The Impact of Land Use/Land Cover Change on Flooding in the Lower Russian River Watershed: 1992 - 2017

By

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Abstract

Changes in land use and land cover are inevitable results of societal development, and they have various impacts on the local environment. This study focuses specifically on the impacts of land use and land cover change in the Lower Russian River watershed (Sonoma County, CA) on the severity of flooding on the Russian River between 1992 and 2017. The change in land cover was found to be statistically significant ($p < 0.1$) for the change in both natural and human-impacted land cover, as well as for three of the five specific land cover classes. It was found that in this case, an increase in cultivated land, forested land, and the broader category of human-impacted land cover (including developed and cultivated land) all result in an increase in flood severity, while an increase in shrubland and the broader category of natural land cover both result in a decrease in flood severity. Increases in herbaceous land were found to decrease flood severity, while increases in developed land were found to increase flood severity, but with a lower statistical significance.

Problem Statement

The loss of natural land cover for human-modified land cover results in an increase of flood severity. Since 1980, the lower Russian River watershed has experienced loss of natural land cover such as forested land and shrubland, and additions of more human development, notably suburbanization, exurbanization, vineyards, and grazing land. The increase in suburban and exurban land has decreased the permeability of the land, resulting in higher volumes of runoff, leading to more severe floods. Similarly, the increases in vineyards and grazing land have increased both soil erosion and rainwater runoff, again ultimately causing an increase in floods.
Introduction

As populations grow and as different industries develop, there are various changes to both the social and natural environments. Often, people think about direct impacts on their lives, such as how a new development will influence traffic, or if the new farm will be exposing nearby residents to pesticides, but often people don’t think of the most obvious change: the physical change in land cover. One major impact that this change has, is an impact on the area’s hydrology. Infiltration and runoff are easily influenced by the land cover, because different covers support various levels. Conversion from natural land covers like grasslands or forests to row crops reduce soil quality, increasing both soil erosion and water runoff, while adding pavement ultimately eliminates infiltration there, and causes either runoff or for water to enter water management systems, bypassing parts of the natural cycle.

1. Land Use/Land Cover Change

Throughout human history, people have had an impact on the planet, including the altering of land cover and land use from the naturally occurring land cover. Some of the most dramatic land use and land cover change has been seen in the northern hemisphere with Europe and highly fertile regions of North America, and in Argentina and Australia in the southern hemisphere, primarily for the conversion to cropland (DeFries, 2004). Land use/land cover change around the globe has been a long occurring practice, but not at the same rates in different regions. For example, much of the world experienced steady land use/land cover change until 1850, and has been experiencing exponential growth since then, whereas Argentina’s rate of change stabilized around 1940 (Ramankutty and Foley, 1999). Also, while the general trend since 1700 has been an increase in cropland, parts of North America and other parts of the developed world have actually seen a decrease in cropland in the last fifty years, primarily for
the conversion to either urban land or in some cases, reforestation (Ramankutty and Foley, 1999).

Land use change can have many effects on the environment ranging from changes in surface water runoff to ground temperature, depending on the environment and what kind of land use/land cover change is taking place. Much of the land use/land cover change that has happened throughout history has been in temperate environments, and much of the change has been for agriculture. Often in these cases, this change has increased primary productivity and a local decrease in surface temperatures (DeFries, 2004). Following current land use/land cover change trends concerning agriculture, however much of the change is occurring in tropical regions which already have extremely high primary productivity. Consequently, when the natural land cover is removed, the trend is for a decrease in primary productivity and a local increase in surface temperature (DeFries, 2004). Looking forward, the effects of modern land use/land cover change could be different, primarily dependent on what the starting and ending land use/land cover classification is, and where it takes place. For example, it was modeled that with continued deforestation in the Amazon, not only will there be an increase in direct effects associated with deforestation, but this could ultimately cause a change in Hadley cells, dramatically altering the monsoon season in Asia (Feddema, 2005).

