain and therefore shows the lowest productivity, shown in yellow (Figures 18, 21, and 24). Sections of the landscape that are productive at 75 m^3/s are low bench areas and more productive vegetation types, such as grass and cottonwoods (Figure 17). Across all seasons, an increase in discharge from 75 m^3/s to 200 m^3/s predicts a slight increase in overall productivity; areas close to the river channel still show higher relative productivity than those further away (Figures 19, 22, and 25). Habitat away from the river channel is predicted to become more productive only at very high discharge rates of 400 m^3/s, when flooding of areas not inundated by the original freshet occurs (Figures 20, 23, and 26). Productivity at high water levels in the early season (Figure 20) is higher than productivity at the same high water levels in the mid (Figure 23) and late season (Figure 26).

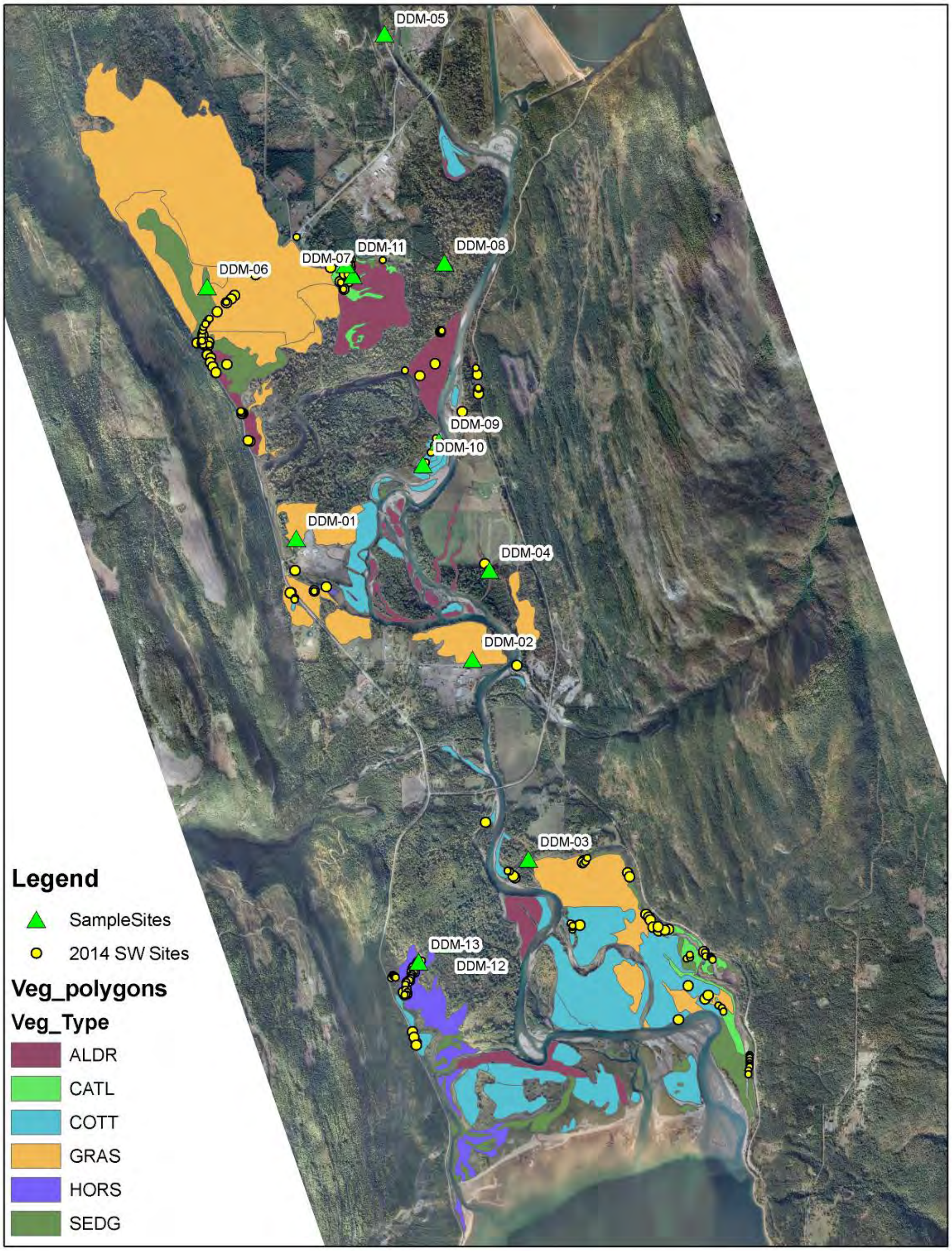


Figure 17: Vegetation polygons and sampling sites for the 2014 spatially-intensive larval sampling across the six dominant vegetation classes. Location of sites are clustered due to availability of larval habitat. GPS coordinates for sites are in Table A1.

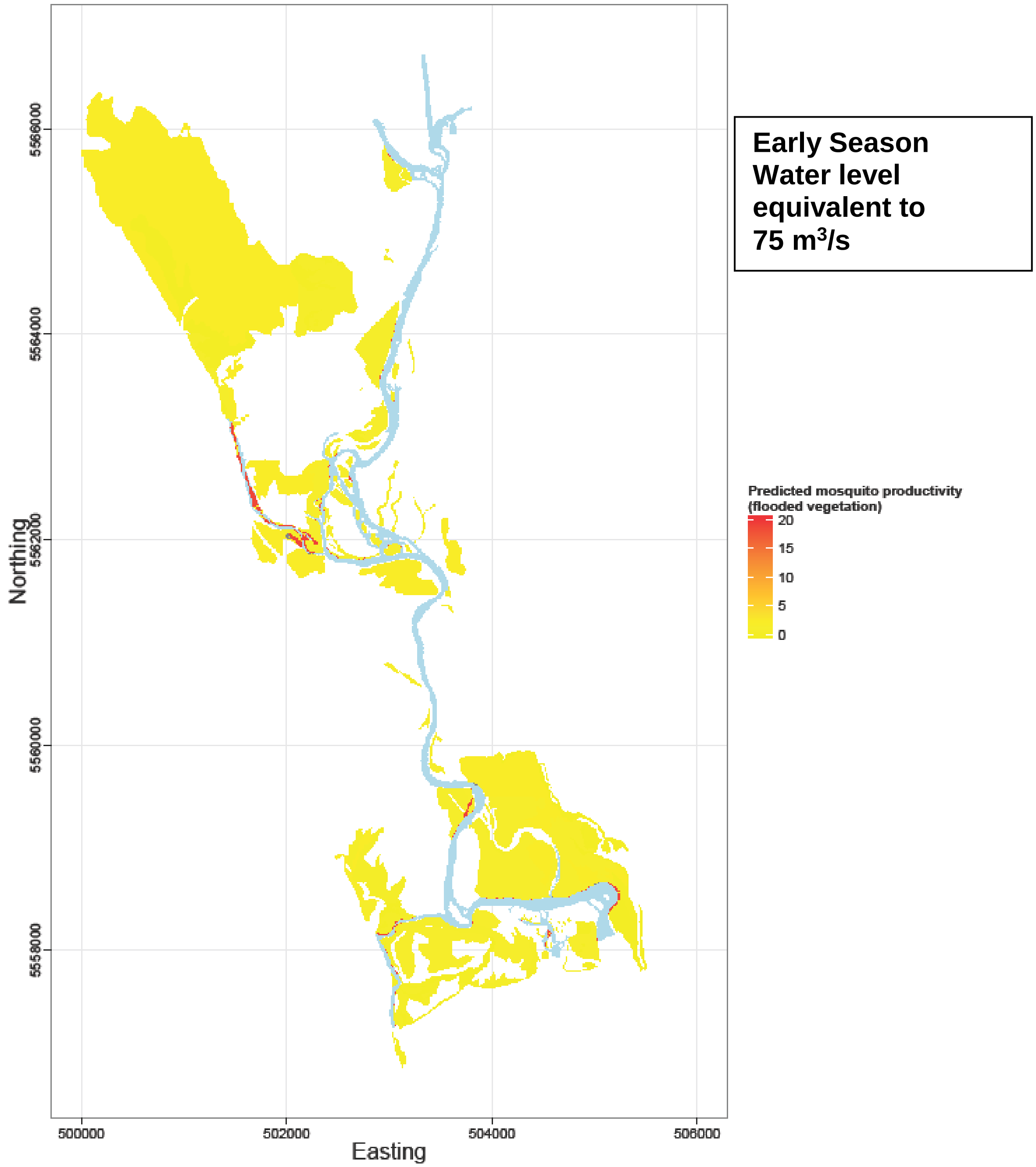


Figure 18: Map of predicted mosquito productivity across different vegetation types on the floodplain during the freshet or early period of the season at a water level equivalent to 75 m^3/s. Colours indicate productivity relative to the range on the map. Default levels of environmental parameter values (air temperature and precipitation) were used (Table A2), and *k* was 0.4.

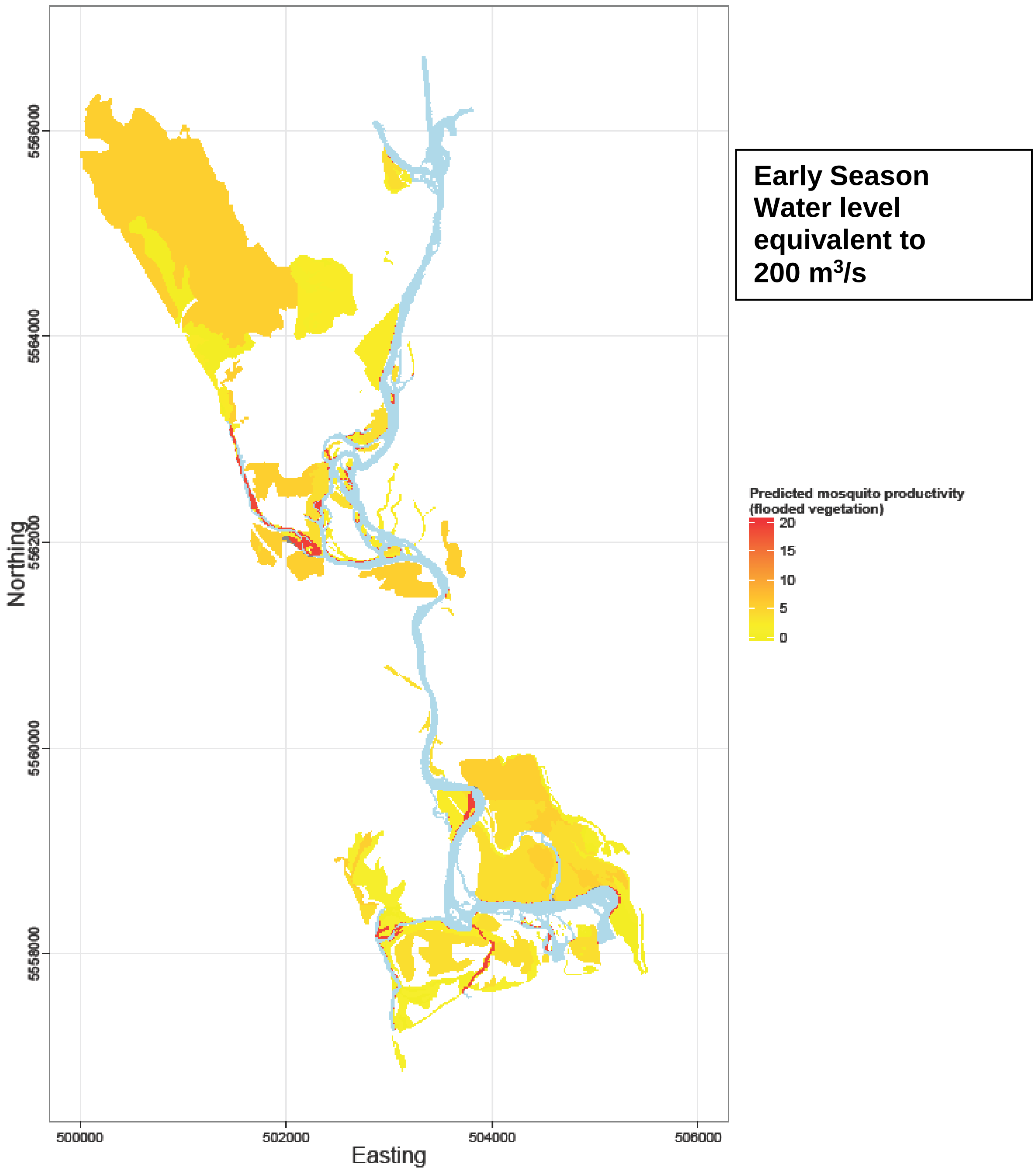


Figure 19: Map of predicted mosquito productivity across different vegetation types on the floodplain during the freshet or early period of the season at a water level equivalent to 200 m^3/s. Colours indicate productivity relative to the range on the map. Default levels of environmental parameter values (air temperature and precipitation) were used (Table A2), and *k* was 0.4.

