STREAM & FLOODPLAIN RESOURCE MANAGEMENT Natural Systems Design RIVER, COASTAL, & BASIN SCIENCE & ENGINEERING


Photo courtesy of Skagit County

Skiyou Rock Removal Impact Analysis

Skagit River

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INTRODUCTION

Natural Systems Design, Inc. (NSD) was contracted by Skagit County Public Works Natural Resources Department to conduct a feasibility study for removal of the remnants of a rock revetment in the Skiyou Reach of the Skagit River at River Mile (RM) 27, approximately three miles east of the city of Sedro-Woolley. The study includes a detailed hydraulic analysis to examine the effect the rock may be having on bank erosion and salmon habitat, and a geomorphic analysis to project future trends of channel migration and associated risk to infrastructure and private property from erosion. The rock in question aligns with the 1969 alignment of the river's right bank (looking downstream) and alignment of the Skagit County parcel boundary, thus was originally placed as a revetment on the river's right bank. The revetment failed to stop the northwesterly migration of the Skagit River since 1969 which has left the rock abandoned in the main channel. Currently, the rock is aligned approximately 40 degrees across the channel (0 degrees being directly upstream), where it extends across the mainstem of the Skagit River in two distinct intact segments. Because of this alignment, the rock acts like a bend-way weir that re-directs lower flows in the river toward the left bank (southeast), immediately upstream of a meander bend at the south side of the Skagit Valley (Figure 1 and Figure 2). This study investigates whether the rock is having an adverse impact on in-stream habitat and South Skagit Highway, where erosion issues have necessitated emergency actions in 2008 and 2010 by the County to place riprap protection (personal communication with Emily Derenne, 2020). Additionally, this study evaluates possible impacts of complete removal of the rock to South Skagit Highway and to existing habitat.

The primary objectives of the study are as follows:

1. Determine impacts to natural processes of rock in its existing state.
2. Assess impacts/benefits to salmonid habitat of the rock in its existing state and if it were to be removed.
3. Evaluate impacts to adjacent properties, including South Skagit Highway, from existing condition and removal.

Based on the findings of this study, recommendations are presented at the conclusion of the report.

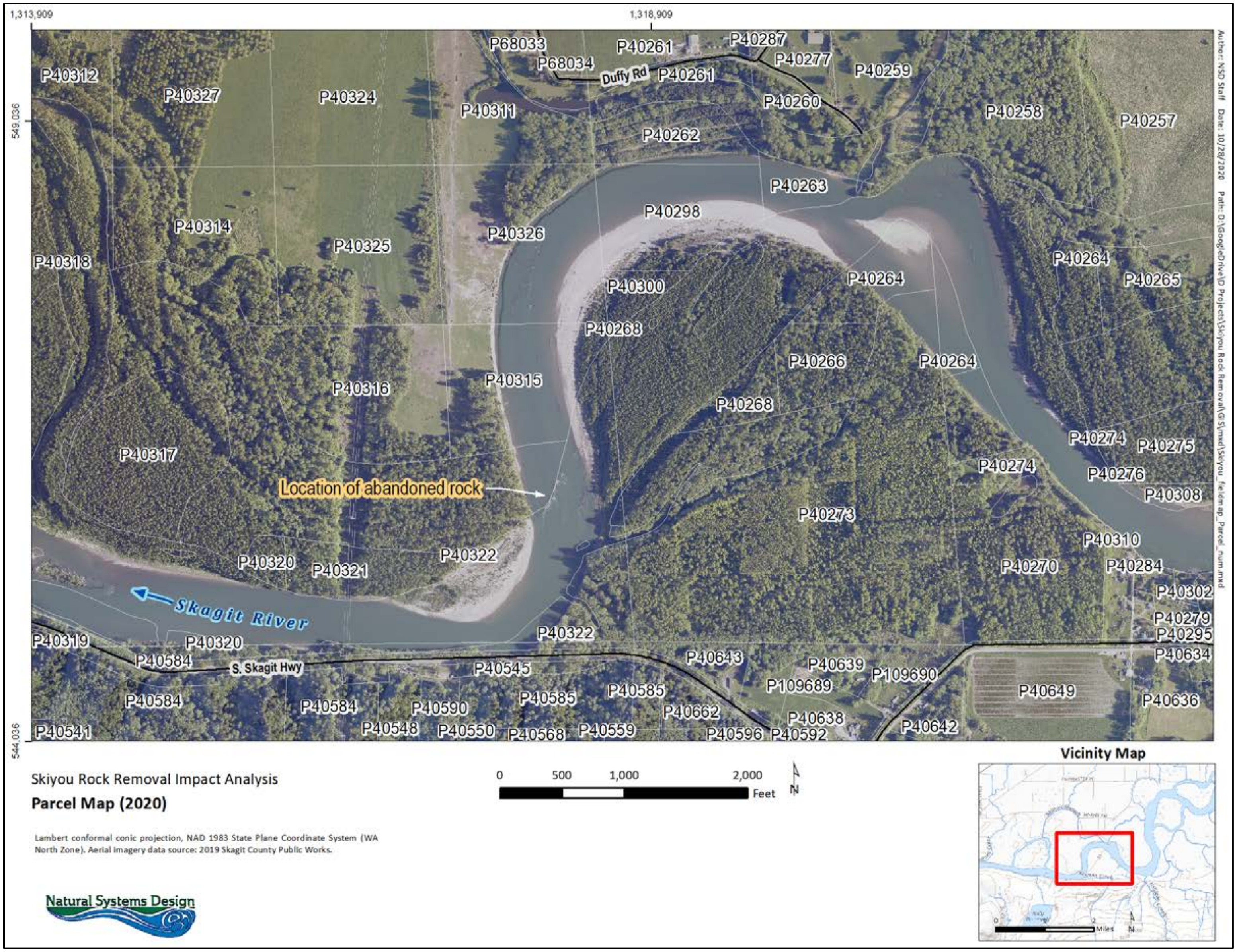

Figure 1. Project location map with Skagit County parcel numbers and boundaries.