1.1 Land Use Change in the United States

In North America, the conversion of land use/land cover to cultivated croplands did not really begin to be noticed until around 1750, and clearing forested land for crops became more common practice in the following years (Ramankutty and Foley, 1999). As populations started to push west, and the Great Plains began to be cultivated, and population centers were primarily
rural, the land use/land cover change has resulted in the loss of almost all natural prairie in favor of cropland (DeFries, 2004). Recently, this concentration in rural population has shifted: in the 1900’s alone, the United States’ population has followed a trend of an urban pull, and has changed from having a majority (60%) living in a rural setting to having a larger majority (~80%) in an urban setting (Poff et al., 2006). This shift in population center can be attributed to numerous reasons, many economic, but it also accounts for the recent urbanization of much of the United States, around 8000 square kilometers of land is converted to urban residential property every year (Poff et al., 2006). With this transition away from having so much focus on agriculture, some of the land has since been reforested, for example, in the eastern United States (Ramankutty and Foley, 1999).

1.2 Land Use Change in the Russian River Watershed

Focusing farther out to California, and up to modern day, in the Russian River Watershed, and other watersheds in Sonoma, Mendocino, and Napa counties are still experiencing land use/land cover change for purposes like urban/suburban development, as well as agricultural land, frequently vineyards. Within the Russian River Watershed, there has been an increase in suburban and exurban development as populations continue to push north from San Francisco. In recent years, there has been an increase in both suburban development, seen in the growth of cities like Santa Rosa, Rohnert Park, and Windsor, and growth in exurban development in more rural parts of the region. In the case of Sonoma County, a survey found that the primary cause of migration to the area was the open space and surrounding natural environment, which has led to the loss of natural and agricultural land for development (Crump, 2003). The primary situation facing the region is the decision to develop through more of an
urban sprawl approach, which ultimately results in a more substantial loss of natural space than more concentrated land use/land cover changes, and “smart growth”, which entails concentrated developments more spread out to try and minimize the effect of widespread development (Crump, 2003).

In addition to suburbanization and exurbanization in the region, there is also a growth in agricultural land, notably vineyards. Sonoma County, Napa County to the west and Mendocino County to the north, slightly less so, are world renowned for their wine production, and vineyards are a common land use/land cover type in the region. Perhaps the most dramatic land use/land cover change in favor of vineyards is the deforestation of coastal forests, particularly redwoods. The Gualala Watershed has experienced and still is undergoing a conversion of these coastal redwood forests to vineyards, sparking controversy in the area for various reasons surrounding the concern about the degradation and local views of what the region’s land use/land cover should look like (Dimson, 2012). In the last 30 years, the acreage in Sonoma County used for wine production has tripled, with 23,639 acres reported in 1980 (SCAC, 1981) and 60,009 reported acres in 2016 (SCAC, 2017). This conversion to crops like wine grapes not only changes the landscape of the region, but increases water runoff and soil erosion and degradation (Dimson, 2012).

2. Hydrological Impacts of Land Use/Land Cover

While land use/land cover and its change have many possible impacts, they are not universal in all regions. What effects come as a result of the land use/land cover are primarily dependent on other characteristics of the study area, i.e., topography and precipitation. Among the many possible impacts of land use/land cover are effects on the hydrology of the region.
Land use/land cover has many ways of altering the hydrology, such as modifying the vegetation leading to a change in soil stability and quality (i.e., cropland), changing the permeability of the land and limiting water filtration (i.e., urbanization), or completely altering the system (i.e., removal of wetlands). On the surface, in the United States alone, over 50% of wetlands have been lost to land use/land cover change (Poff et al., 2006), which leads to a complete shift in the hydrology and the ecosystem as a whole.

