Landslide Warning System: Indian River Stream Gauge

Independent Analysis
(Revised 2/7/20 to include Appendix B, Optimizing Critical Factors)

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Abstract

The Indian River stream gauge measures the height of Indian River just upstream of the bridge on Sawmill Creek Road. Indian River lies in a moderate size drainage, and the river rises quickly during periods of heavy rain and recedes quickly when the intensity of the rain diminishes. The stream gauge may serve as a proxy for measuring factors such as total rainfall, rate of rainfall, ground saturation, and others that are more difficult to measure directly. This analysis examines the possible correlation between the rise of Indian River and the occurrence of landslides along Sitka's road system. In a historical analysis of the period 7/2014 through 9/2019, critical factors were identified that flagged 9 high-risk periods, during which 3 landslides occurred. There were 2 landslides during this period that occurred when the stream gauge did not exceed the critical levels identified in this analysis. The goal of this analysis is to help determine whether the Indian River stream gauge can play a meaningful role in a local landslide warning system. This approach may have relevance to other landslide-prone areas with drainage characteristics similar to Indian River.

Indian River stream gauge:
https://water.weather.gov/ahps2/hydrograph.php?wfo=pajk&gage=irva2

Introduction

In recent years, a number of Sitka residents with a mix of outdoor experience and scientific training have noticed that the Indian River stream gauge behavior seems to correlate with periods of elevated risk of landslides. The Indian River watershed is small enough that the river rises quickly during periods of heavy rain, and falls quickly when the intensity of rain diminishes. A number of us have wondered if it would be possible to identify critical values for the rate of rise of the river, and the total rise of the river, that would help identify periods of elevated landslide risk.

It's important to emphasize that this is exploratory work, and that a warning system has not yet been developed. Some Sitka residents believe that a warning system is already in place, for a number of reasons. Some people have been told that a warning system exists, and some conclude that since we have sensors installed on a few mountains that we must have a warning system in place. Also, in analyzing historical data, we are looking at events that have claimed the lives of three people. In discussions about what a warning system might provide in a situation similar or identical to previous conditions, some people may feel that a system should have been in place previously. We should all be aware of these issues when discussing this kind of historical analysis.

Method

Here is a summary of the approach I have taken with this analysis. If you are interested in seeing the code, it is posted at: https://github.com/ehmatthes/sitka_irg_analysis

- I compiled a list of known slides near the Sitka road system.
    - I made a list of each slide I could remember, and validated each one through news reports.
    - The date and time of the slide is recorded as accurately as possible.
- I compiled a continuous record of the Indian River stream gauge data from 7/2014 through 9/2019.
    - The data from 7/2014 through 2/2016 includes hourly readings.
    - The data from 2/2016 through 9/2019 includes readings taken in 15-minute increments.
- I identified two critical factors to scan the historical data for:
    - Critical Rate
        - We know that slides tend to occur during periods of intense rainfall. This shows up in stream gauge data as a rapid increase in the height of the river.
        - This factor is identified in the code as M_CRITICAL, for "critical slope". The current analysis looks for a sustained slope of 0.5, which corresponds to the river rising at a rate of 6 inches per hour.
    - Critical Rise
        - We know that slides tend to occur when enough rain falls to saturate the slopes. This shows up in stream gauge data as the total rise over a period of hours.
        - This factor is identified in the code as RISE_CRITICAL. The current analysis looks for a total rise of 2.5 feet.
    - These values were chosen based on having watched the stream gauge closely during periods of intense rain that led to slides, and periods of intense rain that did not lead to slides.
- I wrote code that scans the entire data set, and looks for moments where the rate of rise and the total rise exceed these critical values. These moments are referred to as "critical points". For a critical point to occur, the rate of rise must have averaged at least 6 inches per hour over the period of time that led to a rise of at least 2.5 feet.
    - When a critical point is identified, 24 hours of data on each side of the critical point are pulled from the data set for further analysis.
    - For each critical point, a plot is generated showing the stream gauge data over the 48-hour period. All critical points are plotted in red, and non-critical points are plotted in blue.
        - If a known slide occurred during this 48-hour period, a vertical line is drawn when that slide is likely to have occurred. The line is labeled with the name of the slide, along with its date and time.
        - A "notification time" is shown also. This is the amount of time between the first critical point, and the time of the slide.
    - A summary is generated listing the following:

        - How many critical events were identified.
        - How many critical events were correlated with known slides. (True Postives)
        - A list of the slides associated with critical events.
        - How many critical events were not correlated with known slides. (False Positives)
        - How many slides occurred that were not associated with critical events. (False Negatives)
            - A 48-hour plot is generated for these slide events as well.
        - A list of known slide events that occurred outside the period represented by the data set.
    - All data processing is done in UTC, but plots and reports display AKDT or AKST.

Results

Here is the raw summary of the data:

```
--- Final Results ---

Data analyzed from: 07/14/2014 to 10/01/2019
  Critical rise used: 2.5 feet
  Critical rise rate used: 0.5 ft/hr
  9 plots generated

Notifications Issued: 9

True Positives: 3
  South Kramer Slide 8/2015 - Notification time: 41 minutes
  HPR Slide 9/2017 - Notification time: 60 minutes
  Medvejie Slide 9/2019 - Notification time: 35 minutes

False Positives: 6
  09/06/2014 21:00:00
  09/13/2016 13:00:00
  09/15/2016 05:45:00
  09/27/2017 03:15:00
  11/17/2018 21:49:00
  01/26/2019 14:30:00

False Negatives: 2
  Starrigavan Slide 9/2014 (time of slide unknown)
  HPR Slide 9/2016 (minor slide)

Slides outside range: 2
  Beaver Lake Slide 11/2011 (wind and snowmelt?)
  Redoubt Slide 5/2013 (not on Sitka road system)
```

All generated plots are included in the appendix.

Confusion Matrix

The following table summarizes the results in a confusion matrix:

	Notification not issued	Notification issued
No slide occurred	-	6
Slide occurred	2	3

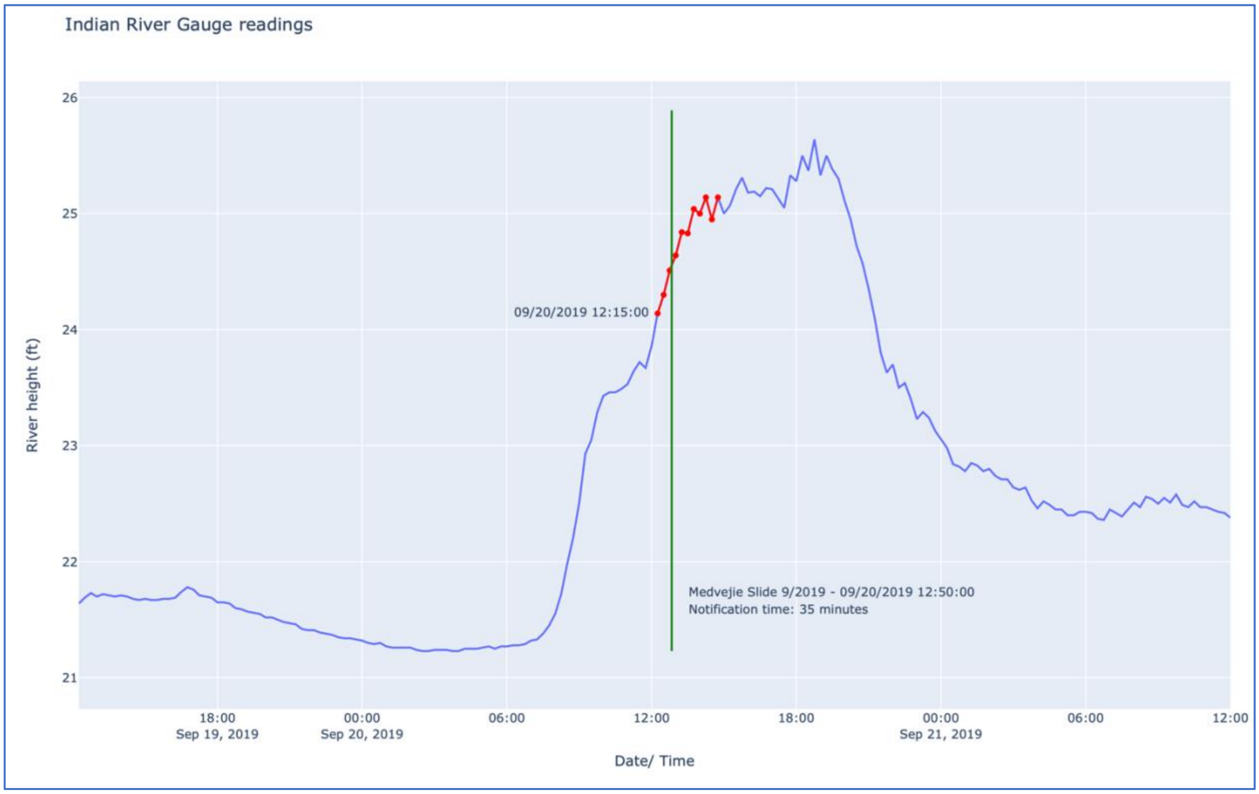
Discussion

For historical analysis, there isn't a significant difference between analyzing hourly data and 15-minute data. For each dataset, we consider a random point in the dataset and ask how far we'd have to look back to identify that this was a critical point. Using the parameters chosen for this analysis, we need a total rise of at least 2.5 feet, with an average rate of rise of 6 inches per hour. This works out to looking back 5 hours for each data point. In the hourly data sets, the code examines the previous 5 data points, calculating average rate of rise and total rise. If any of these previous points meet these critical values, the current point is considered a critical point. In the 15-minute data set, the code examines the previous 20 data points. The number of points to look back over is calculated, so the code should work for either of these data sets without modification. The code does assume that all readings within a data file have a consistent reading interval.