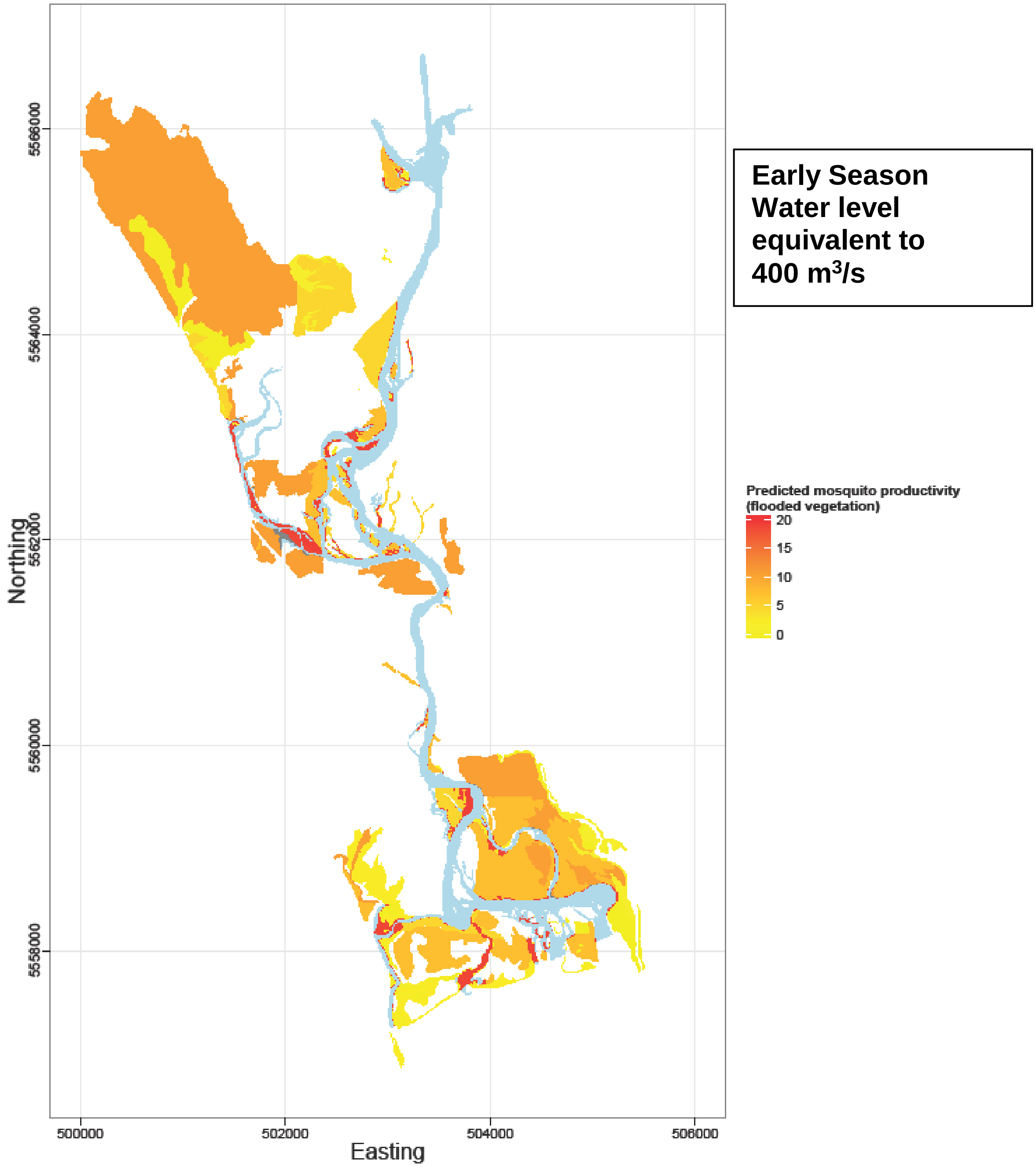


Figure 20: Map of predicted mosquito productivity across different vegetation types on the floodplain during the freshet or early period of the season at a water level equivalent to 400 m^3/s. Colours indicate productivity relative to the range on the map. Default levels of environmental parameter values (air temperature and precipitation) were used (Table A2), and *k* was 0.4.

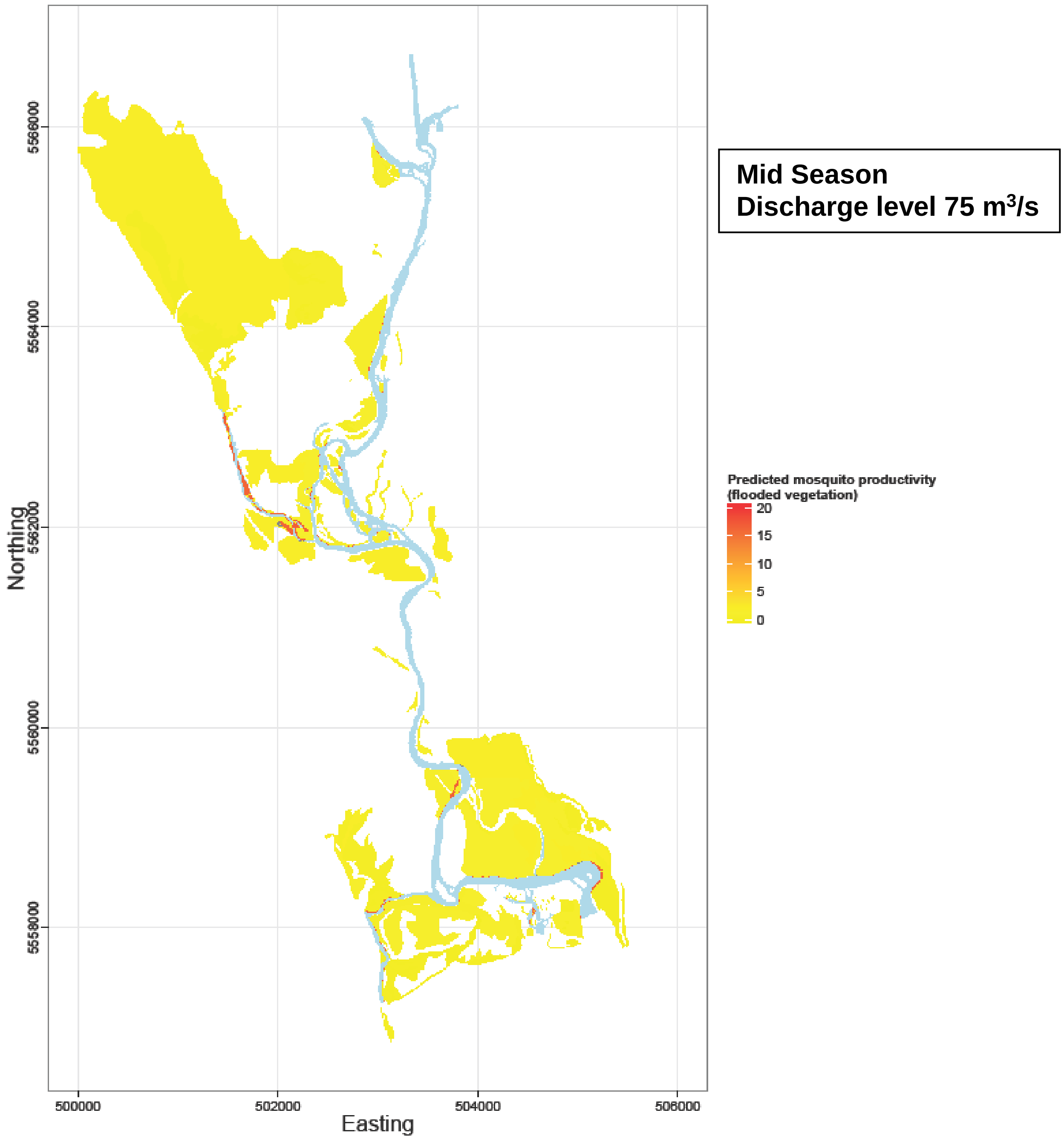


Figure 21: Map of predicted mosquito productivity across different vegetation types on the floodplain for a discharge level of 75 m^3/s, and during the middle period of the season. Colours indicate productivity relative to the range on the map. Default levels of environmental parameter values (air temperature and precipitation) were used (Table A2), and *k* was 0.4.

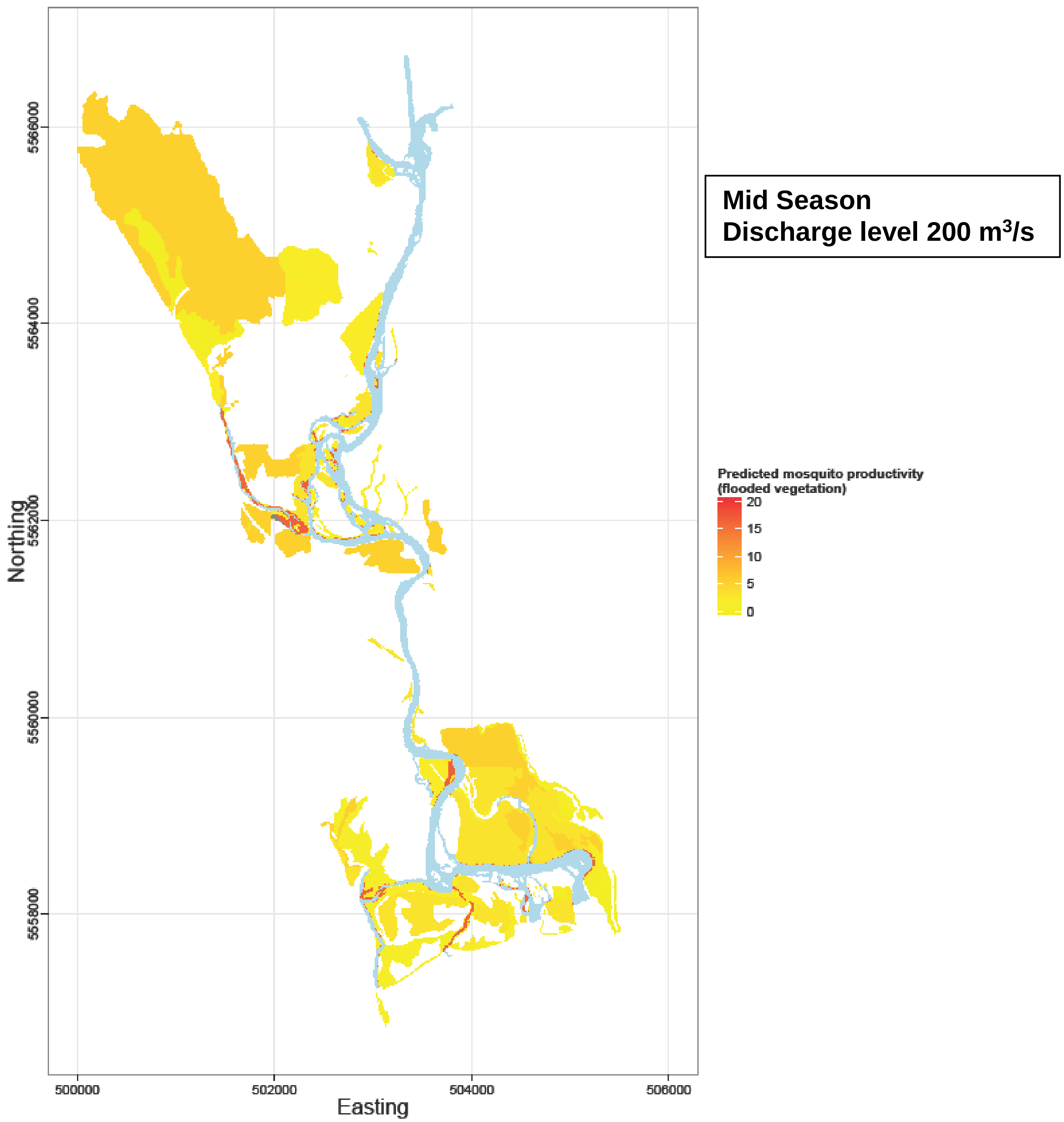


Figure 22: Map of predicted mosquito productivity across different vegetation types on the floodplain for a discharge level of 200 m^3/s, and during the middle period of the season. Colours indicate productivity relative to the range on the map. Default levels of environmental parameter values (air temperature and precipitation) were used (Table A2), and *k* was 0.4.

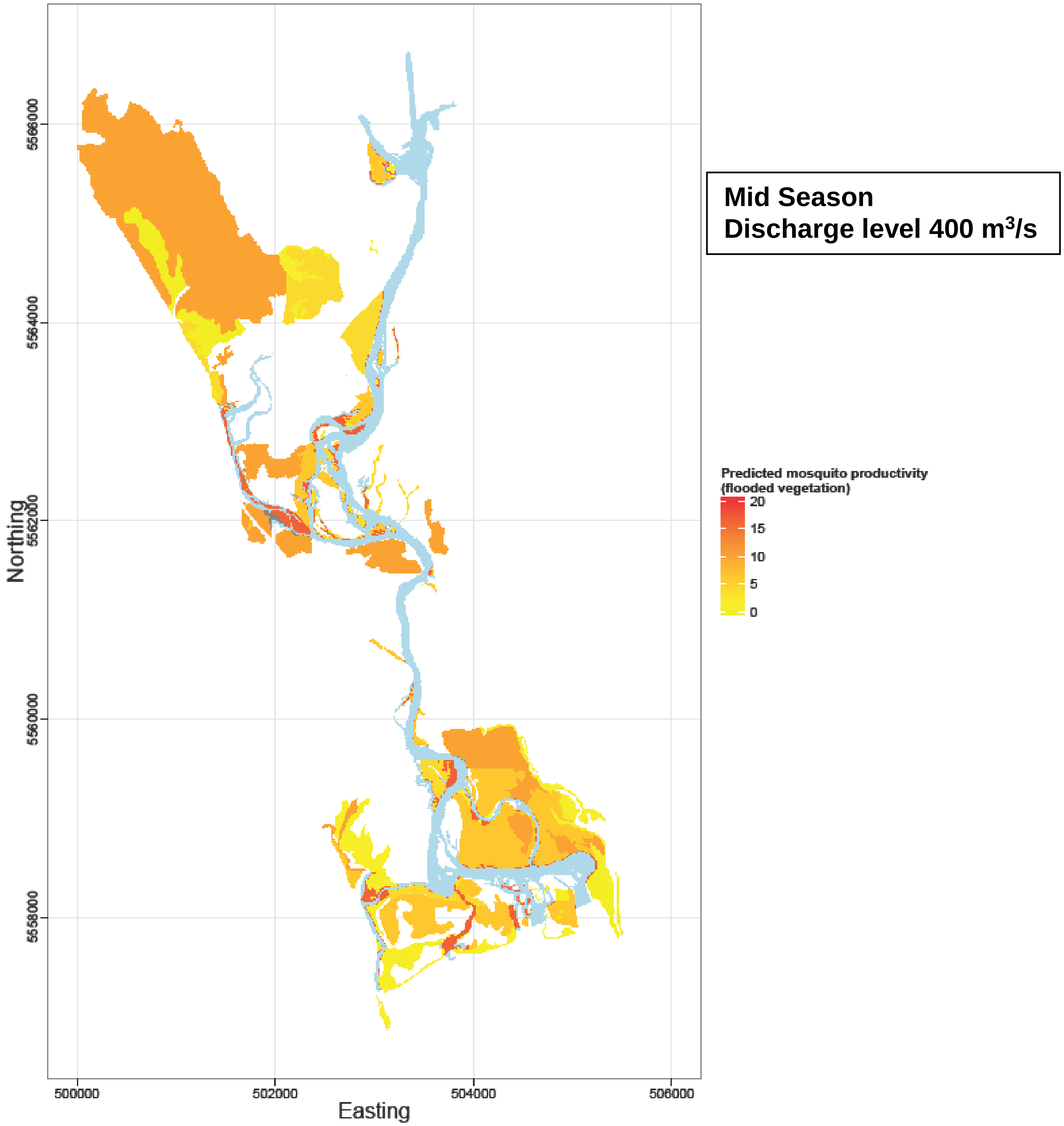


Figure 23: Map of predicted mosquito productivity across different vegetation types on the floodplain for a discharge level of 400 m^3/s, and during the middle period of the season. Colours indicate productivity relative to the range on the map. Default levels of environmental parameter values (air temperature and precipitation) were used (Table A2), and *k* was 0.4.