The initial loss of the natural land cover is only the most basic effect. In a study conducted by Brath et al. (2006), it was concluded that land use/land cover change played a significant role, notably with a degree of uncertainty, in the period between peak flows of the Samoggia River, using rainfall simulation based on the typical patterns in the region. In this study, the land use change seen was not a massive shift towards urban land cover, changing from 0.7% to 4.4% between 1955 and 1980, but the changes were a significant loss in meadows (23.7% to 3%) compared to increases in unproductive areas (0.6% to 9.1%) and arboreal cultivation (2.3% to 10.1%) (Brath et al., 2006). Hence not only urbanization and the shift towards cropland impact the hydrology of a study area, but even just a loss of natural vegetation with no real usage can influence it as well. It is important to note that these results were found on a relatively small scale, with a study area of 178 square kilometers. As the target area of analysis increases, the impact of land use/land cover tends to decrease (Bonnel et al., 2007).

2.1 Urban Land

One of the major global shifts in land use/land cover is for urbanization. For example, in the Zhujiang Delta in China, between 1989 and 1997 there was rapid urbanization, where a 47.68% increase in urban land occurred (Weng, 2002). An urban development like this, slower
urban development, and the long-lasting presence of urban land all have effects on the hydrology of the surrounding area. In a 2006 study by Poff et al., spanning four geographic regions of the United States, it was found that both urbanizations can have varying impacts. With an increased proportion of urban land, the recorded maximum flows increased in the Southeast and Central study areas, while increased minimum flows were also found in the Central and Northwest study areas (Poff et al. 2006). With regard to runoff, urbanization at the expense of forested land can result in an increase of surface runoff by as much as 1200% (Mishra et al., 2010).

In addition to the regional variables influencing the effect of land use/land cover on flooding and hydrologic characteristics, the effects of the land use/land cover can be dependent on the characteristics of the rainfall itself. In a 2002 study by D. Niehoff et al., it was found that urbanization in catchment basins of the Rhine River has a much higher effect in convective storms (shorter, smaller storms but very heavy rainfall) than advective storms (longer, larger storms but with relatively less heavy rainfall).

Urbanization not only increases runoff, but also increases the rate at which water runs off. The impermeability of urban land leads to the streamflow after rainfall to increase, as more water is entering the stream due to a lack of filtration. Additionally, the maximum flow for the storm event is pushed forward, and reaches that point much faster (Leopold, 1968). Again, with scale being a large factor, these patterns are primarily seen on a smaller scale, as opposed to over an entire river basin (Niehoff, 2002). In addition to an increase in flood events themselves, there are more consequential effects of urbanization, particularly with regards to soils and erosion. As runoff and streamflow increases with urbanization, this often makes the surrounding area, especially the stream bank, subject to higher rates of erosion due to increased frequency of high
gage heights and increased streamflow rates. Subsequently, this causes the river size to increase both in depth and width (Leopold, 1968).