When I originally attempted this analysis, I tried to include other factors such as wind speed and temperature. I got bogged down in working with too many data sets, and couldn't finish the analysis in the time I had available. When I began this more recent round of analysis, I decided to just focus on the two factors, rate of rise and total rise of the stream gauge readings. This made the analysis much more straightforward. I believe some of the false positives could be eliminated by including some of these other factors. For example, slides are unlikely to occur when the ground is frozen. Including a rule to ignore any data points during periods of sufficiently cold weather might eliminate some of the critical points during the winter months.

Example True Positive Notification

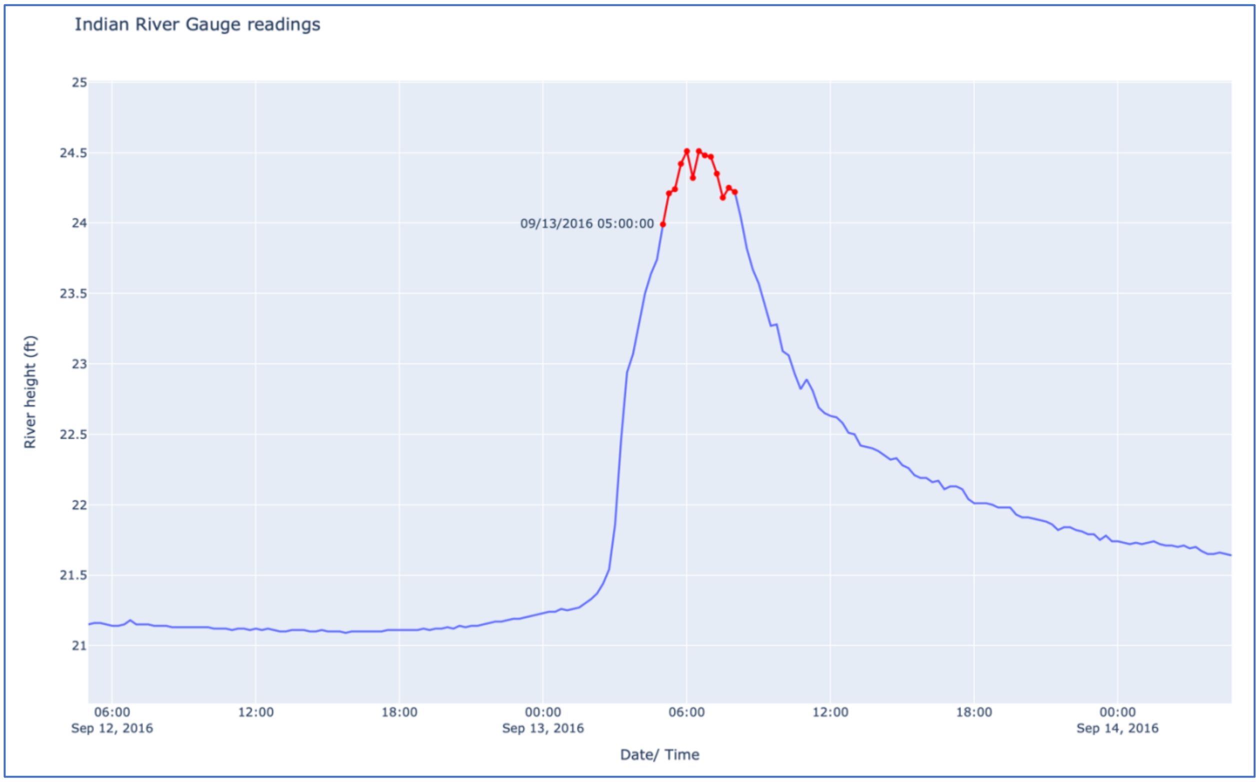
Here's the plot for a critical period that occurred on September 20, 2019:



In this 48-hour period, the river began to rise around 7:00 in the morning. The first critical point occurred at 12:15 pm. It's interesting to note that this point occurred after a slight pause in the river's rise. The rate of rise had been critical before this time, but the total rise was not critical until 12:15. The slide occurred "shortly before 1:00 pm", according to a KCAW news article. I believe we can also pinpoint the time of this slide because it caused a city-wide power outage for a short period of time.

Example False Positive Notification

A critical event occurred on 9/13/2016:

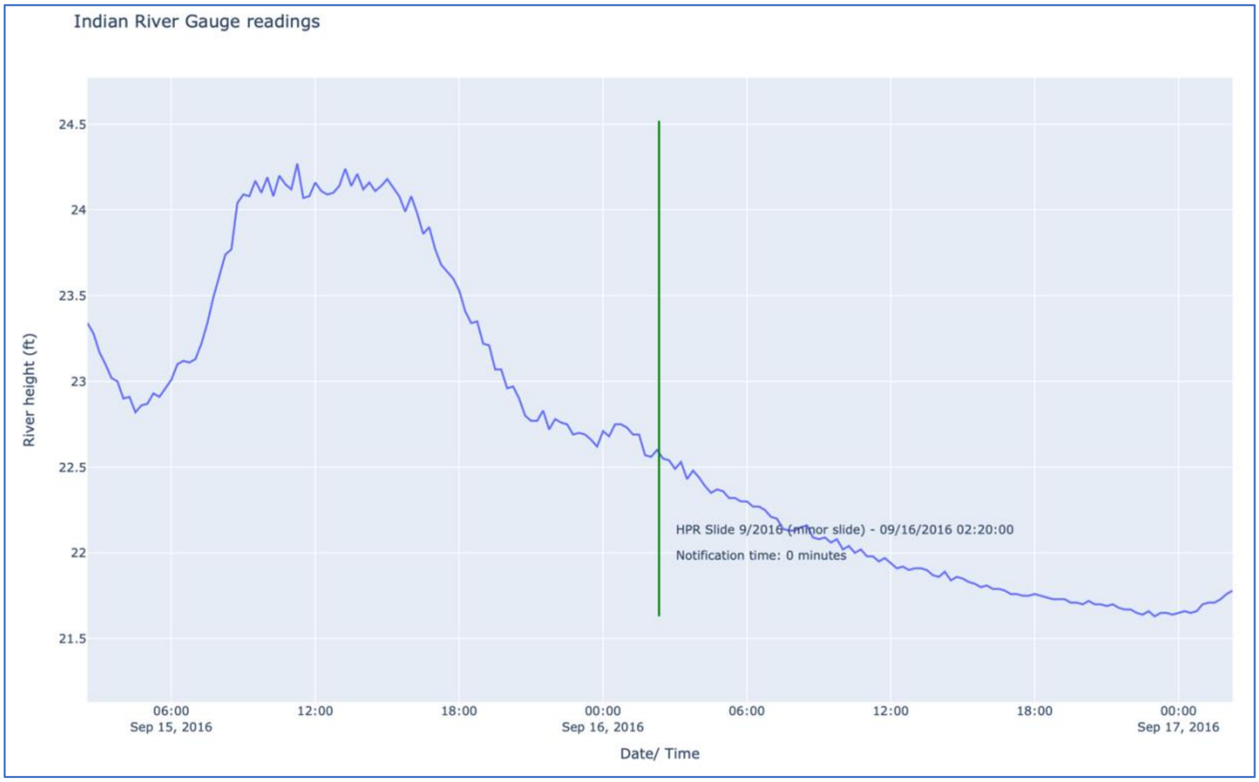


The river started rising shortly after midnight, and the first critical point occurred at 5:00 in the morning. The river stayed critical until 8:00 am, but no slide that I'm aware of occurred on this date. It's possible a minor slide occurred that I'm not aware of; it's important to make sure the list of known slide events is complete before fully assessing the results of this analysis.

It's tempting to look for values of the critical factors that would eliminate an event like this, because we know after the fact that no slide occurred. It's important to realize, however, that during this kind of rainfall event a good portion of the population of Sitka are on edge. This is particularly true for people living near areas that are prone to sliding. We may be able to determine after the fact that no slide occurred, but it's impossible to say what another half hour of heavy rain would have done. Clearly we need to find critical values that rule out too many notifications, but we also need to be mindful of periods that are right on the edge of criticality.