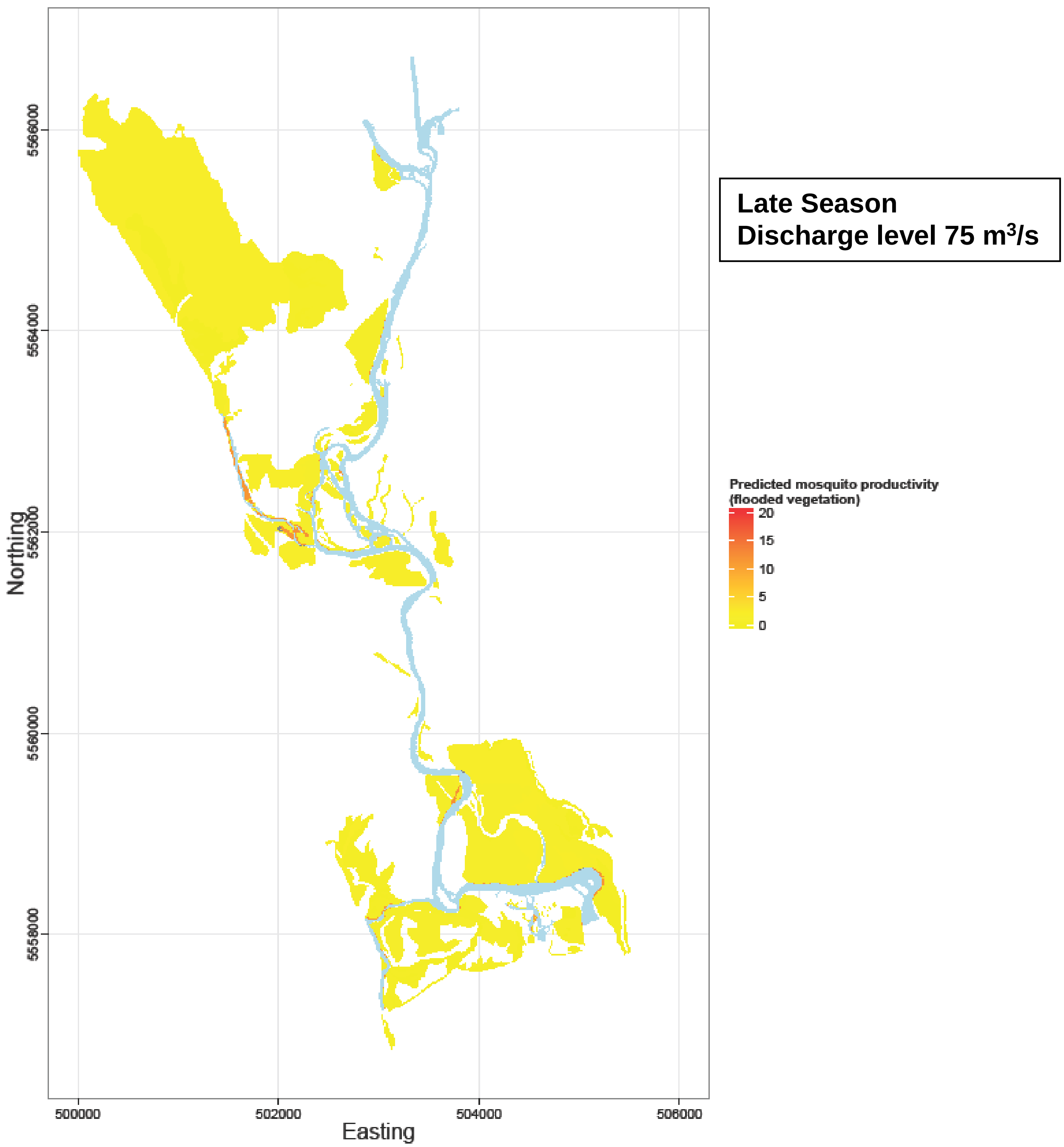


Figure 24: Map of predicted mosquito productivity across different vegetation types on the floodplain for a discharge level of 75 m^3/s, and during the late period of the season. Colours indicate productivity relative to the range on the map. Default levels of environmental parameter values (air temperature and precipitation) were used (Table A2), and *k* was 0.4.

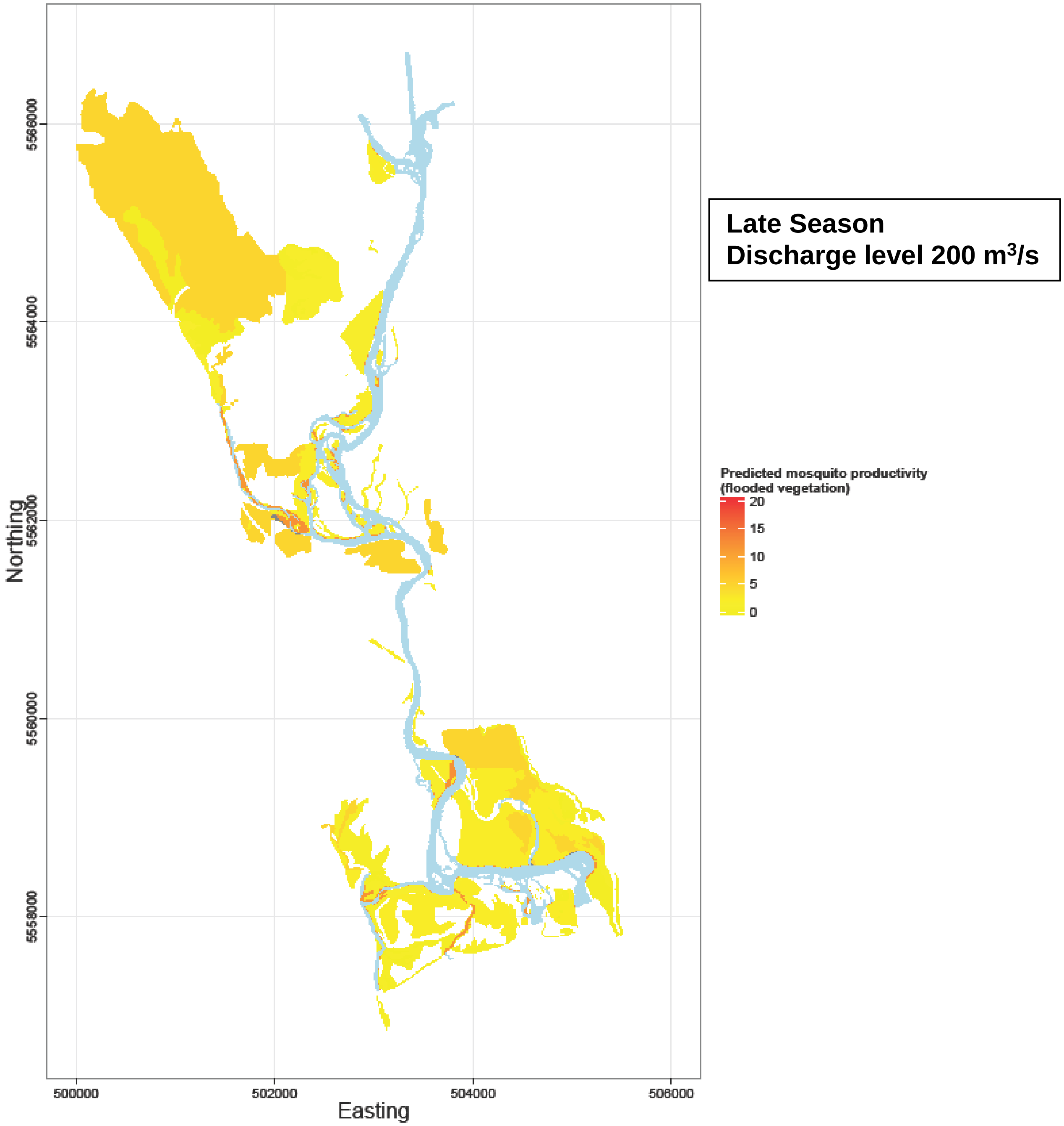


Figure 25: Map of predicted mosquito productivity across different vegetation types on the floodplain for a discharge level of 200 m^3/s, and during the late period of the season. Colours indicate productivity relative to the range on the map. Default levels of environmental parameter values (air temperature and precipitation) were used (Table A2), and *k* was 0.4.

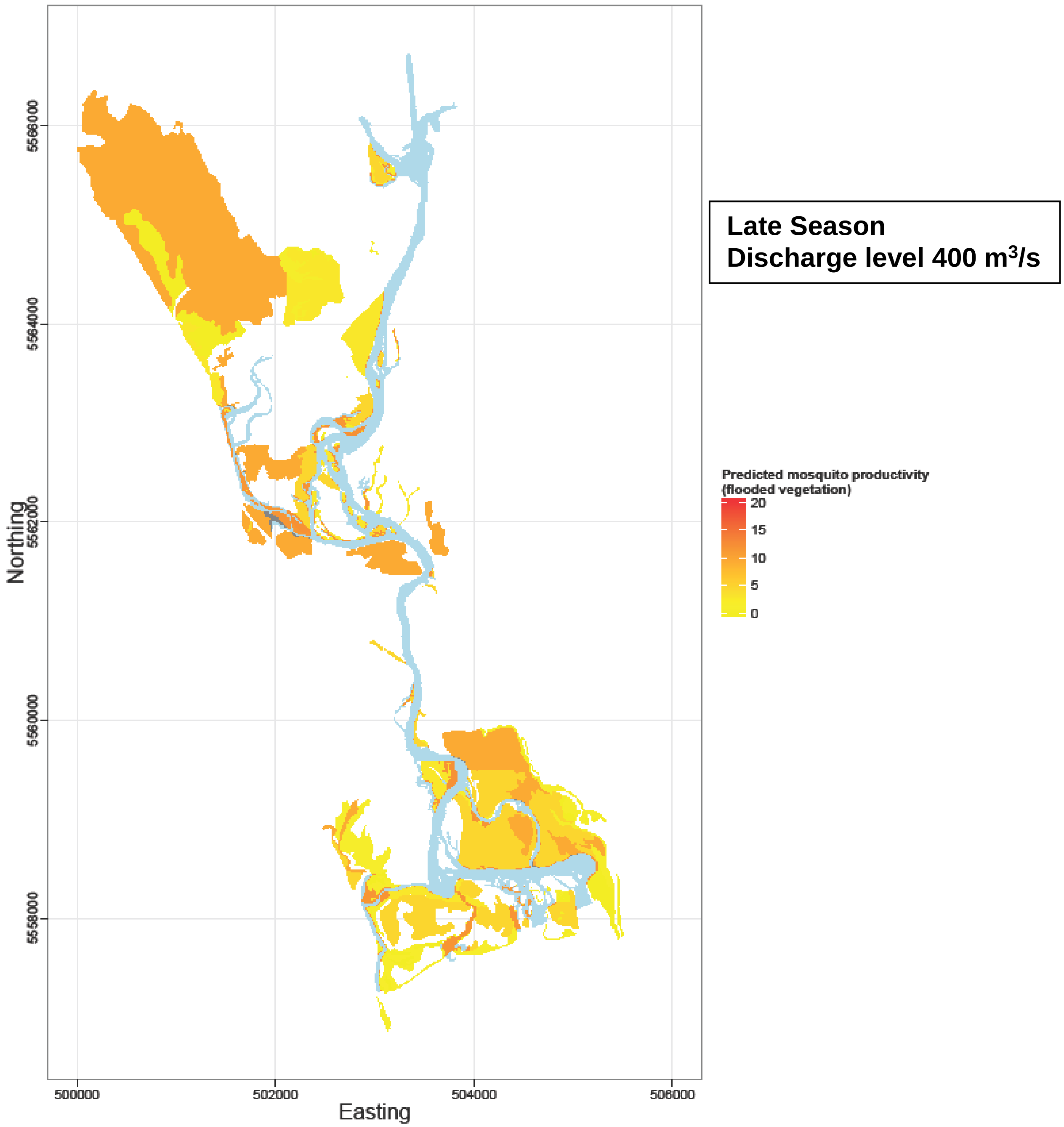


Figure 26: Map of predicted mosquito productivity across different vegetation types on the floodplain for a discharge level of 400 m^3/s, and during the late period of the season. Colours indicate productivity relative to the range on the map. Default levels of environmental parameter values (air temperature and precipitation) were used (Table A2), and *k* was 0.4.