2.2 Agriculture

The trends of land use/land cover change for crop land have changed recently in history for many developed nations, as focus has moved off of agriculture. Even though in many regions there has been a loss of cropland due to urbanization, there is still natural land cover lost in favor of agriculture around the world. As with other types of land use/land cover change, the impacts of a shift from natural cover to agriculture is largely dependent on the characteristics of the environment and natural cover composition. In the Maying River basin of China, shrubland and high-coverage grassland were found to have decreased by 34.32% and 54.57%, respectively (Wang, 2006). In the same study, this shift was found to have a strong influence in the decrease of base flow, peak discharge, and mean annual discharge (Wang, 2006). Also in China, Xiao et al. (2014) found that on the Loess Plateau, soils on land used for agriculture held much higher volumes of water than those with other cover types including grasslands, forests, and shrubland. This increase in soil moisture capacity corresponds to a decrease in water runoff, as more is able to infiltrate and be held within the soil. Conversely, it was found that in Wisconsin, a conversion from forested land to cropland resulted in an increase in runoff by 20% (Mishra et al., 2010). This contrast highlights that the impacts of a given land use/land cover are not universal across all locations. Variables which can impact are the ecology of the vegetation which is being removed, what crops are being added, what is happening to the grade of the land, as well as many others. Despite the lack of a universal effect from the shift towards agriculture from natural land cover, the effect is still present.
Being situated in a major wine-growing region, the Russian River watershed is home to many vineyards, and notices the resulting hydrologic impacts. Adding to these effects, many new vineyards in the adjacent Napa County are being started on hillsides (Battany et al., 2000), and the same is being seen in the Russian River watershed. The same study found that these sloped vineyards showed higher levels of runoff and soil erosion, impacting stream and river flow in the valley (Battany et al., 2000). The impact of vineyards on runoff and the surface hydrology of a region, like that of many other variables, is somewhat dependent on the hydrology itself. Sloped vineyards in Italy were found to have less runoff in storm events which happened when the soil already was moist compared to storm events after dry periods (Tropeano, 1984). Furthermore, vineyards which were more heavily tended with machinery and human work often resulted in having less vegetation cover on the vineyard, which in turn caused significantly more runoff than less mechanized vineyards (Tropeano, 1984). Regardless of the methods used on a vineyard, this specific LULC has higher runoff rates than many other agricultural uses. Hilly areas with vine cover were found to have the highest runoff rates when compared to cereals, vines, olives, eucalyptus, and natural shrubland along the Mediterranean (Kosmas et al., 1997). This study is particularly relevant to the Russian River watershed, because of the similarities in climate. California’s typical climate of dry summers and wet winters is similar to that of the Mediterranean, and many of the vineyards are on hilly slopes as well. Ultimately, any change in land use or land cover can have an impact on the surface hydrology of a region, but vineyards cause significant increases in runoff relative to other agricultural land uses.

3. Flooding in the United States
Flooding events are seen throughout the world, from highly developed regions to unpopulated regions: the Red Cross estimates that between 1965 and 1990, over 1.5 million people were impacted worldwide. While not all floods are of much concern due to their remote locations, the increase in floods worldwide is widely accepted to be due to an intensification of the water cycle, leading to more intense rainfall, caused by climate change (Pickle and Downton, 2000). While the change in precipitation patterns is the primary cause of increased flooding in many regions, that is not to discount the impact of anthropogenic modification of the ecosystem. Vogel et al. (2011) found that across the United States, streamflow rates increased across regions, but in areas with more land use/land cover change and human impact, there were more substantial increases found. It was also found that a natural increase in flooding is easily magnified by land use/land cover change in the area, highlighted by the examples of extremely urbanized regions, like Chicago and Los Angeles (Vogel et al. 2011).

3.1 Atmospheric Rivers

Atmospheric rivers are streams of water vapor in the atmosphere which travel away from the tropics, which often cause either rain or snow when they make landfall. On average, they carry the same volume of water vapor as water which flows at the mouth of the Mississippi River (NOAA, 2015), and are stretch 2,000+ kilometers in length by a few hundred kilometers in width (Ralph et al., 2006). These atmospheric events are not only a significant carrier of water vapor, but they account for as much as 90% of water vapor transported towards the poles (Zhu and Nelwell, 1998). Atmospheric rivers are seen around the globe, but the primary location where these are seen in the United States is along the West Coast, where atmospheric rivers quickly result in rainfall due to orographic lift. Here, atmospheric rivers are not only significant in the
occurrence of flooding, but many do not result in such heavy precipitation and are essential in maintaining water supply (NOAA, 2015).

On the West Coast, and specifically California, atmospheric rivers are an important resource to maintain the water supply, but like other weather-related events could alter with climate change. With atmospheric rivers having such high variability in the volume of water released upon landfall, the difference between a drought year and a damagingly wet year can be a couple of strong storms (Dettinger et al., 2011). With the recent drought coupled with some of the wettest winters on record, the frequency, and the lack thereof, of atmospheric rivers has greatly impacted the local environment. As the climate continues changing, these extreme years are projected to increase: in years where there are more heavy atmospheric river-related storms, the number and duration of storms are not projected to increase in the future. However, the frequency of these heavy years is expected to (Dettinger, 2011). With the duration not expected to increase, but the frequency, this may not cause too heavy of an increase in floods. A study by Ralph et al. (2013) found that storms are lasting two times longer than another storm resulted in five times of increase in gage height, indicating that the duration of a single storm is the primary indicator in the severity of flooding.