Example False Negative

On September 16, 2016, a small slide occurred on a disturbed hillside along HPR. This slide was not associated with a critical event:

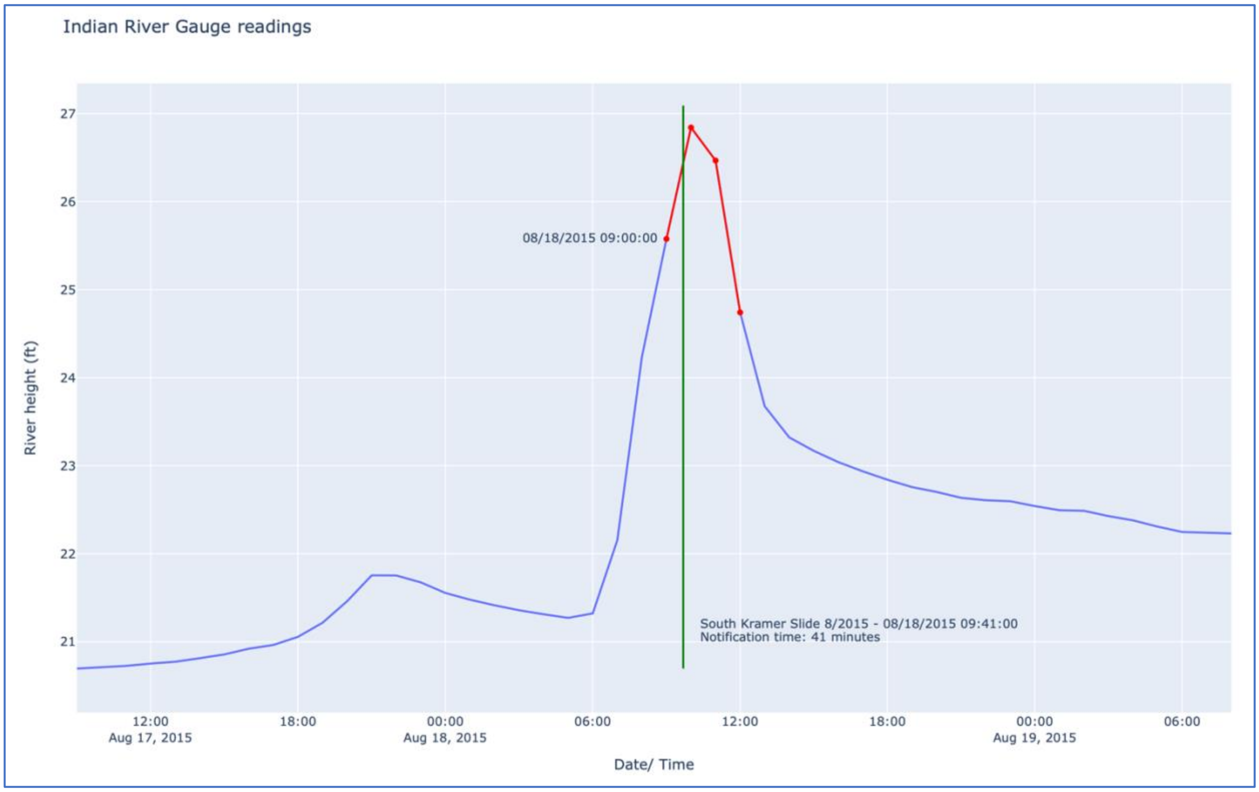


It's not clear whether this kind of slide should be included in the dataset, or whether it should be categorized differently than other slides. It's interesting to look at the river data at this point, however. The river height was between 24 and 25 feet prior to the slide, but there were no critical points because the river was already high. Since it was already high, it would have to rise to almost record levels to attain another 2.5 feet of new rise. This may suggest refined rules for identifying critical points, which include the current river height as well as rise and rate of rise.

The timing of this slide is also not clear. This slide was reported by a motorist at 2:20 am, but there is little traffic at that time. This is a bound for how late the slide may have occurred, but it could have occurred hours before that.

The Kramer Avenue slide

This is the slide that many people first think of when they consider the impact of landslides on the Sitka community. Here's what the Indian River stream gauge data looked like for the 48-hour period surrounding the Kramer Ave event:



The Kramer Ave slide occurred during a time when only hourly readings were available. The river began to rise shortly after 6:00 am, and the first critical point was reached at 9:00 am. This was about 41 minutes before the slide occurred. I am not aware of more specific times for the other slides that occurred on this same date, so they are not shown as separate events on this chart.

Further analysis

If this analysis seems to be useful in the development of a landslide warning system, there are a number of steps to take to refine the analysis:

- Improve the list of known slides.
    - Add any slides that are missing.
    - Categorize the severity of the slides.
    - Note whether each slide occurred in a disturbed or undisturbed area.
    - Include an assessment of the reliability of the timing of the slide. This can probably be done best with an assigned time, an earliest time, and a latest time.
    - Include any references needed to establish the time, including social media posts about slide events. Power outage times are also helpful; I wonder if the electric department maintains a list of outages with precise times.
- Review the analysis.
    - I made numerous mistakes in the process of doing this analysis; it's quite possible that important mistakes remain in the analysis. For example some datasets are in UTC, some in AKDT, and some in AKST. I believe I handled all the conversions correctly, but that should be verified.
- Include other factors.

    - Current river height.
    - Temperature, perhaps over the previous 7 days?
    - Wind speed and direction.
- Find optimal critical factors.
    - It would be good to run the analysis repeatedly with different combinations of critical factors. We want to look at the confusion matrix produced by each set of factors, while watching how those factors affect the notification time for known slides. There's no use in finding perfect historical critical factors that lead to minimal notification time.
- Explore real-time visualization options.

The role of the stream gauge in a landslide warning system

Many Sitka residents already look at the Indian River stream gauge readings during periods of heavy rain. Some people have a reasonable idea what to look for, while others start to worry any time the river starts to rise. While we need to avoid any message that landslides can be predicted with certainty, we also have a responsibility to share some information about how to assess the critical factors that help determine the risk of an imminent slide.

When considering the impact of a warning or information system, it's also critical to understand the anxiety that many people in the community feel any time it rains hard. There are a significant number of people who begin to get anxious when it rains hard for ten minutes. These people have no context for distinguishing between a routine heavy rain event, and an extended heavy rain event that may lead to slides. There is tremendous value not just in notifying people when slides may be imminent, but also in helping people let go of anxiety when there is no objective reason to be concerned about slides.

I have had numerous conversations with people involved in this project, and residents with different areas of expertise, about how we might incorporate the stream data into an overall landslide information system. We want to present the data in real time, and give people contextual information that helps them make sense of the data in real time. Here's one of the clearest suggestions I've heard so far:

- Present real-time data on a graph that includes historical data from critical events. The real-time data would be dark, and the historical data would be light.
    - Rather than seeing a 1-foot rise in the river height at a critical slope with no context, people would see that most historical events have occurred with a much larger rise. This would tell people to continue watching the gauge, but help them understand that a slide is probably not immediately imminent.
    - Identify critical values, and show how close current readings are to these critical values. This requires hard decisions on the part of people in this group, but without these values people are going to make these decisions on their own. Some people will get extremely anxious any time the factors are anywhere near critical; others will underestimate the severity. If there are critical values that can be identified, there is good reason to consider doing so. Such factors may include the lowest values that have been observed in correlation with a slide. These factors could be stated numerically, or shown visually on a real-time chart.

Building a real-time visualization system

I have tried to build a real-time visualization of stream data, but as soon as I started to do so I found that the real-time data is less reliably available than the historical data. I don't want to start making a real-time system that's built on unreliable data. I have communicated with a number of the people involved in maintaining the stream gauges and the associated datasets, but I don't want to bother them further for my own individual analysis. If this project is worth taking further, I would prefer to contact the people responsible for this data with the backing of this group.

I would want to know the best source for real-time data, how reliable it is, and how consistent the data format is. I also want people to know how important this data is, and make sure they understand what's being done with this data.

Other stream monitoring sites

It may be worth considering monitoring the heights of other rivers along the Sitka road system. There are some critical characteristics of Indian River that may contribute to its usefulness in a landslide monitoring system:

- Its watershed is large enough to be representative of local weather, and small enough to be uninfluenced by non-local weather.
- There are no lakes along the river.

It may be interesting to collect and analyze stream gauge data from Starrigavan Creek, Cascade Creek, and Medvejie River. Starrigavan and Cascade Creek do not have lakes; Medvejie does, which may make it less helpful in monitoring the behavior of new rainfall in the associated watershed.

Conclusions

There seems to be enough correlation between the behavior of the Indian River stream gauge readings and the probability of landslides occurring to warrant further investigation, and to warrant including this data in the overall warning or notification system. The stream data does not take the place of more specific data such as mountaintop saturation readings, but it may provide a compelling proxy for a number of these factors. This gauge is also relatively accessible; if the data does prove to be valuable, it may be worthwhile to invest further in the reliability and accuracy of this gauge.