4.0 Discussion and Conclusions

4.1 Addressing Management Questions

i. How significant is the Duncan Dam in creating adult mosquito nuisance to residents of the Lower Duncan Floodplain? Can we better predict the potential nuisance mosquito production associated with vegetation types?

It was not feasible to measure adult mosquito dispersal but it is important to note that any larval nuisance mosquitoes present in the Lower Duncan Floodplain may disperse widely from their larval habitat, the females traveling as much as 10-15kms to find a blood meal. The NMPM provides a reasonably accurate prediction of the potential nuisance larval productivity associated with different vegetation types, and this is correlated with the presence of nuisance adult mosquitoes. Grass was considerably more productive than all the other vegetation types, and also makes up the largest area of any vegetation type on the floodplain (Table 6). Any grass areas that are flooded will therefore produce many more nuisance mosquitoes than other vegetation types.

ii. Is the current Nuisance Mosquito Performance Measure effective at predicting the potential production of late outbreaks of nuisance mosquitoes related to Duncan Dam operations?

The NMPM predicts mosquito productivity based on different environmental variables across the season and can therefore predict nuisance mosquito productivity following Dam discharge in the late season. If discharge levels in the late season exceed 300 m^3/s, the rate of mosquito productivity increase is predicted to rise by 7% (Figure 16). This should be expected because this discharge exceeds the river level reached by the freshet in the same season and eggs are stimulated to hatch when they are flooded. Another 2% increase in the slope of the mosquito productivity discharge relationship (Figures 15 and 16) would occur if discharge levels exceeded 375 m^3/s, as this is when discharge levels exceed the inundated area predicted by the hydraulic model. Compared with earlier in the season, overall productivity in the late season is lower as *Aedes* mosquitoes are better adapted to early season conditions.

iii. Can we more accurately predict when outbreaks of nuisance mosquitoes are most likely to occur given particular environmental and climatic conditions?

Yes. The NMPM calculator predicts relative productivity of nuisance mosquitoes as a function of time of season, recent mean air temperature, and recent mean precipitation. Warmer, wetter conditions are more likely to produce mosquitoes, irrespective of dam discharge (Figure 13 & 14).

iv. What can the current mosquito abatement program (managed by the Regional District of Central Kootenay, RDCK) do to improve its effectiveness based on the information collected in this program?

Early in the season, environmental conditions, such as river level, snowpack, precipitation, and temperature should all be closely monitored by the abatement contractors. Higher air temperature and precipitation levels correspond to higher predicted abundance of larval nuisance mosquitoes (Figure 13 & 14). The NMPM can be used to make predictions based on current environmental variables to show where potential mosquito problems may arise.

The model reveals where nuisance problems are most likely to occur at different discharge rates and at different times. Figures 18-26 can be used to identify areas that would require attention following high discharge levels. Low lying grasslands close to the river should be a top priority, particularly when discharge levels exceed

300m^3/s, as this is the most productive vegetation type for nuisance mosquitoes. Cottonwood is also a productive vegetation type, particularly in areas that lie very close to the river and are therefore liable to flooding when discharge levels are very high. Communication between BC Hydro and the abatement operators would assist in quick and effective management of susceptible areas if and when discharge levels are likely to exceed 300 m^3/s.

The current abatement program manages mosquito populations in known larval mosquito development locations. Although numbers of larvae are roughly counted at known locations no samples are taken for identification to species and no records are kept of what is found where. All mosquitoes are considered as being nuisance mosquitoes and areas are treated solely on the basis of larval counts. In order to meet with the requirements of a modern integrated mosquito pest management approach it would be more effective to provide detailed records of samples from specific GPS locations using standard sampling protocols and identifying at least a proportion of those samples to species. Incorporating this knowledge with that gained from the NMPM will enable abatement operators to make more sophisticated and finely targeted management decisions. This data could also be used to refine the timing of treatments and the full extent of the mosquito season. By also collecting some environmental data at each sampling site, such as water temperature and water depth, that could be stored in a relational database with species data, a much greater understanding of the precise requirements of different species would emerge over time, further reducing the need for use of pesticides. With this technique charts can be developed that follow the efficacy of the abatement program over time and also at specific sites, such as ones from different wetland vegetation types (Figure 28).

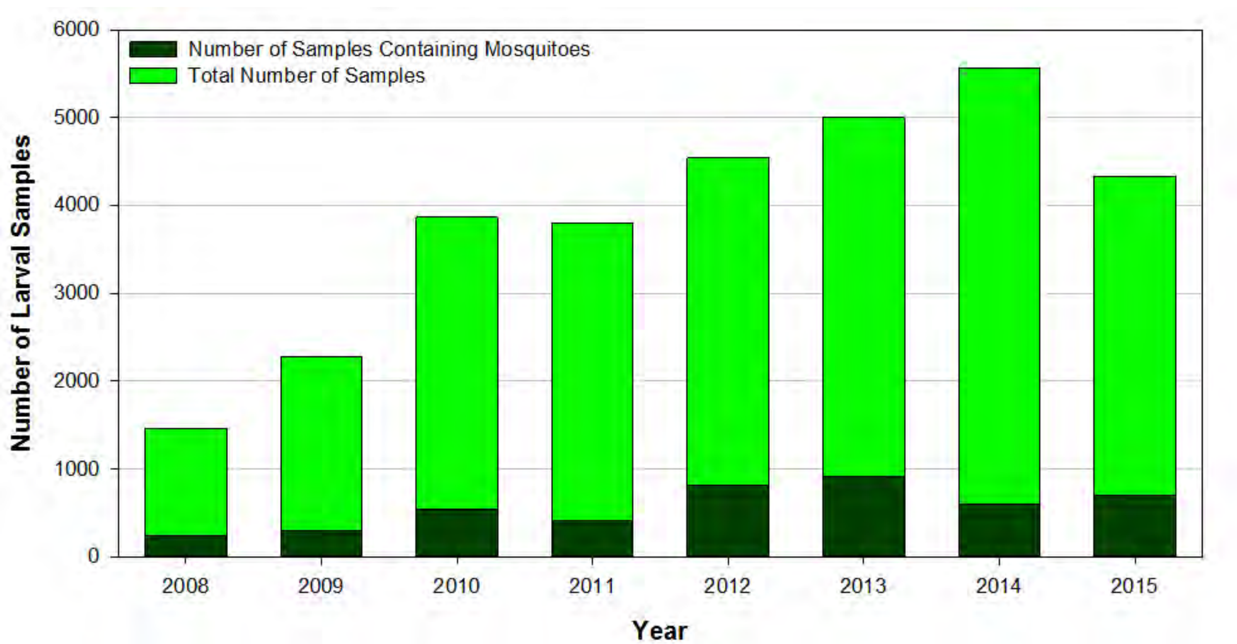


Figure 27: The number of samples taken over the years of a nuisance mosquito control program.

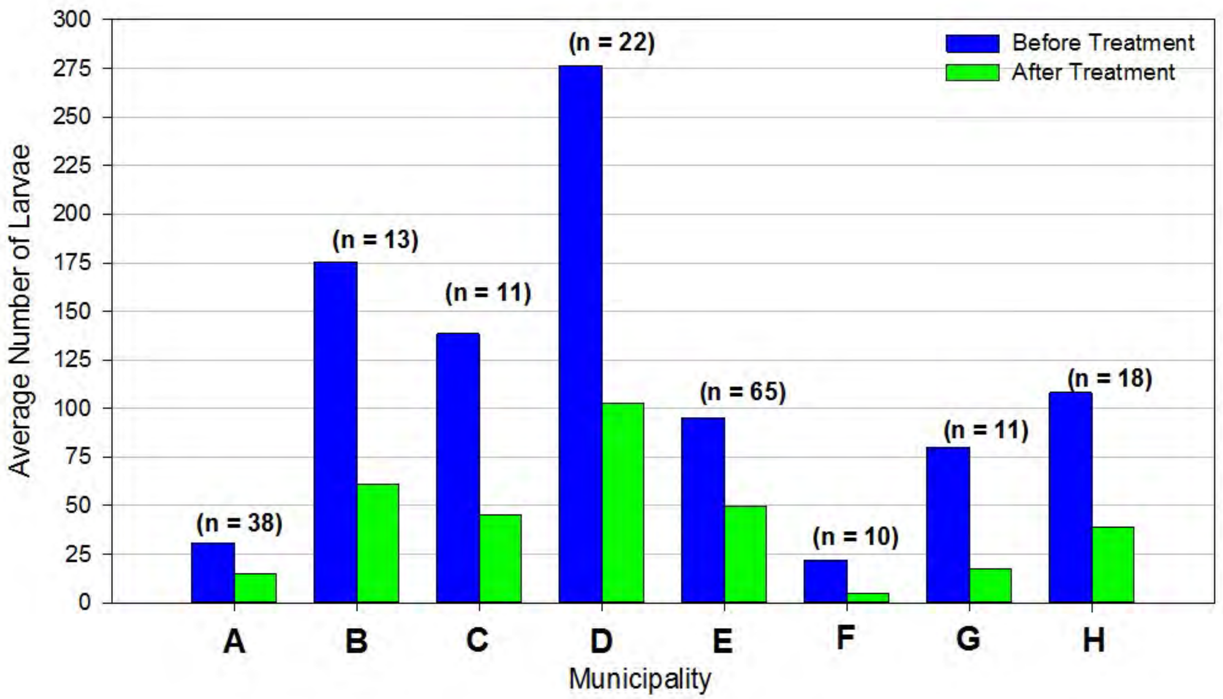


Figure 28: A comparison of the number of larvae before and after larviciding treatments in eight different municipalities.

The areas covered by past aerial and ground-based larviciding treatments conducted on behalf of the Regional District are currently only poorly mapped. In particular, aerial treatments are only recorded as somewhere along the flight path of the helicopter and do not show where and when treatments actually took place. It would not be difficult for treatments to be more precisely mapped and recorded using more sophisticated GPS technology that shows when and where the pesticide treatments actually occurred. More accurate maps could then be overlaid onto the areas of highest nuisance mosquito production predicted by the NMPM model and which would help inform the abatement program. This could lead to significant reductions in the efficacy and costs of the treatments.

Efficacy can only be reliably investigated by taking randomly distributed samples before and after treatments using identical sampling protocols. The results can then be plotted to identify sites where the abatement may not have worked as well as expected (Figure 29). These sites can then be revisited and dealt with accordingly.

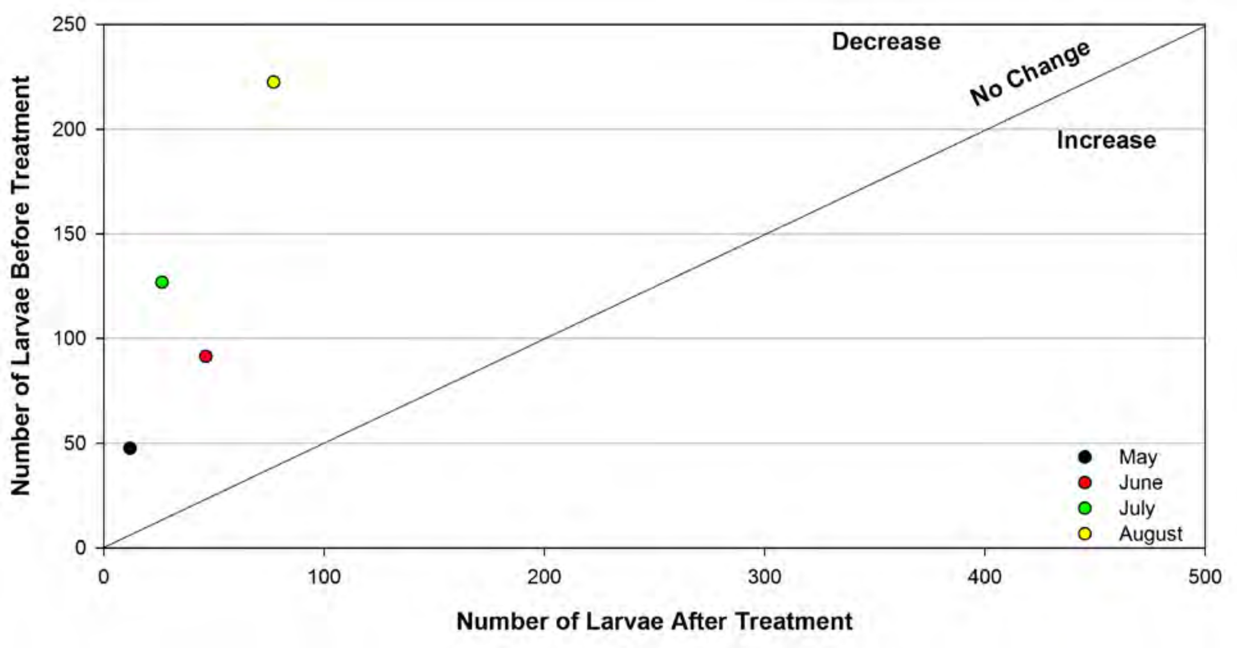


Figure 29: A plot of the number of larvae found before and after treatment, separated by month.

Treatment decisions will be most effective when they are targeted and based on several key characteristics such as life cycle stage, habitat type, and threshold levels for the target species. As the abatement operators collect more data, the sensitivity and effectiveness of the RDCK program will improve and this will invariably help to reduce the overall cost. Through using informed decision making procedures created by the NMPM, the abatement program in the Duncan Floodplain can be further enhanced to the benefit of residents, businesses and visitors.

v. How may discharges from the Duncan Dam affect production of *Aedes* mosquitoes through inundation of Low Bench areas in the Lower Duncan and Lardeau floodplains from May to September?