The Russian River watershed is home to much of one of the primary metropolitan statistical areas north of San Francisco: Santa Rosa, CA. Similar to the rest of the state, nearly all of the rainfall in the Russian River watershed is attributed to atmospheric rivers. Furthermore, every major flooding event on the Russian River has happened during an atmospheric river event since 1997 (Ralph et al., 2006). There are multiple smaller watersheds which all drain into the Russian River as part of the larger watershed, including the Laguna de Santa Rosa. The Laguna
acts not only as a feeder to the Russian River but also as a reservoir and floodplain in the event of inundation of the river (Potter and Hiatt, 2009). As suburbanization, exurbanization, and the conversion of natural lands to vineyards and other crops occurs in the Laguna, which could impact the hydrology of both the Laguna de Santa Rosa and the Russian River watershed.

4. Remote Sensing of Land Use/Land Cover Change

    LULC and its change can be mapped out using collected field data, but requires extensive resources while using remotely sensed imaging provides a more manageable method. The use of satellite imagery has been a key tool in doing this analysis because it provides accurate data while using less resources. Two standard methods of determining LULC change are image subtraction and map subtraction. However, image subtraction is much more accurate because there is less error to be caused by the process of making the map (Green et al., 1994). Furthermore, conducting this image subtraction post-classification is important because it consolidates LULC types, making the result more understandable (Shalaby et al., 2007).

    In the process of identifying LULC change, there are many different LULC types which need to be identified through classification. These separations range from broad classification differentiations like urban versus forested land to more specific differentiations like between two different vegetation cover types. Furthermore, remotely sensed data, such as Landsat imagery, is more accurate in assessing land cover change than land use change (Green et al., 1994). In various situations, a single land cover could lend itself to multiple land uses. When working with either land use or land cover, or both, under these different scales of differentiation, Landsat imagery proves to be better suited for some applications than others.
The effectiveness of satellite imagery for image classification is largely dependent on what different classes are desired, and if it can be achieved with the available spatial and spectral resolution. Carlson and Arthur (2000) found that in Chester County, PA, a region which is and has been experiencing rapid urbanization, Landsat proved reliable to create ten classifications. Additionally, it was concluded that despite the coarser spatial resolution of satellite imagery, like Landsat, the availability of non-visible light bands and the temporal resolution give it an advantage in some LULC differentiation than air photos (Carlson and Arthur, 2000). When it comes to more specific differentiation, Landsat’s reliability is not as strong. In a comparison of Landsat and SPOT, Basham May et al. (1997) found that Landsat was well suited to differentiate the spectral signatures between shrubland and meadow. However, it was not effective in recognizing different types of meadow. While Landsat imagery does pose some problems with more specific classification, it is shown to work well with slightly less specific requirements. Expanding from uniquely vegetation identification, remotely sensed imaging can work well when applied to the edges between different cover types, and in areas where the line between different classifications may not be as clear. Treitz et al. (1992) concluded that when attempting to produce LULC classification at the “rural-urban fringe,” SPOT proved more useful, primarily due to its higher spatial resolution. They also concluded that for much of North America, imagery with a 30-meter resolution accomplishes the goal as well. When working on the edge of different LULC types, a higher spatial resolution is desired, meaning with a resolution of 30-meters, Landsat could produce less accurate results. Despite this drawback, the results could be verified with the aid of higher resolution aerial imagery (Trietz et al., 1997).
**Hypotheses**

Null 1: The change of natural land cover in the Lower Russian River watershed from 1984 to 2017 has no role in the severity of flooding.

Alternate 1: The decrease of natural land cover in the Lower Russian River watershed from 1992 to 2017 increases the severity of flooding

Sub-Hypothesis Null 1.1: The change of forested land in the Lower Russian River watershed from 1992 to 2017 has no role in the increase in the severity of flooding.