Appendix A: Summary of Known Slide Events

The following is a list of slides that have occurred along the Sitka road system since 2011. For each slide event, the date and most accurate time available is listed, along with a description of the slide location. Links to news articles and other resources related to each slide are also listed, when available. This list may not be complete, and should be further validated.

Beaver Lake Slide 11/2011 (wind and snowmelt?)

11/12/2011 19:00:00

Beaver Lake, Bear Mountain shoreline

- https://www.kcaw.org/2011/12/19/mass-wasting-event-destroys-popular-sitka-trail/

Redoubt Slide 5/2013 (not on Sitka road system)

05/13/2013 19:00:00

Redoubt Lake, near Redoubt Lake Cabin

- https://www.kcaw.org/2013/05/13/couple-escapes-as-landslide-destroys-cabin/

Starrigavan Slide 9/2014 (time of slide unknown)

09/18/2014 20:00:00

Starrigavan Valley

- https://www.kcaw.org/2014/09/24/landslide-destroys-starrigavan-restoration-projects/
- http://www.sitkanature.org/wordpress/2014/09/26/starrigavan-landslide/

South Kramer Slide 8/2015

08/18/2015 17:41:00

South end of Kramer Ave

- https://www.adn.com/alaska-news/article/3-missing-after-heavy-rain-prompts-landslides-sinkhole-sitka/2015/08/18/
- https://www.kcaw.org/2015/08/18/three-landslides-prompt-sitka-to-declare-state-of-emergency/
- https://www.cityofsitka.com/documents/Sitka_SKramerLandslideReport.pdf

HPR Slide 9/2016 (minor slide)

09/16/2016 10:20:00

HPR, near Davidoff Street

- https://www.kcaw.org/2016/09/16/small-mudslide-generates-big-response-in-sitka/

HPR Slide 9/2017

09/04/2017 20:00:00

HPR, near Valhalla Drive

- https://www.kcaw.org/2017/09/04/landslide-closes-halibut-point-road-sitka/
- https://www.kcaw.org/2017/09/04/no-injuries-sitkas-pretty-impressive-labor-day-landslide/

Medvejie Slide 9/2019

09/20/2019 20:50:00

Medvejie Hatchery

- https://www.kcaw.org/2019/09/20/slide-cuts-off-green-lake-road-hatchery-access/

Appendix B: Optimizing Critical Values

The critical values were chosen based on a best guess from having observed the stream gauge during periods of heavy rain. They seem to provide reasonably good results, but it would be good to explore variations on these values and determine if there is a better combination of values.

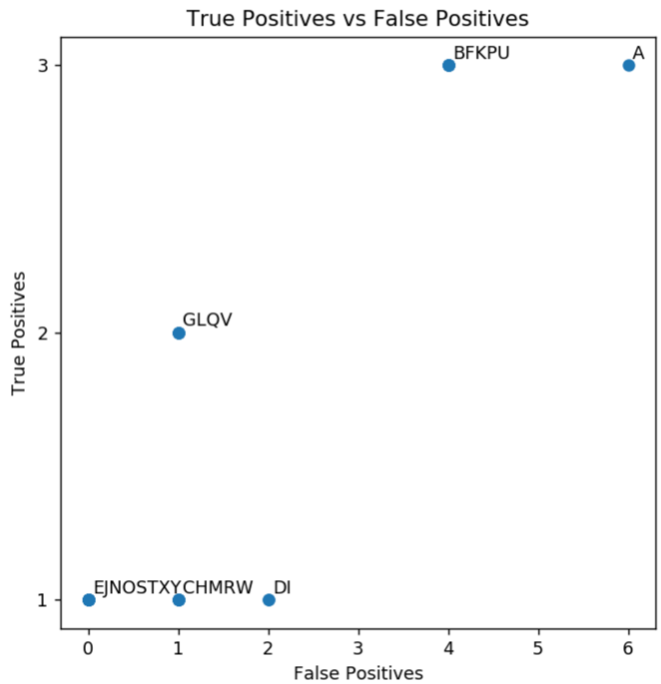
The critical values cannot be fully optimized until the list of known slides has been validated. There will probably be a couple slides whose times can't be accurately identified, and that needs to be taken into account when calculating ROC factors. This may be a small enough data set that precise calculations aren't needed to make the necessary decisions about how to use this data in an information or warning system.

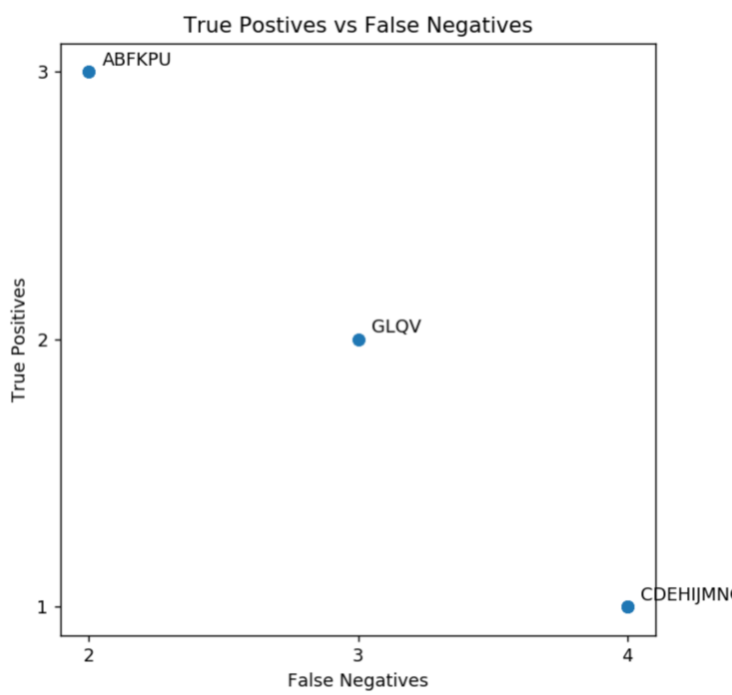
Results

Here are the results of varying the value for the Critical Rate from 0.5 ft/hr to 1.0 ft/hr, and the Critical Rise from 2.5 ft to 3.5 ft:

Trial	**R_C**	**M_C**	**TP**	**FP**	**FN**	**Notification Times**
A	2.5	0.5	3	6	2	[35, 41, 60]
B	2.5	0.625	3	4	2	[-25, 41, 60]
C	2.5	0.75	1	1	4	[41]
D	2.5	0.875	1	2	4	[41]
E	2.5	1.0	1	0	4	[41]
F	2.625	0.5	3	4	2	[5, 15, 41]
G	2.625	0.625	2	1	3	[-25, 41]
H	2.625	0.75	1	1	4	[41]
I	2.625	0.875	1	2	4	[41]
J	2.625	1.0	1	0	4	[41]
K	2.75	0.5	3	4	2	[5, 15, 41]
L	2.75	0.625	2	1	3	[-25, 41]
M	2.75	0.75	1	1	4	[41]
N	2.75	0.875	1	0	4	[-19]
O	2.75	1.0	1	0	4	[41]
P	2.875	0.5	3	4	2	[5, 15, 41]
Q	2.875	0.625	2	1	3	[-25, 41]
R	2.875	0.75	1	1	4	[41]
S	2.875	0.875	1	0	4	[-19]
T	2.875	1.0	1	0	4	[41]
U	3.0	0.5	3	4	2	[5, 15, 41]
V	3.0	0.625	2	1	3	[-25, 41]
W	3.0	0.75	1	1	4	[41]
X	3.0	0.875	1	0	4	[-19]
Y	3.0	1.0	1	0	4	[41]

It would be good to generate an ROC curve based on these results, but it's not clear in this context how to calculate the false positive rate. Here's a plot of TP vs FP, and TP vs FN:





In both of these plots, the upper left is the optimal region; we want the highest possible number of true positives and the lowest number of false positives and false negatives. But we also want reasonable notification times. With the small number of true positives, we would probably only consider models that have 3 true positives in this analysis. That gives us ABFKPU to consider.