Results from the NMPM show increasing total productivity of mosquitoes in response to higher levels of dam discharge throughout the mosquito season (Figure 15). This general prediction is based on the principle that dam discharge has a positive relationship with availability of larval habitat. However, the productive potential of larval habitat declines through the mosquito season due to fewer eggs and less optimal conditions for nuisance mosquitoes. Mid-season productivity of nuisance mosquitoes is predicted to be higher than late-season (Figure 15). Warmer air temperature and greater precipitation are associated with higher productivity (Figure 13 and Figure 14). This precipitation effect is independent of the predicted area of habitat on the floodplain. Dominant vegetation had a strong effect on larval productivity, with the grass classification showing by far the highest productivity for *Aedes* nuisance mosquitoes (Table 6).

During the spring freshet and initial flooding, productivity of *Aedes* mosquitoes is expected to be much higher than later in the season. This is supported by data collected across five years that demonstrates high larval mosquito numbers in May-June (Figure 12). *Aedes* females lay their eggs across wide areas in wetted areas that become subject to flooding, such as amongst grasses (Horsfall et al 1975). The first flooding event of spring stimulates hatching of the majority of eggs that were laid the previous season. A small proportion of eggs require more than one flood to be stimulated to hatch (Hearle 1926) and therefore within-season re-flooding of areas will yield additional, but much lower, rates of hatching. This dynamic was accounted for in the NMPM (see Materials and Methodology for details). Figures 15 and 16 show an increase in the total productivity index at discharge levels over 300 m^3/s. This prediction is driven by larval productivity being higher in areas that were not previously flooded during a typical freshet and is only seen when the extent of post-freshet flooding exceeds that of an average freshet, which occurs under high levels of discharge.

Larval productivity during and immediately following the spring freshet was not evaluated in the model because of the limited dam operation seen during this period. The NMPM calculator estimates the area of available aquatic larval habitat using the hydrological model and statistical associations between the Lower Duncan River and water depths at the 13 long-term larval sampling sites. Early-season sources of water from snowmelt runoff affecting the Lardeau River, and other channels that intersect the floodplain, are unregulated and therefore not assessed. Without a means of estimating the extent of flooding during the freshet the NMPM calculator would underestimate total early season larval productivity.

4.2 The Nuisance Mosquito Performance Measure calculator

The NMPM calculator predicts relative productivity of nuisance mosquitoes as a function of multiple input variables. These variables include:

i. Time of season
ii. Recent mean air temperature
iii. Recent mean precipitation
iv. Recent discharge from the Duncan dam.

This tool allows managers of the Duncan Dam to better evaluate costs and benefits associated with operational scenarios under different times of season and weather conditions. Further, the predicted index can be used to inform nuisance mosquito control operations as to the location and relative severity of hatches of nuisance mosquito larvae.

Predictions are based on the number of larvae observed per sample. These predictions are an index that is proportional to population size rather than estimates of the actual number of larvae on the floodplain. An index rather than a direct estimate is provided for two important reasons:

1. Mosquito habitats are generally small and ephemeral and it is not feasible to accurately predict the total habitat area for an entire floodplain
2. Larval abundance is proportional but not identical to the adult female population, which exerts the nuisance.

In general, the NMPM calculator predicts a positive relationship between dam discharge level and larval production on the floodplain. These predictions are derived from two main sources. These are:

1. Observations of how larval abundance is affected by local vegetation, time of season, air temperature, and precipitation; and
2. Empirical predictions of how dam discharge will affect availability of larval habitat across the floodplain.

The predicted relationship between discharge and larval productivity may change depending on the environmental and operational scenario used for prediction. It may also change if different assumptions are made regarding how discharge level relates to availability of larval habitat. The predictions reported here used average levels of recent air temperature and precipitation for each seasonal period, and they assume that high water during the last spring freshet was three metres. These assumptions can be relaxed by using the NMPM calculator to generate new predictions using different levels of environmental input variables. Appendix II provides detailed instructions for using the NMPM calculator.

4.3 Conclusion

The NMPM calculator is informed by a rich and extensive long-term data set and incorporates season-specific environmental variables, mosquito ecology and phenology, hydraulic dynamics, and the distribution of the dominant vegetation type in a spatially-explicit context.

The long-term data show the highest abundances of nuisance mosquitoes during the early mosquito season, intermediate abundances in the mid season, and lowest abundances in late season. The NMPM predicts abundances for the nuisance species, *Aedes vexans* and *Ae. sticticus* although other mosquito species do occur across the season in low numbers (Figure 3), which do not act as a serious nuisance to human populations. The NMPM model was designed to predict larval productivity for the mid and late seasons only. This is because there are many sources of water that occur during the freshet, including the Lardeau River which is a natural unregulated watercourse, and these are not accounted for in the hydraulic modelling.

Total mosquito productivity increases with availability of aquatic larval mosquito habitat. Different dominant vegetation classes have different rates of mosquito productivity. Grass is by far the most productive vegetation type (Table 6) and should therefore be of key concern for the mosquito abatement program. Within a season, larval productivity increases as air temperature increases (Figure 13). Similarly, productivity increases as precipitation increases, independent of predicted area of larval habitat (Figure 14). The NMPM also predicts that nuisance mosquito productivity in the mid-season is higher than in the late season and that incremental changes in relative rates of larval productivity occur as dam outputs increase from 50 to 400 m^3/s (Figure 15). The greatest change in the rate of increase of mosquito productivity is predicted to be 7% which occurs over discharge rates of 300-325 m^3/s. (Figure 16).

Under average environmental conditions, the NMPM indicates that larval abundance may increase in the middle and late season with very high levels of dam discharge. However, productivity of early season *Aedes* mosquitoes always far exceeds that of the late season. The NMPM calculator can be used as a tool to predict mosquito productivity based on several complex factors. Subtle changes in these factors may alter the predicted, relative productivity of nuisance mosquitoes and therefore the NMPM calculator has been provided to allow for predictions based on dynamic scenarios. This tool will allow BC Hydro to work together with mosquito abatement operators to ensure that levels of nuisance mosquitoes are kept to bearable levels throughout the season.

4.4 Next Steps

Model validation and sensitivity analysis

Predictions from the NMPM are grounded in data, however, ecological models are simplifications of complex processes, and it is important to assess their performance and test their predictions. The NMPM was developed using output from the 2D hydraulic model. These hydraulic data were central to the working model framework and full assessments of model performance have not yet been conducted. Tasks to be completed in future include validating the model, by comparing predictions with real data, and a sensitivity analysis.

A comprehensive sensitivity analysis will systematically assess the relative influence that levels of input variables have on model predictions. This will provide distributions of likely and possible model predictions, which will then be compared to historical observations. This process provides insight into how different input factors affect one another, as well as the relative influence different factors could have on model outcomes. Additionally, model validation to assess model accuracy will be conducted. Historical environmental data will be used to generate model outputs, and the resulting predictions will be compared to corresponding historical observations from 2009-2014. Together the sensitivity analysis and validation process will assess real-world relevance and reliability of the model across ecological contexts.

Within the current model framework, total production is the predicted larval abundance summed across the wetted areas predicted by the hydraulic components of the model. Consequently, how hydrology is modeled has a major influence on model predictions. The NMPM predicts a relatively monotonic positive relationship between dam discharge and larval productivity. Initial results suggest that this pattern is largely driven by the model assumption that habitat availability across the flood plain is a linear function of discharge level. If the sensitivity analysis confirms this role and model validation shows it is inconsistent with historical larval production, it will be appropriate to re-evaluate this assumed relationship.

Applying a linear relationship between discharge and habitat availability was computationally and ecologically reasonable. However, this relationship may be modeled differently. For instance, a limit could be placed on the proportion of each vegetation class that is potential mosquito habitat. Another option would be to assume no relationship (or a much-reduced one) between discharge level and habitat availability below some threshold of dam discharge level or river depth. Such a scenario would reflect a river level at which water starts encroaching the floodplain. This two-tier approach has some support from the data; Figure 10 shows a discharge-depth regression line for the entire range of data from the 13 sites. However, the shape of these data appear to differ between the left and right sides of the plot, and the data show different trends if the data are analyzed separately for discharge levels above and below 200 m^3/s (Table 2). The difference in slopes below and above this threshold is five-fold and would likely influence the character of the discharge-productivity curve shown in Figure 12.

Additionally, larval mosquitoes only occupy the edges of stagnant pools of water, they are not found in the middle; therefore it is the edges of wetted areas that provide mosquito habitat, rather than the entire wetted area. While this approach is ecologically valid, it is complicated by the relationship between perimeter length and habitat shape. Consequently it may be appropriate to further evaluate effects of this model assumption. Also, flooding may reduce larval habitat by scouring action or by reducing temperatures below those required for hatching, which is often the case in deeper water, and is a factor not considered in the current NMPM.

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Appendix I

Table A1: List of Site Codes, Local Site Names and Coordinates of each Sampling Location

Database Site Code	"Local" Site Name	Northing	Easting
DDM-01	Old Mill	5562488.395	501762.641
DDM-02	Meadow Creek Cedar	5561506.849	503196.949
DDM-03 & DDM-03A	Lake	5559881.750	503651.785
DDM-04	Jacob's	5562230.019	503335.090
DDM-05	Lardeau - Control Site	5566590.018	502482.482
DDM-06 & DDM06A	Halloran Site	5564532.817	501040.256
DDM-07 & DDM-07A	Janet's Swamp	5564625.625	502226.414
DDM-08 & DDM-08A	Old Channel	5564728.637	502970.392
DDM-09 & DDM-09A	Gravel Pits	5563275.997	502923.268
DDM-10 & DDM-10A	Carex Beds	5563088.192	502795.401
DDM-11 & DDM-11A	Block Swamp	5564712.988	502166.600
DDM-12 & DDM-12A	Lardeau-Duncan Flats - Cottonwoods	5559185.281	502970.474
DDM-13	Lardeau-Duncan Flats	5559049.881	502760.718

Table A2. Default parameter levels for environmental parameters - air temperature, precipitation, and high river level during spring freshet.

Parameter	Time of Season	Default Value
Air temperature	Early	13.36301
(averaged over previous 10 days, units = °C)	Mid	18.32499
	Late	17.74432
Precipitation	Early	2.523302
(averaged over previous 10 days, units = mm)	Mid	1.639041
	Late	0.7155844
fthresh (freshet river level threshold, units = m)	n/a	300

Appendix II

Instructions for the Nuisance Mosquito Performance Measure calculator

The NMPM calculator produces predictions as a function of levels of multiple input variables that specify the ecological and operational scenario of interest. The calculator is in the form of an R function named prediction(). Using this function requires R, a free command-line computing platform for programming, statistics, and graphics. Up-to-date versions can be found at http://cran.r-project.org/. Downloading and installing RStudio is also recommended. It provides a powerful, user-friendly interface for R. See http://www.rstudio.com/products/rstudio/.

The code for the prediction() function is found in the R script file "Prediction_Function_Code.R" in the folder "…\DDM_Mosquito_Productivity\R objects and scripts", along with its associated GIS files, other R script files and R data objects.

To use the NMPM calculator to predict mosquito productivity under different scenarios of environmental conditions and dam discharge, open the R script file "Performance_Measure.R", which is in the folder "…\DDM_Mosquito_Productivity."

Then edit "Performance_Measure.R" to specify the desired levels for each input variable. The file can be edited in RStudio or a text editor. R assigns values to variables using the "<-" convention . For example, x <- 2, creates a variable called "x" and assigns it a value of 2. Leaving the file unedited will cause default values to be used. The required input variables are described in the table below (as well as in the R script file).