Sub-Hypothesis Alternate 1.1: The decrease of forested land in the Lower Russian River watershed from 1992 to 2017 increases runoff, therefore accounting for an increase in flood severity.

Sub-Hypothesis Null 1.2: The change of shrubland in the Lower Russian River watershed from 1992 to 2017 has no role in the increase in the severity of flooding.

Sub-Hypothesis Alternate 1.2: The decrease of shrubland in the Lower Russian River watershed from 1992 to 2017 increases runoff, therefore accounting for an increase in flood severity.

Sub-Hypothesis Null 1.3: The change of herbaceous land in the Lower Russian River watershed from 1992 to 2017 has no role in the increase in the severity of flooding.
Sub-Hypothesis Alternate 1.3: The decrease of herbaceous land in the Lower Russian River watershed from 1992 to 2017 increases runoff, therefore accounting for an increase in flood severity.

Null 2: The change of human-impacted land cover in the Lower Russian River watershed from 1984 to 2017 has no role in the severity of flooding.

Alternate 2: The increase of human-impacted land cover in the Lower Russian River watershed from 1992 to 2017 increases the severity of flooding.

Sub-Hypothesis Null 2.1: The change of cultivated land in the Lower Russian River watershed from 1992 to 2017 has no role in the severity of flooding.

Sub-Hypothesis Alternate 2.1: The increase of cultivated land in the Lower Russian River watershed from 1992 to 2017 increases runoff, therefore accounting for an increase in flood severity.

Sub-Hypothesis Null 2.2: The change of developed land in the Lower Russian River watershed from 1992 to 2017 has no role in the severity of flooding.

Sub-Hypothesis Alternate 2.2: The increase of developed land in the Lower Russian River watershed from 1992 to 2017 decreases permeability, which in turn increases runoff, and accounts for an increase in flood severity.
Methods

Study Area:

The study area includes the lower portion of the Russian River watershed. The larger watershed in its entirety is 1,485 square miles (3,846 square kilometers), covering portions of both Sonoma and Mendocino Counties in northern California. The lower Russian River watershed covers 541 square miles (1401 square kilometers), all within Sonoma County. The watershed has many different land covers, ranging from coastal redwood forests, chaparral, hilly grassland, agriculture, vineyards, suburban development, and others. The watershed includes both coastal mountains in the west, the Mayacamas Mountains to the east, and the valley between the two ranges.

Figure 1: Lower Russian River Watershed Map

Data:

Images for land use/land cover classification used in this study are imagery from Landsat 4, 5, (TM) and 8 (OLI), having a 30 meter x 30 meter resolution for 1992, 1996, 2001, 2006, 2011, and 2016. It should be noted that Landsat 7 data is avoided due to the system malfunctions causing there to be lapses
in images. To aid in classifications, the classifications done by the Multi-Resolution Land Cover Consortium (MRLC) for 2001, 2006, and 2011 were used as references when identifying classes. Hydrological data includes precipitation rates and totals, gage height, and streamflow, all sourced from the California Department of Water Resources (CDWR). Using that data, flood years are identified when there is an event when the gage height of the river at the Hacienda Bridge (HAC) monitoring site reaches 34.0 feet. Lastly, all precipitation data is taken from the Santa Rosa (STA) monitoring site. All hydrological data is reported on an hourly basis, and each flood event is defined as the hour recorded precipitation starts to the hour when the stage falls below the flood monitoring stage, 31.0 feet.

**Data Analysis:**

To test my hypotheses, the imagery was classified using an unsupervised classification method in Esri ArcGIS Pro into the following categories: water, forested land, barren land, developed land, scrub, herbaceous land, and planted/cultivated land - the same classification schema used by the National Land Cover Database (NLCD). Each unsupervised classification was done using a pixel based classification, and the NLCD 2011 classification schema. While pixel based classification results in a more “salt and pepper” look than object based classification, which takes into account surrounding pixels when determining how it is identified, it ensures that smaller pieces of land are accurately classified. Vineyards specifically, in the region are not always on massive plots of land, and some are small which could result in them being omitted in an object based classification. All default training settings were used, except that the maximum number of classes used is 40. Pixels’ spectral signatures are automatically assessed and grouped with other pixels with signatures the most similar into a maximum of 40 bins. Each of these classes was then cross referenced with the Landsat image used for classification alongside aerial photos.
when needed, and was identified as one of the classes included in the schema. Once all of the output classes are identified, any clear misclassifications were adjusted manually.