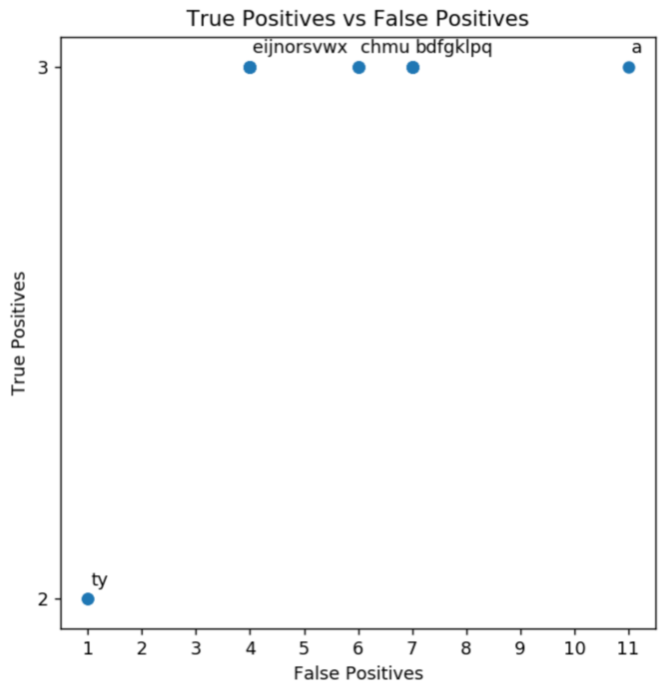
These all have the same number of false negatives, but BFKPU all have one less false positive than A. When we look at notification times, BFKPU are all unsatisfying; one has a negative notification time, and the others have a notification time of 5 minutes for one slide.

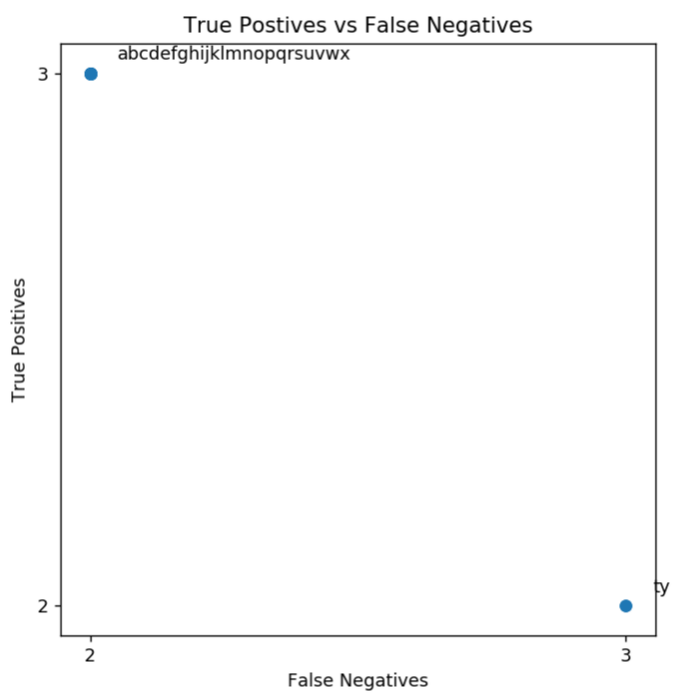
A second round of optimization

If A is the best candidate so far, what happens if we do finer variations around A? Here are the results of varying Critical Rate from 0.375 ft/hr to 0.625 ft/hr, and Critical Rise from 2.25 ft to 2.75 ft:

Trial	R_C	M_C	TP	FP	FN	Notification Times
a	2.25	0.375	3	11	2	[75, 95, 101]
b	2.25	0.4375	3	7	2	[35, 41, 60]
c	2.25	0.5	3	6	2	[35, 41, 60]
d	2.25	0.5625	3	7	2	[50, 75, 101]
e	2.25	0.625	3	4	2	[-25, 41, 60]
f	2.375	0.375	3	7	2	[35, 41, 60]
g	2.375	0.4375	3	7	2	[35, 41, 60]
h	2.375	0.5	3	6	2	[35, 41, 60]
i	2.375	0.5625	3	4	2	[15, 20, 41]
j	2.375	0.625	3	4	2	[-25, 41, 60]
k	2.5	0.375	3	7	2	[35, 41, 60]
l	2.5	0.4375	3	7	2	[35, 41, 60]
m	2.5	0.5	3	6	2	[35, 41, 60]
n	2.5	0.5625	3	4	2	[15, 20, 41]
o	2.5	0.625	3	4	2	[-25, 41, 60]
p	2.625	0.375	3	7	2	[35, 41, 60]
q	2.625	0.4375	3	7	2	[35, 41, 60]
r	2.625	0.5	3	4	2	[5, 15, 41]
s	2.625	0.5625	3	4	2	[15, 20, 41]
t	2.625	0.625	2	1	3	[-25, 41]
u	2.75	0.375	3	6	2	[5, 15, 41]
v	2.75	0.4375	3	4	2	[5, 15, 41]
w	2.75	0.5	3	4	2	[5, 15, 41]
x	2.75	0.5625	3	4	2	[15, 20, 41]
y	2.75	0.625	2	1	3	[-25, 41]

Here are the TP vs FP and TP vs FN plots:



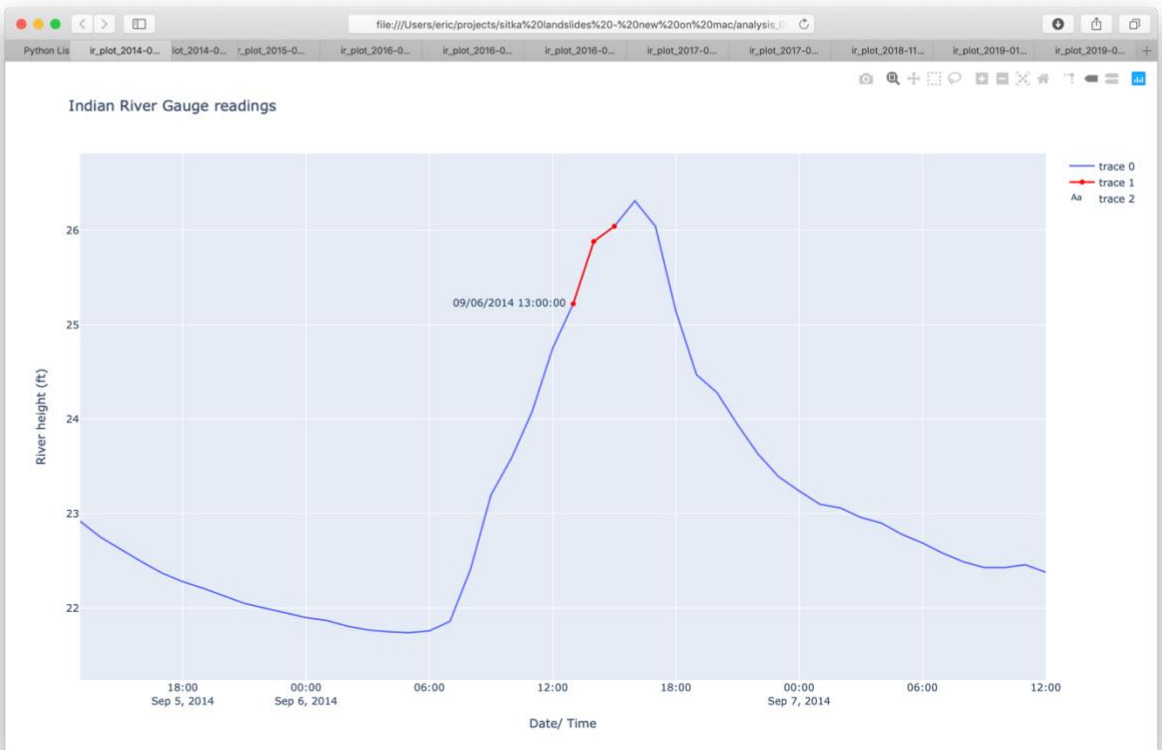


Looking at the values that result in 3 true positives, trials [eijnorsvwx] result in 4 false positives. Of these, trials [insx] have notification times of 15, 20, and 41 minutes. Trials [chm] have 6 false positives, but they result in notification times of 35, 41, and 60 minutes. (The original critical rates match those of trial m.) All the trials mentioned here result in 2 false negatives.