Table A3: Names of input variables required by the R function prediction()

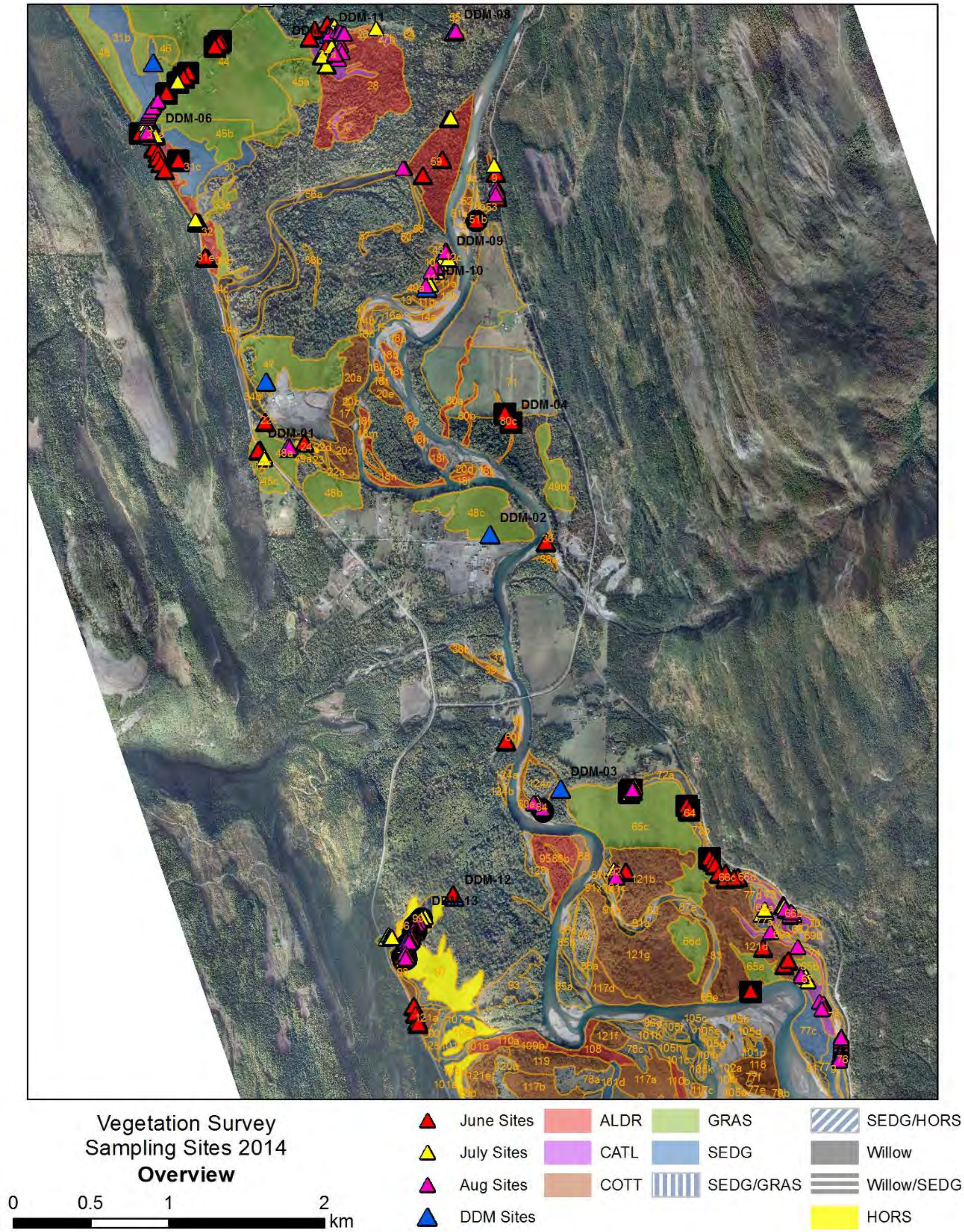
Variable name	Definition
figs_y_n	The character "y" or "n" indicating whether the user wants to produce a histogram and map showing relative levels of mosquioto productivity
season	Time of season specified as "early", "mid", or "late". "early" corresponds to the period after the spring freshet but before June 29. "mid" corresponds to the period from June 29 to August 8. And "late" corresponds to the period from August 8 onward.
temp	Mean air temperature for the 10 days preceding the estimation date (°C). Will default to historical mean for specified time of season.
precip	Mean precipitation for the 10 days preceding the estimation date (mm). Will default to historical mean for specified time of season.
fthresh	High level of the Lower Duncan river during spring freshet of the year (m)
discharge	Daily average level of dam discharge (m^3/s)

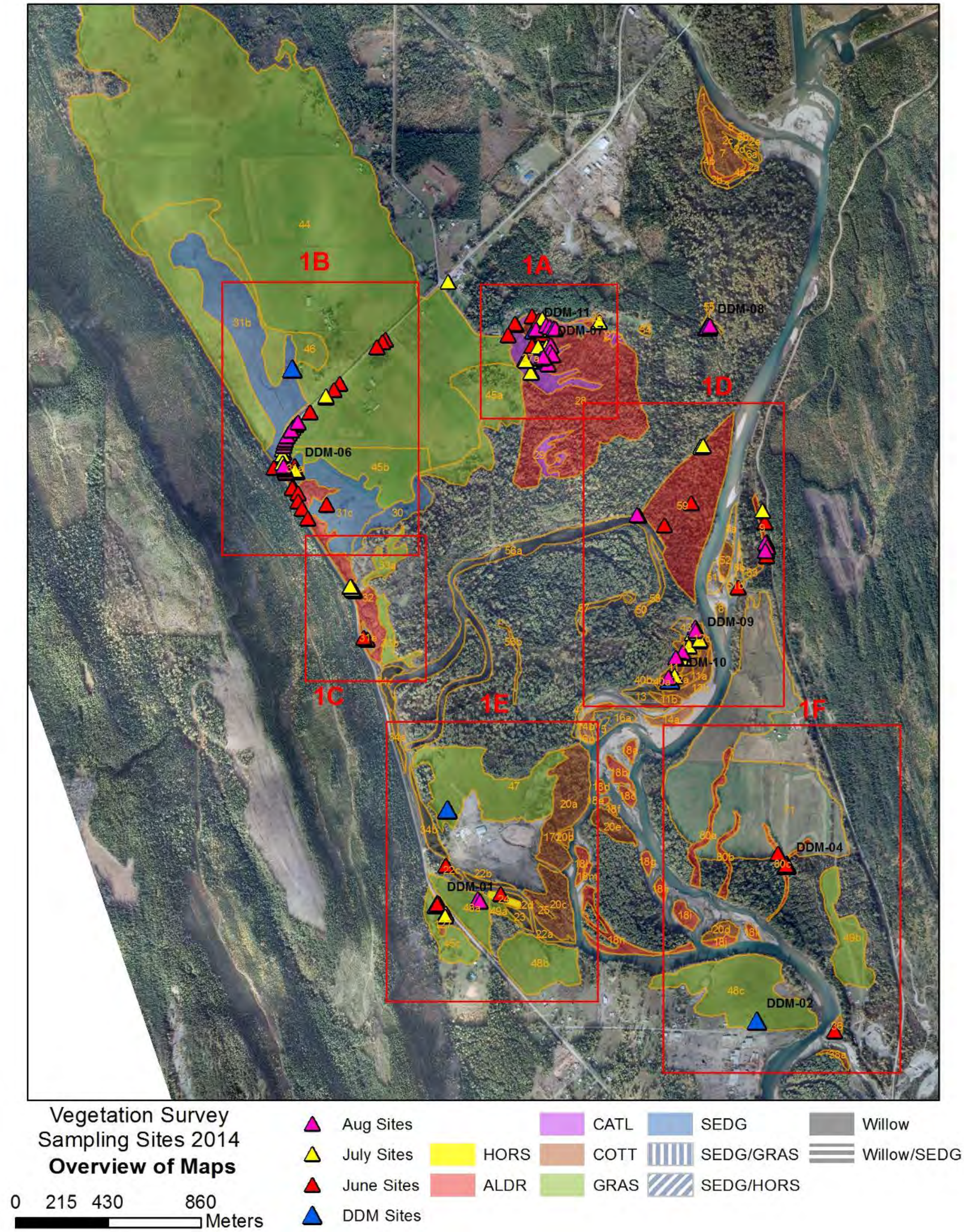
Once the script "Performance_Measure.R" has been edited, then run all of the code therein. This may be accomplished by copying and pasting all the code (including comments) directly to the R console, or by selecting the code in RStudio and pressing ctrl+enter. This will implement and run the function prediction(), parameterized at the input values you have specified.

The final line of code in "Performance_Measure.R" runs prediction() and saves the summary output in an R object named "summary_output." Running the function also saves the same output data to a .csv file to the folder "…\DDM_Mosquito_Productivity\Results". And if the value of the variable figs_y_n is "y", then a map of productivity across the floodplain (see Figures 14-22 for examples) is generated and saved to the same folder in pdf format. A histogram of productivity levels across the floodplain is also produced in a graphics window.

For support, please contact Culex Environmental at m.jackson@culex.ca.

Appendix III
Vegetation Maps

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DDM-07
DDM-08
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DDM-04
DDM-02
Vegetation Survey
Sampling Sites 2014
Overview of Maps
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Meters
Aug Sites
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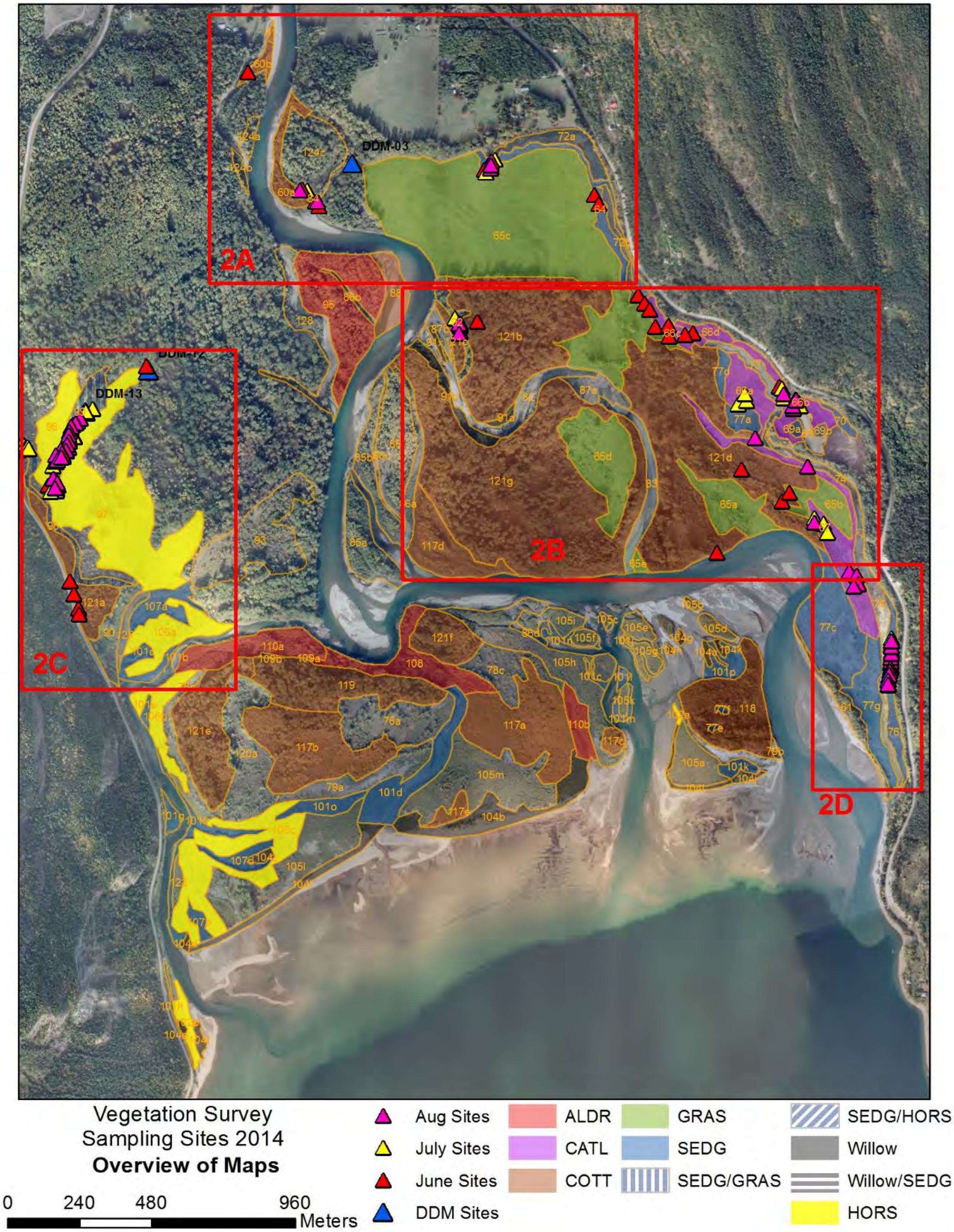
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Vegetation Survey
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Overview of Maps
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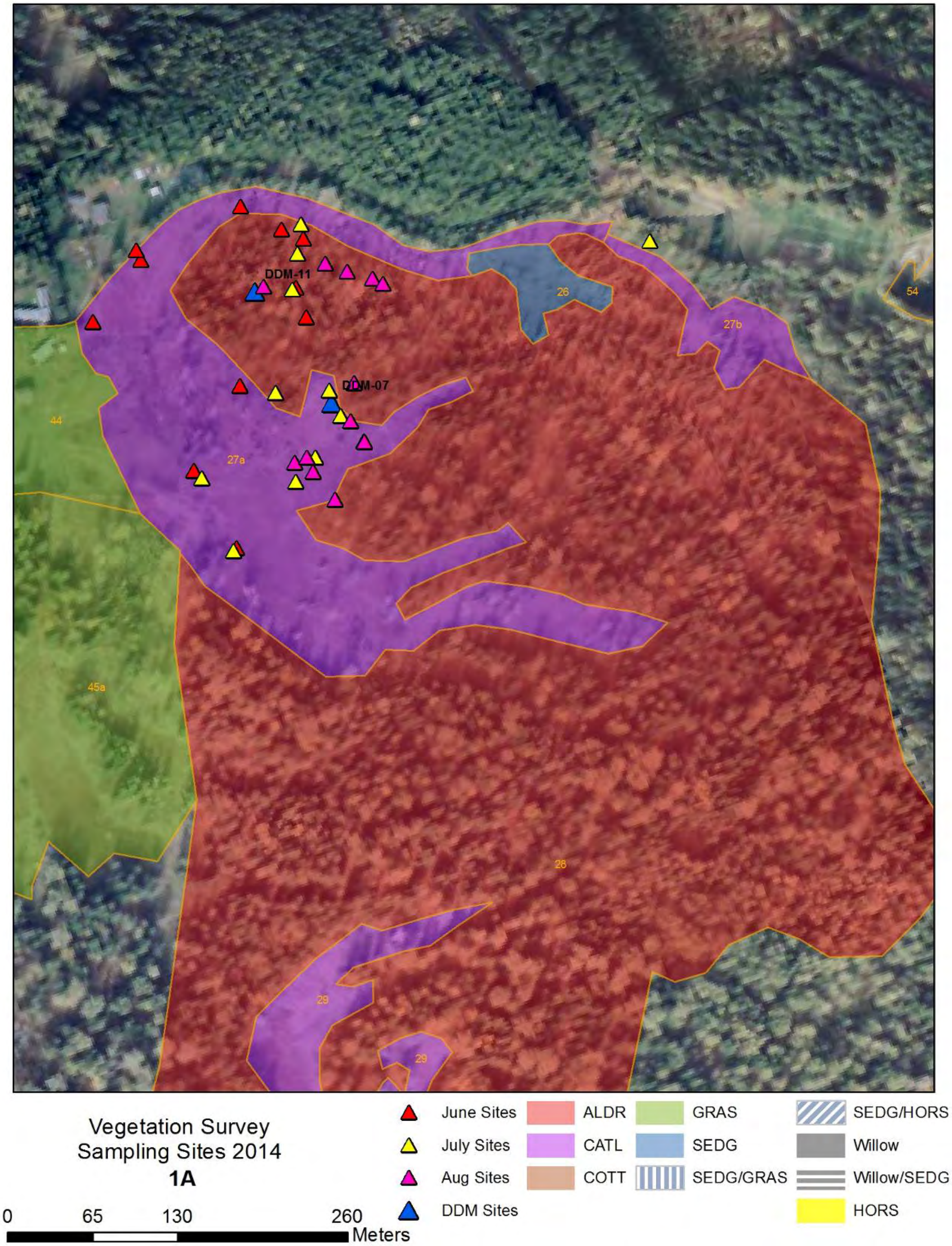