Using the number of hours above flood stage as the dependent variable, and precipitation total, hours of precipitation, river stage at the start of the precipitation event, and the land cover percentage as independent variables, SPSS was used to run a multiple linear regression. There was one regression run for each land cover class, as well as one for the total natural land cover and one for the total of human-impacted land cover. This shows the impact of each individual land cover on the flood event, as well as the two broader categories. For years in which there was a flood that fall between two classified years, the land cover data is attributed from the previous classification.

**Results**

Linearly plotting the land cover percentages over time shows the trends of each specific cover. Developed land, cultivated land, and forested land are all increasing, while herbaceous land and shrubland are decreasing (Figure 2). Both water and barren cover show next to no change over the study period (Figure 2). These combines trends can also be seen in a graph comparing the natural land cover and human impacted cover (Figure 3), where there is a decreasing trend for natural land cover and an increasing trend for human-impacted land cover. Classifications for 1992, 1996, 2001, 2006, 2011, and 2016 are shown in Figures 4, 5, 6, 7, 8, and 9, respectively.
Figure 4: Lower Russian River Watershed 1992

Figure 5: Lower Russian River Watershed 1996
Figure 6: Lower Russian River Watershed 2001

Figure 7: Lower Russian River Watershed 2006
Figure 8: Lower Russian River Watershed 2011

Figure 9: Lower Russian River Watershed 2016
A total of seven multiple regressions were run, five specific to a single land cover class, and two grouped as either natural or human-impacted land cover. Of the five cover-specific regressions, forested land, shrubland, and cultivated land all have p-values which reject the null hypotheses at a 95% confidence level (Table 1), and the other two cover-specific regressions had p-values just outside of the 90% confidence interval (Table 1). Despite not all of the cover-specific null hypotheses being rejected, both of the more generalized null hypotheses were rejected at a 90% confidence level (Table 1).

**Table 1: Multiple Regression Results**

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<th>Developed</th>
<th>Forest</th>
<th>Shrubland</th>
<th>Herbaceous</th>
<th>Cultivated</th>
<th>Natural</th>
<th>Human Impacted</th>
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<td>R- Square</td>
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<td>0.731</td>
<td>0.579</td>
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<td>Regression p-Value</td>
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<td>0.022</td>
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<td>0.104</td>
<td>0.032</td>
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<td>Regression Coefficient</td>
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<td>-2.172</td>
<td>-0.029</td>
<td>3.923</td>
<td>-2.078</td>
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**Discussion**

The results of this study rejected the null hypotheses regarding the change in forested land, shrubland, cultivated land, natural land cover, and human impacted land cover with a 90% or higher confidence interval, while the null hypotheses focused on developed land and herbaceous land could not be rejected at that confidence interval. This means that this study supports the hypotheses that increases in cultivated land, human impacted land, and forested land result in an increase in flood severity, while a decrease in cultivated land and natural land have similar outcomes. None of the individual regressions had very high r-squared values, however this is to be expected because land use and land cover are not the
only factors which would have an impact on the flooding, and the number of sample points was relatively low. Having thirteen floods over the study period, means that there were only 13 data points for regression analysis, limiting the strength of the correlation. One possibly way to get a better understanding of the effects of land cover change in the lower Russian River watershed would be to lower the cutoff stage to define an event and focus on more than just flood events. By lowering the threshold to constitute an event, there would be more data, and could produce less temporal gaps in the data.