Appendix C: Plots for all critical events

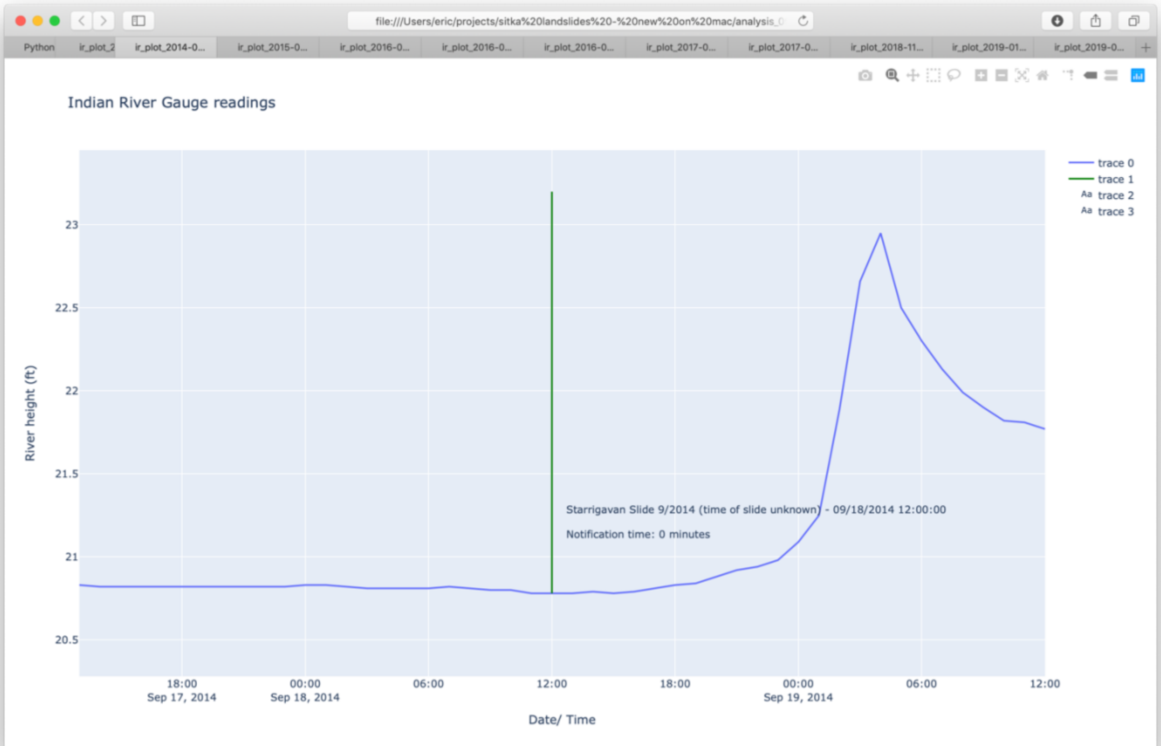
This appendix includes all 48-hour periods around critical points, and also 48-hour periods around known slides that are not associated with critical points. The full set is included here because it can be helpful to see what the stream gauge data looks like during a variety of critical periods. You can find these images online at:
https://github.com/ehmatthes/sitka_irg_analysis/tree/master/current_ir_plots

9/6/2014



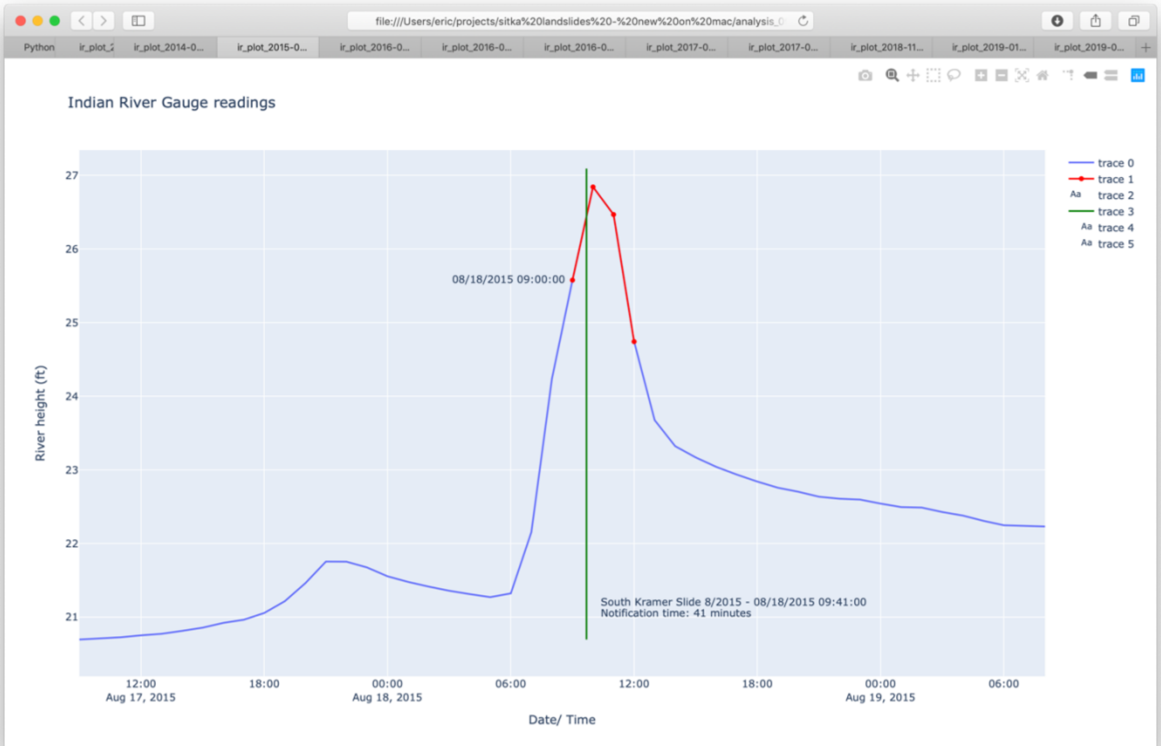
9/2014

There was a large slide in the Starrigavan valley in September of 2014. I am not clear on the date of this slide. It would be good to place this slide more accurately, and look at the stream gauge data around the time of the slide.