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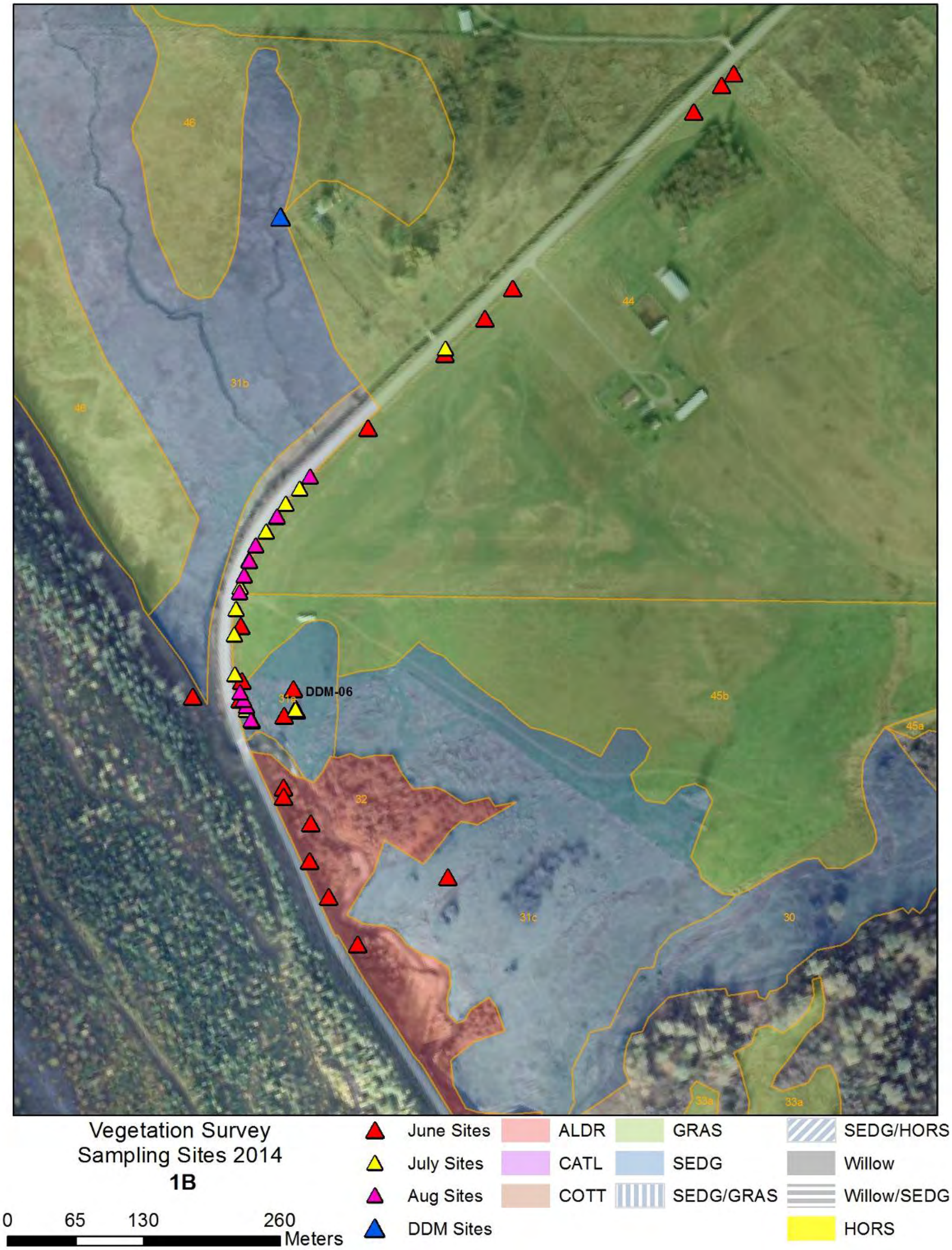
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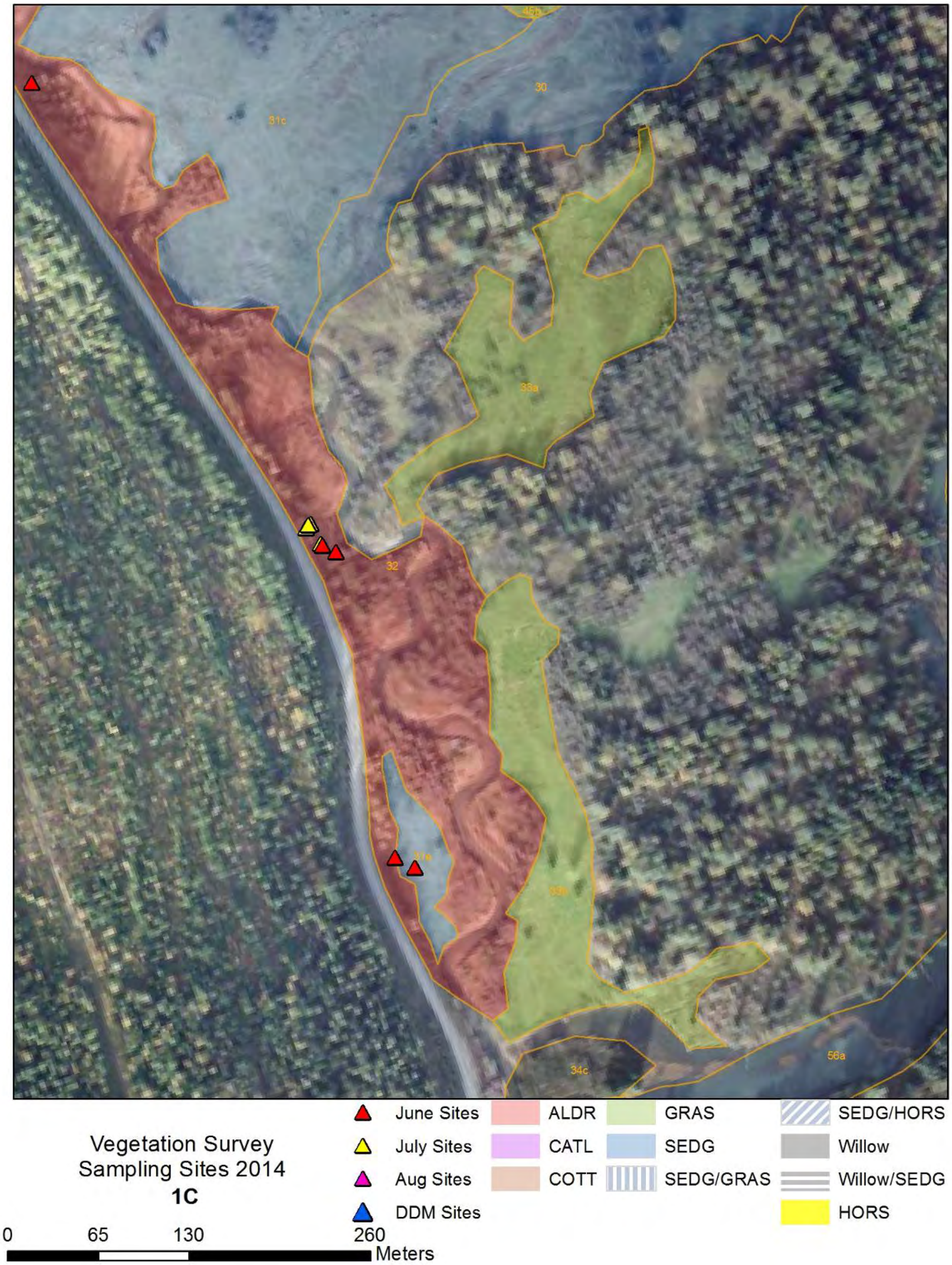
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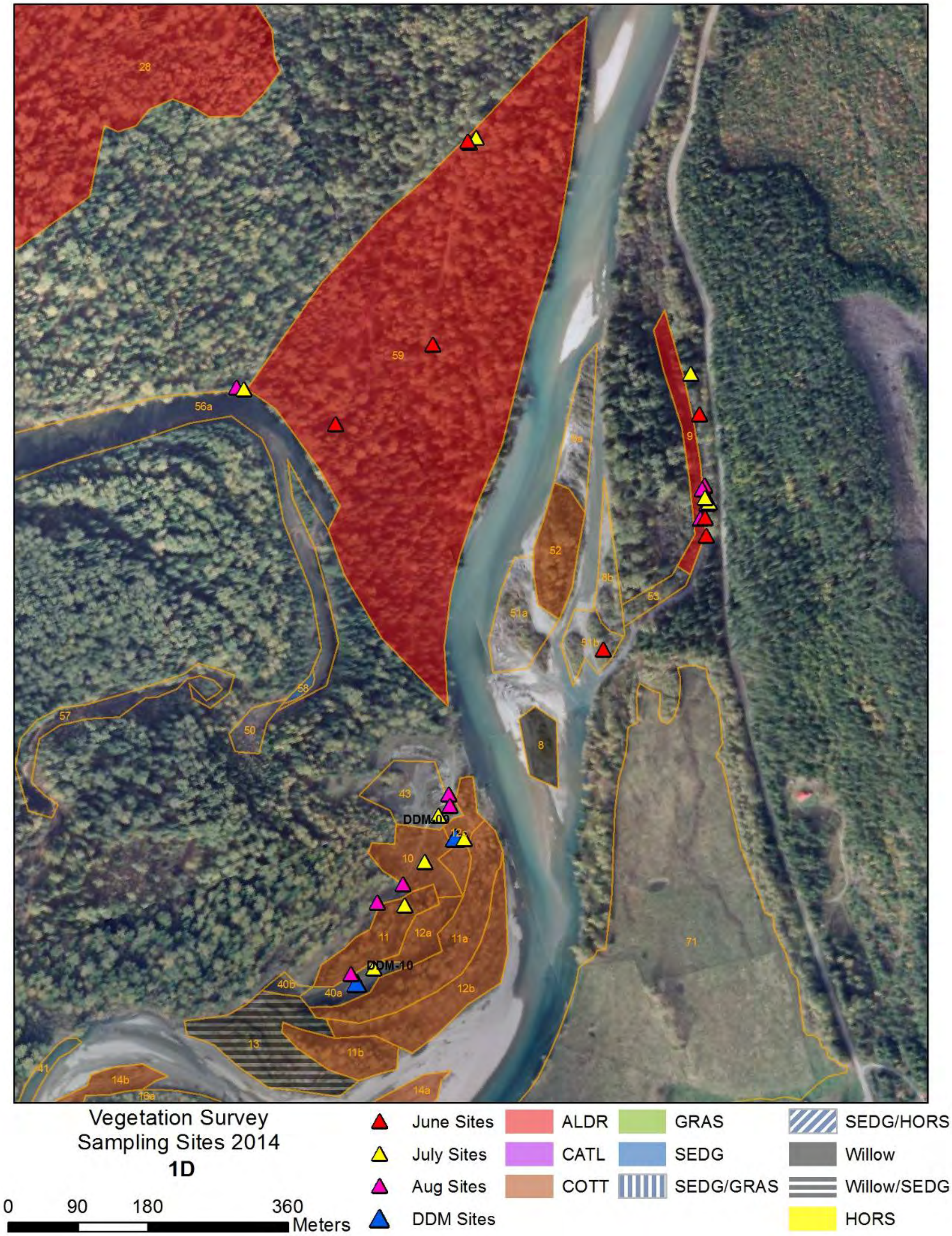
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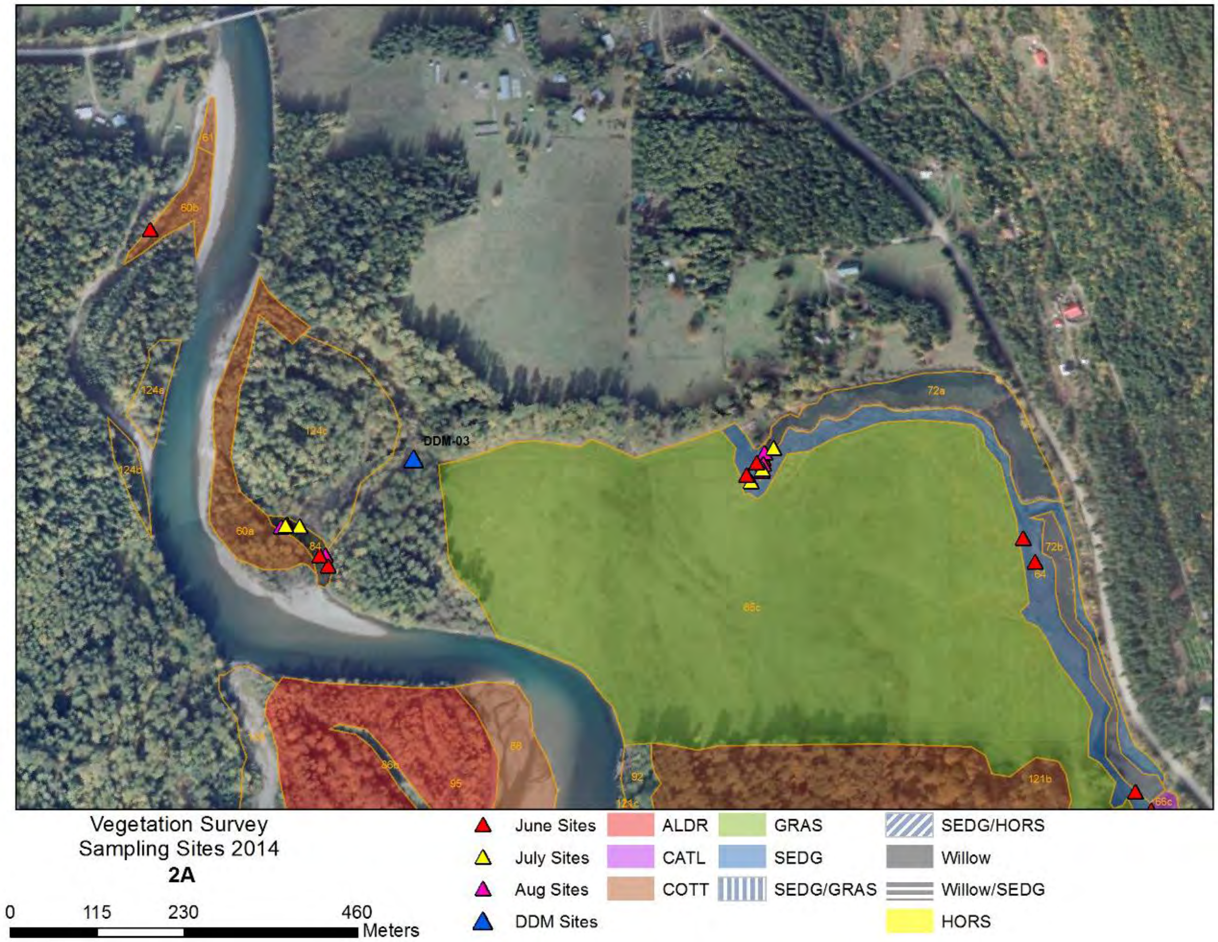
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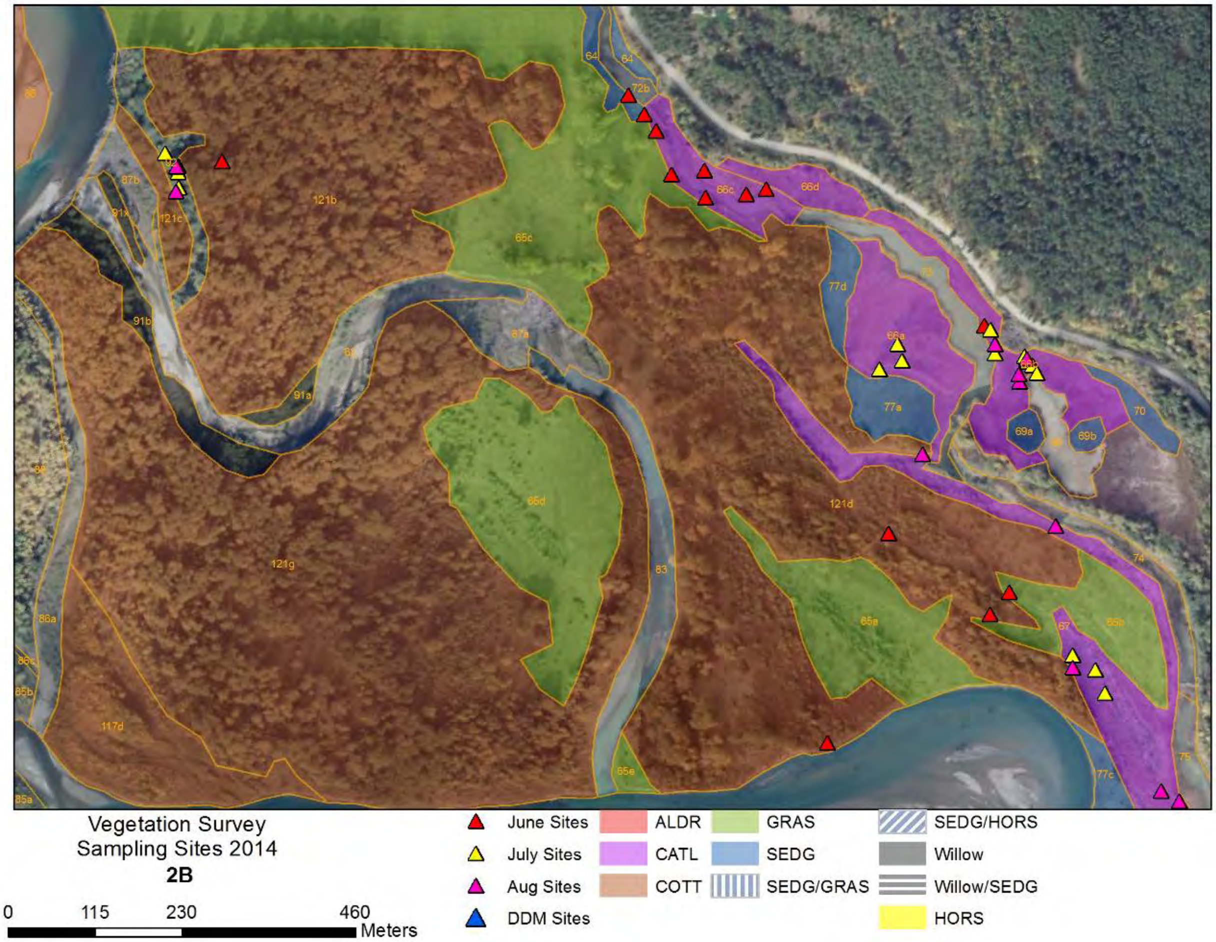
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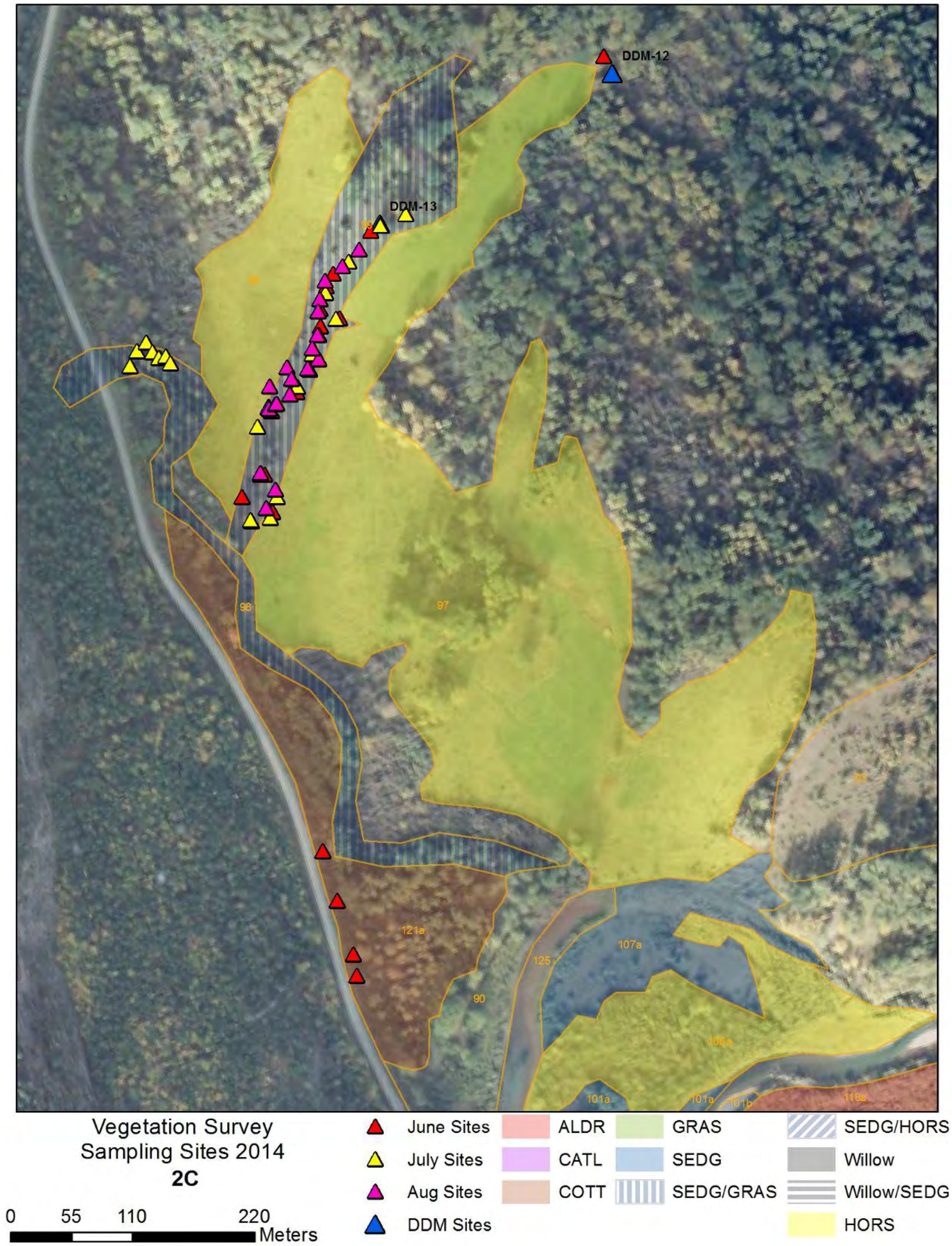
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Appendix IV