The accuracy of these classifications is inherently limited to the availability of usable multispectral imagery of the study area. Landsat was used, and its 30x30 meter spatial resolution is one of the most hindering factors. For this watershed specifically, this posed to be an issue in spectrally differentiating herbaceous and planted/cultivated land. In this region, the cultivated land is primarily vineyards, and are often in areas with herbaceous land, and the rough spatial resolution results in these two categories having many mixed pixels. Now that SPOT imagery has been released as public access, with 20x20 meter resolution, that could prove to be more effective, however SPOT has more limited spectral resolution. With fewer infrared bands, SPOT could prove to be less effective in differentiating different types of vegetation, but the higher spatial resolution could be more beneficial.

In addition to the spatial resolution being a limiting factor, the temporal resolution of Landsat imagery posed some issues specific to the region. Vineyards and grasslands would be most spectrally different in the summer months, when the vines are in their growing season and the grass is primarily dead due to lack of water, so these are the prefered months for imagery. Unfortunately, the summer months are also when the marine fog is most prominent, and the 16 day temporal resolution puts a tight limit on the number of summer imaging opportunities available. Due to this temporal resolution, there are few opportunities to have data from days without high cloud/fog cover. For image selection, cloud cover was a priority over the time of the image, resulting in images being taken from different times of the year. These varying times of the year, coupled with drought stress, could also contribute to some
misclassification between forest and shrubland. Having all of the images from the same time of the year would remove that variable from the possible sources of misclassification.

These temporal and spatial limitations could be the cause of a few irregularities in the results. Starting with specific years’ classifications, there are a few findings that seem to be possible errors. Perhaps the most apparent, is the jump from being 12.1% shrubland in 1996 to being 25.4% shrubland in 2001, followed by the drop back to 12.1% in 2006. Being coupled with a 1996-2001 drop in herbaceous land from 40.3% to 26.4%, this could suggest classification errors being the source of the spike of shrubland in 2001. The second result that stands out is the entire dataset for cultivated land. The jump from 8.3% to 15% between 2011 and 2016 seems unrealistic. While there has been a growth of cultivated land, particularly vineyards and some apple orchards, the growth was not up to the rate suggested by the data, suggesting that either 2016 was over-classified, or the other years were under-classified.

Of the rejected null hypotheses, the results supported the alternate hypotheses, except those for forested land. The coefficient for forested land in the regression suggests that an increase in forested land correlates to an increase in flood severity, which goes against expectations; in general, it would be expected for an increase in forested land to reduce flooding.

Future research on the topic could take form in a few different ways. One possible research outlook would be to do a similar study, but with a different type of satellite imagery. Using a satellite with higher spatial resolution, like SPOT, could prove to be beneficial for the strength of the results. Farther in the future, it could be possible to do a similar study along a different timeline once the Sentinel program has been active for long enough to have sufficient temporal coverage. Having more resources to complete the study would also strengthen the outcomes. The restriction to free satellite imagery makes options limited and having the ability to use higher resolution paid imagery, as well as more time for high detail ground truthing and verification of the classifications would produce better results.
The land cover change throughout the watershed has impacts on runoff and flooding, but this study does not include the varying degrees of impact based on distance from the river. For example, development in Rohnert Park, on the southern edge of the watershed still has an impact on runoff and flooding, but development in Windsor, much closer to the river, would have more of an impact. Developing a method for accounting for this discrepancy would make it possible to better understand this relationship.

All of the native land cover types in a given area are adapted to live together, and human impact on the land results in disturbances to this balance. Water runoff and flooding is just one of many different impacts this change has on a system. Populations are still increasing, but that is not to mean that natural land cover should not be restored, or that it can not be restored. The natural vegetation cover helps reduce water runoff, increasing the time it takes for a flood to begin, and decreasing the peak stage, reducing the end severity of the flood. Further development may be inevitable due to the social and economic demands on the region, but it is crucial to consider both the original and destination land cover to assess the impacts such change will have not only on a social or economic basis, but the change it will cause to the hydrology and other natural systems as well.
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