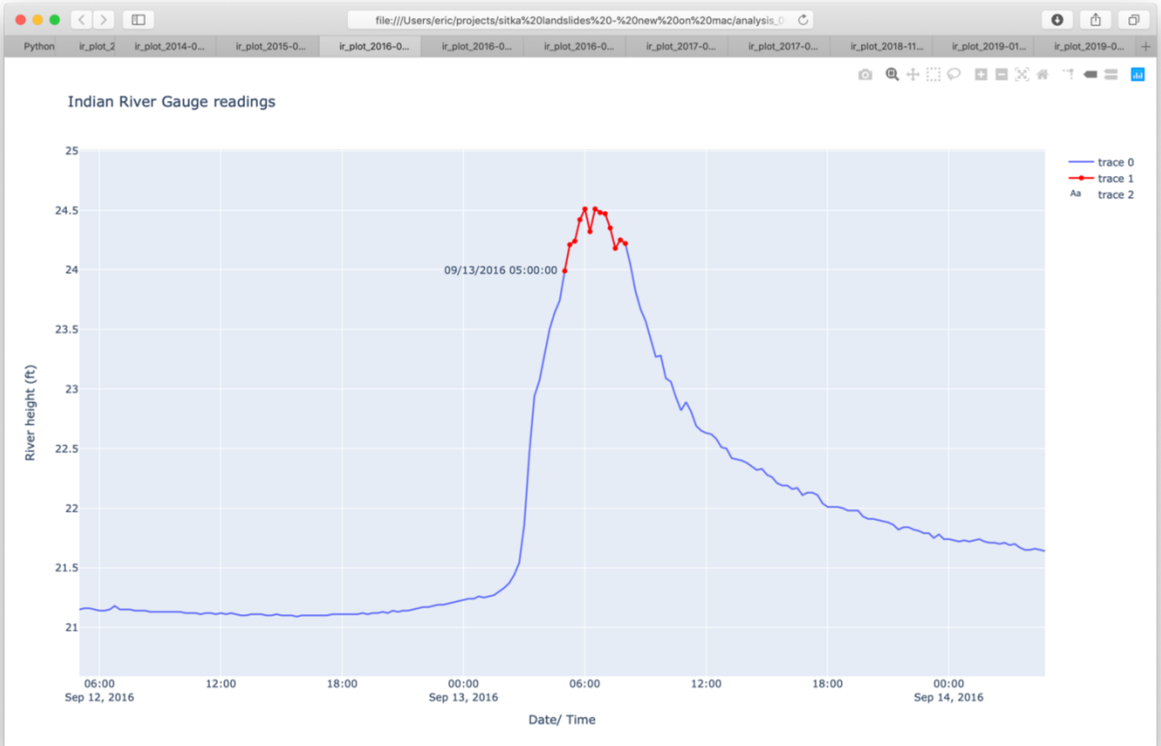


8/18/2015

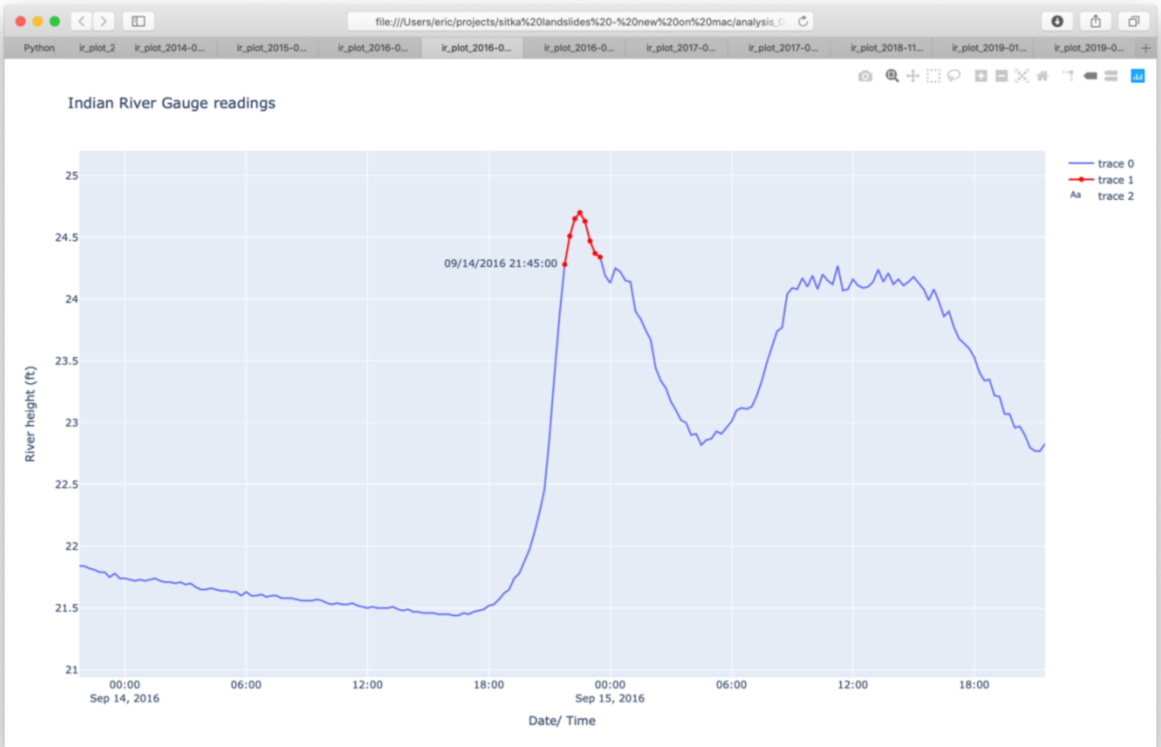
Kramer Avenue Slide



9/13/2016

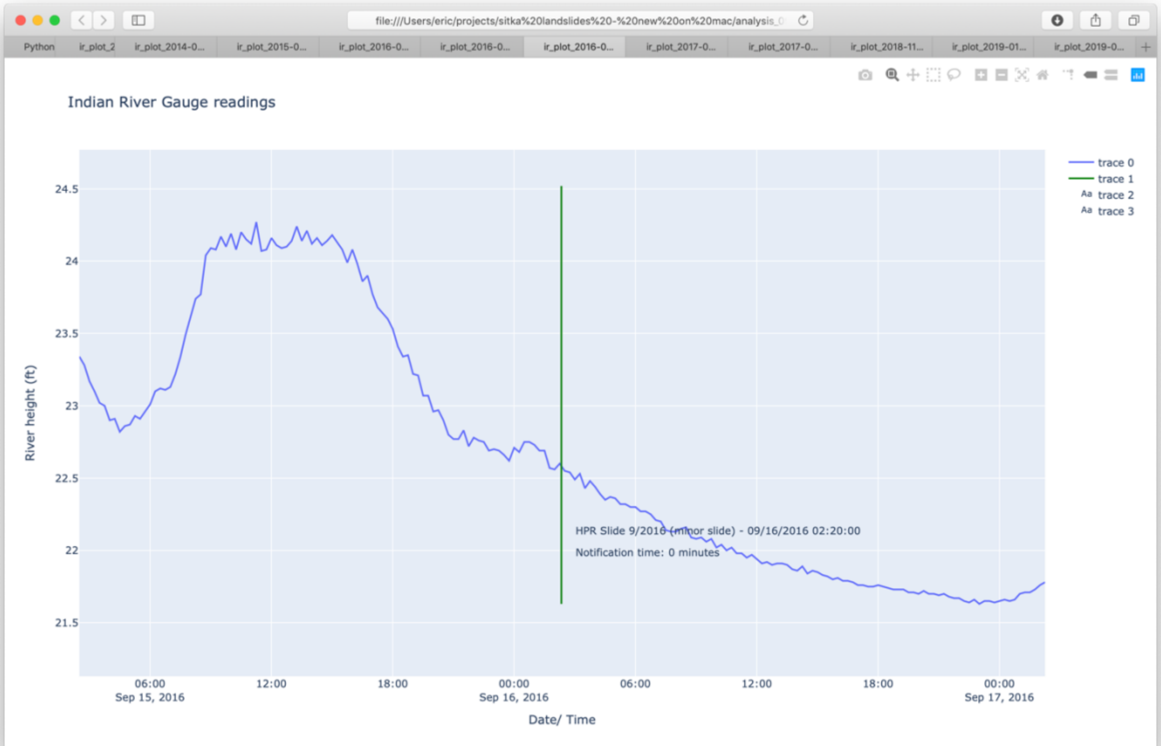

file:///Users/eric/projects/sitka%20landslides%20-%20new%20on%20mac/analysis
Indian River Gauge readings
River height (ft)
Date/ Time
09/13/2016 05:00:00
trace 0
trace 1
trace 2
25
24.5
24
23.5
23
22.5
22
21.5
21
06:00
Sep 12, 2016
12:00
18:00
00:00
Sep 13, 2016
06:00
12:00
18:00
00:00
Sep 14, 2016

9/14/2016


file:///Users/eric/projects/sitka%20landslides%20-%20new%20on%20mac/analysis_
Indian River Gauge readings
trace 0
trace 1
trace 2
09/14/2016 21:45:00
River height (ft)
25
24.5
24
23.5
23
22.5
22
21.5
21
00:00
Sep 14, 2016
06:00
12:00
18:00
00:00
Sep 15, 2016
06:00
12:00
18:00
Date/ Time