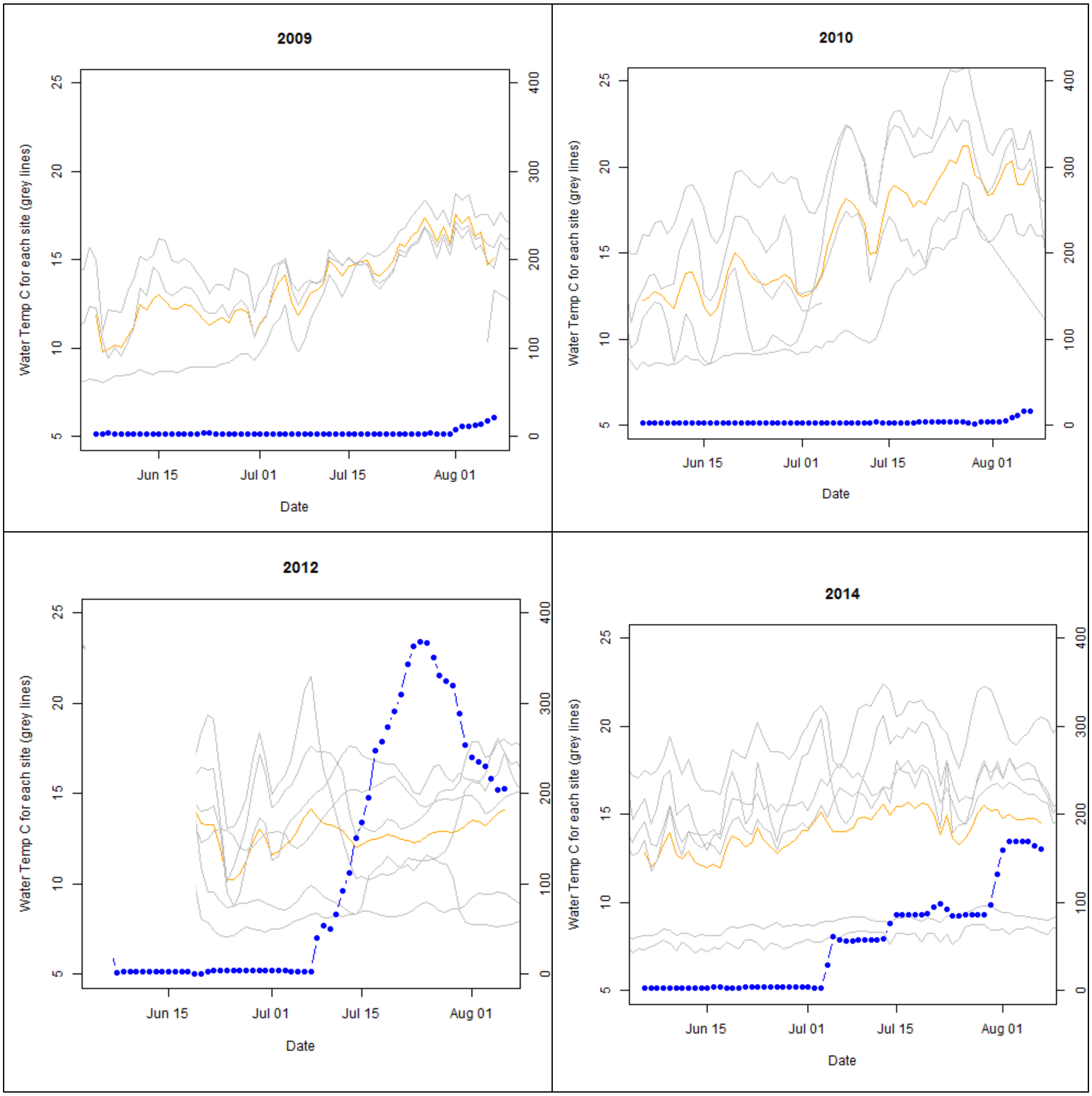

Figure 1. Water temperature at the 13 sampling sites across four years of sampling. Water temperature for each site is shown in grey. The grand mean for all sites is shown in orange. Dam discharge is shown in blue.