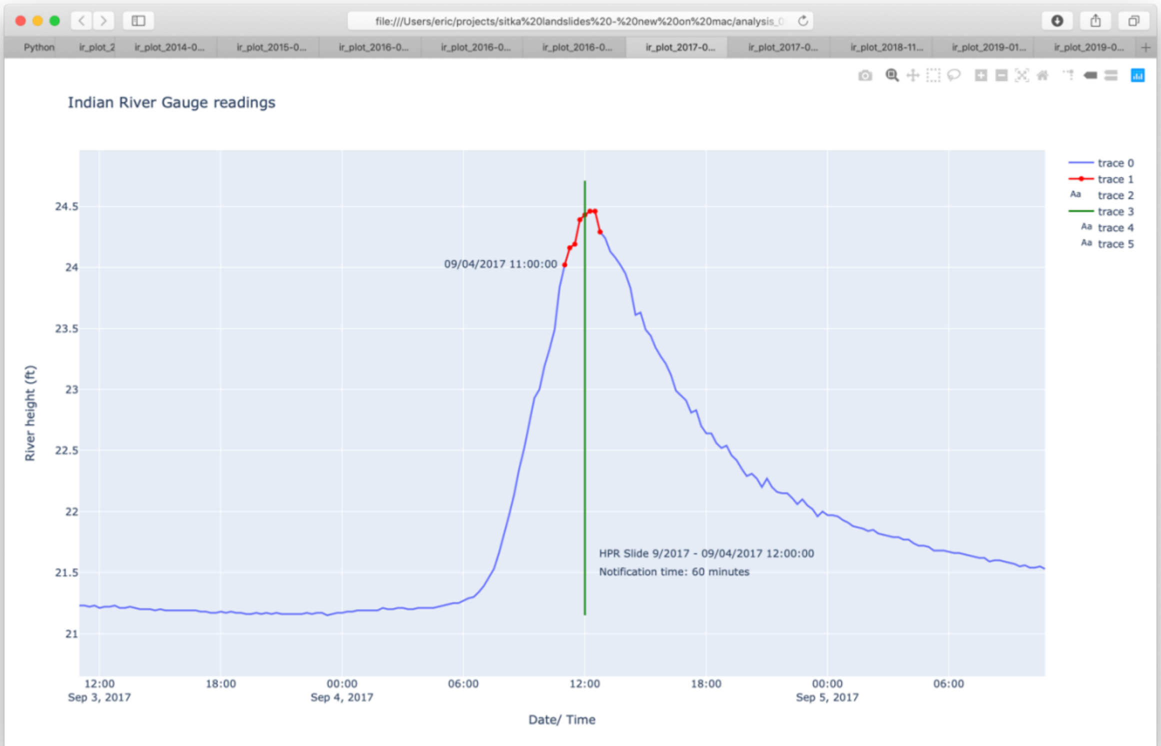
9/16/2016

Minor slide in a disturbed area along HPR; unclear time of slide

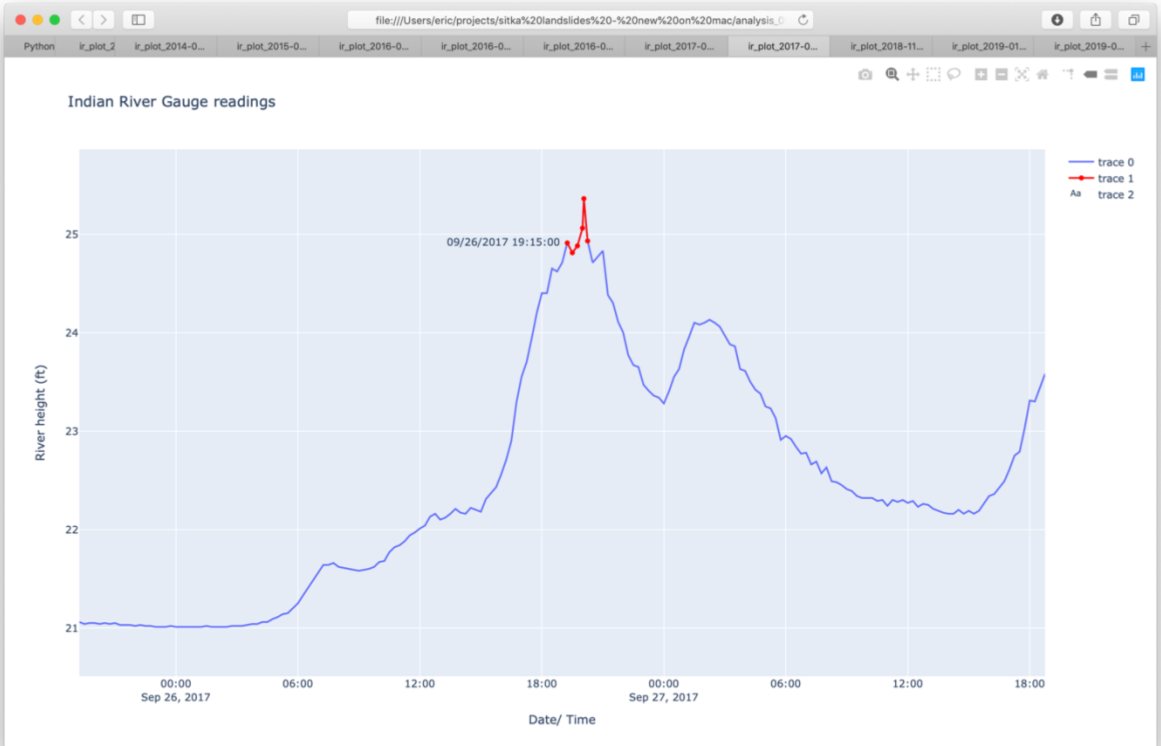


9/4/2017

A slide blocked all traffic on HPR.

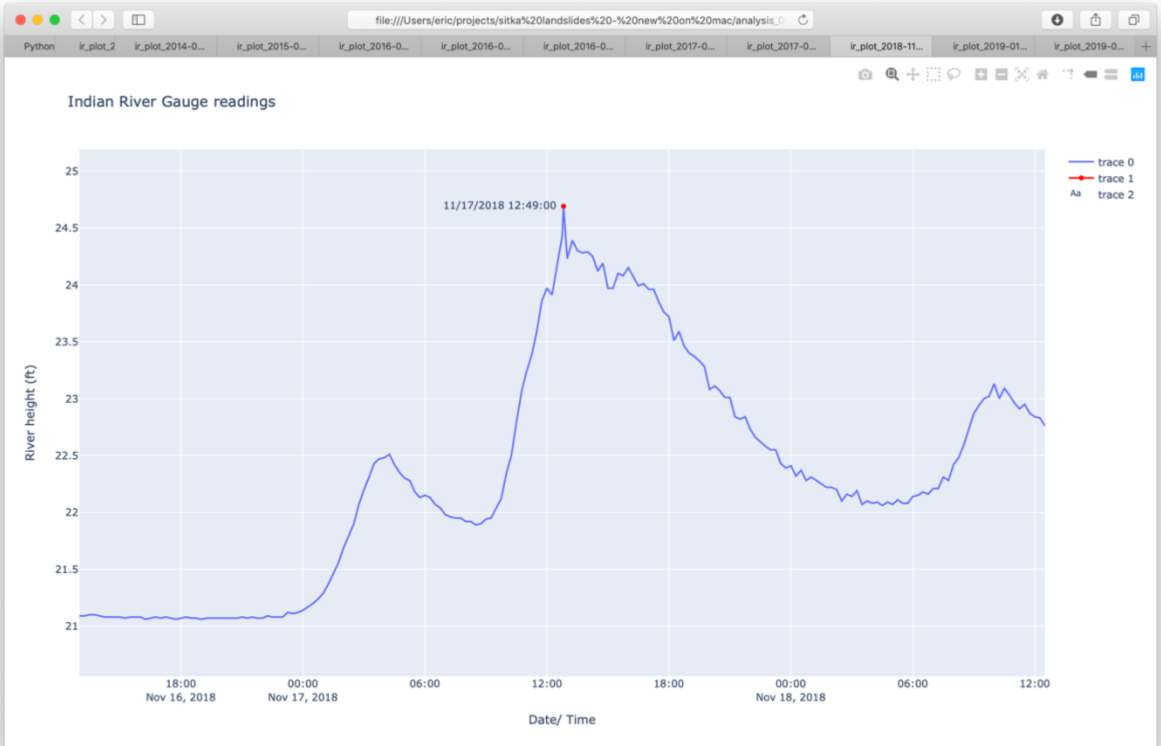


9/26/2017



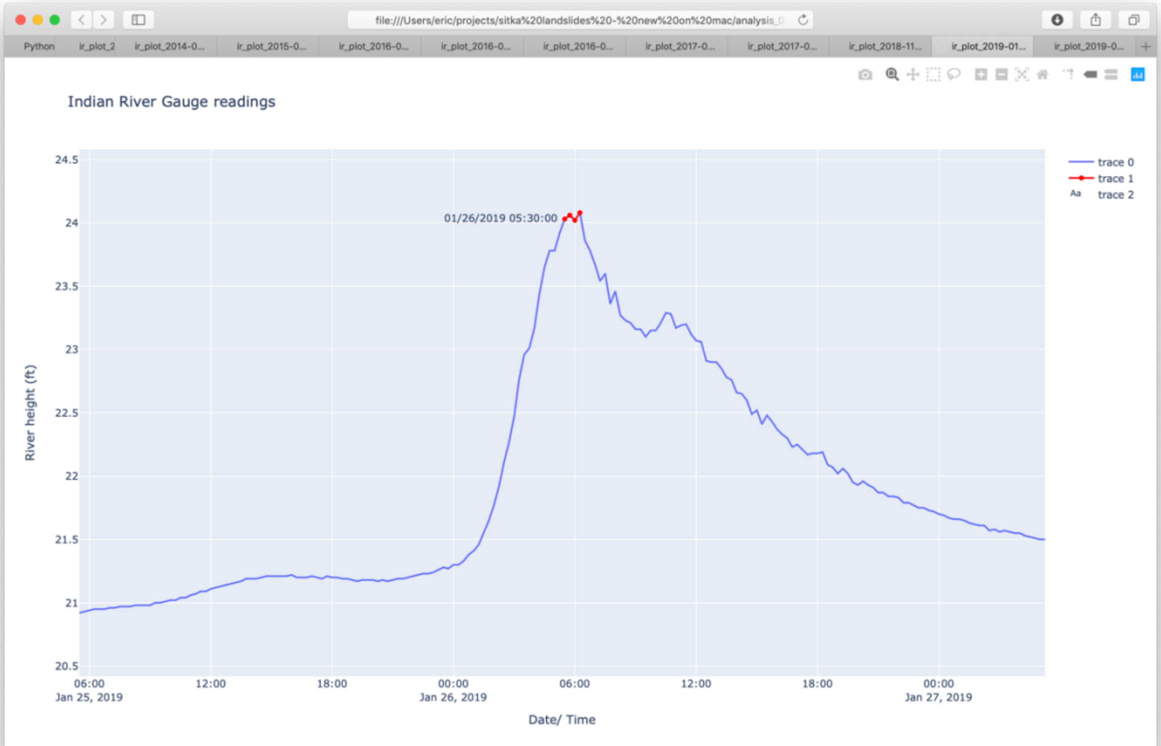
Indian River Gauge readings
09/26/2017 19:15:00
trace 0
trace 1
trace 2
River height (ft)
25
24
23
22
21
00:00
Sep 26, 2017
06:00
12:00
18:00
00:00
Sep 27, 2017
06:00
12:00
18:00
Date/ Time

11/17/2018



file:///Users/eric/projects/sitka%20landslides%20-%20new%20on%20mac/analysis_
Indian River Gauge readings
11/17/2018 12:49:00
trace 0
trace 1
trace 2
River height (ft)
25
24.5
24
23.5
23
22.5
22
21.5
21
18:00
Nov 16, 2018
00:00
Nov 17, 2018
06:00
12:00
18:00
00:00
Nov 18, 2018
06:00
12:00
Date/ Time

1/26/2019



Indian River Gauge readings
24.5
24
23.5
23
22.5
22
21.5
21
20.5
River height (ft)
01/26/2019 05:30:00
06:00
Jan 25, 2019
12:00
18:00
00:00
Jan 26, 2019
06:00
12:00
18:00
00:00
Jan 27, 2019
Date/ Time
trace 0
trace 1
trace 2

9/20/2019

A slide blocked Green Lake Road just north of the Medvejie Hatchery.