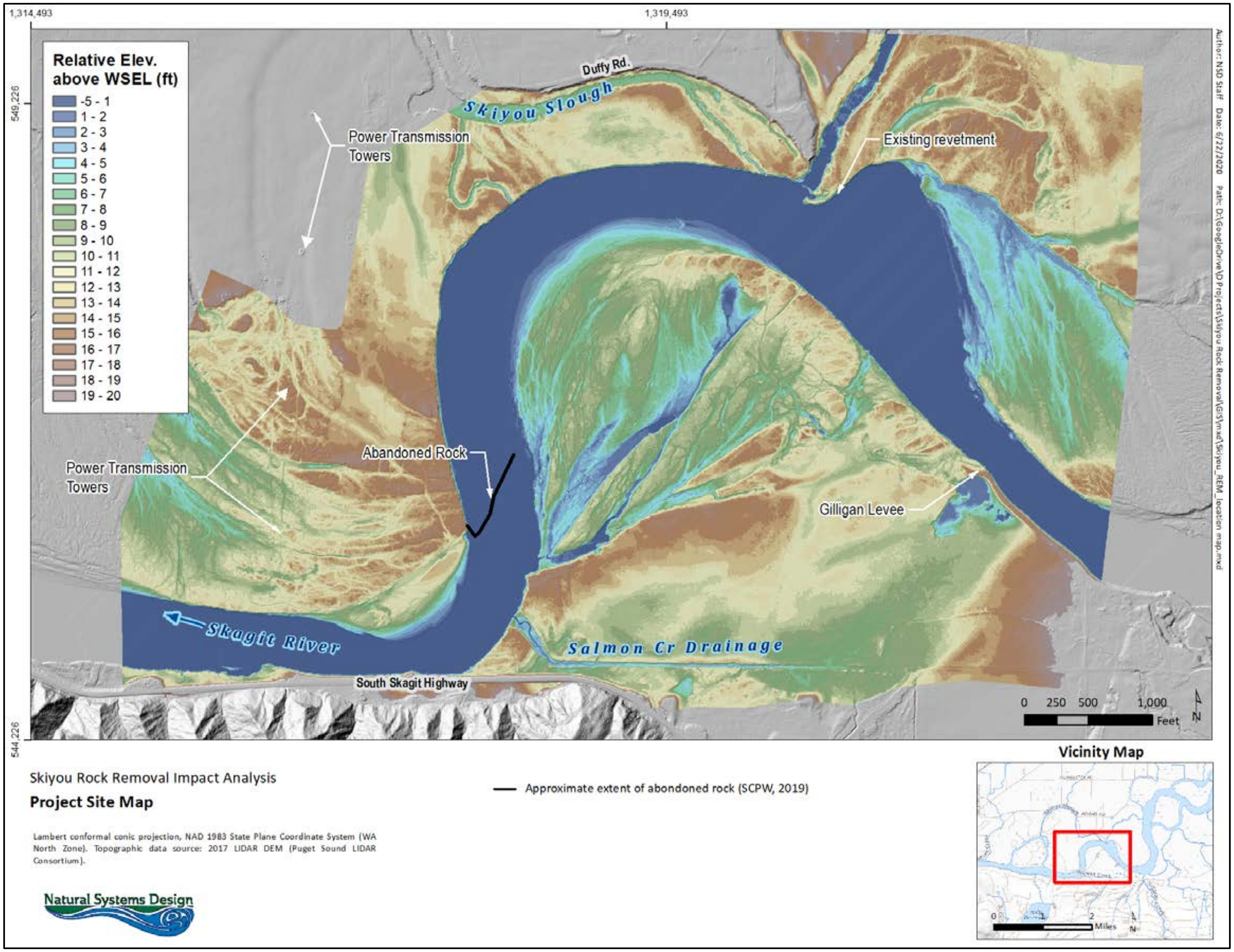

Figure 2. Project site map with elevations relative to river water surface. Abandoned rock revetment is delineated in downstream limb of river meander. Rock is aligned with right bank of river when rock was placed prior to 1969. Since 1969 the river has migrated northwest over 1500 ft. Relative elevation mapping based on 2016 LiDAR.

FIELD RECONAISSANCE AND DATA COLLECTION

NSD and Skagit County Public Works staff conducted a field reconnaissance and data collection effort on March 10, 2020. Activities included a site investigation by boat and foot, bathymetric survey, and limited topographic survey from RM 25.6 to approximately RM 28 under the current channel alignment. Observations of bank erosion, condition of existing revetments, large wood, pools, and general floodplain connectivity were recorded. Refer to Appendix A for a selection of field photos.

The rock was surveyed using a boat-mounted single-beam sonar unit to capture the extent of the intact segments, and a series of GPS RTK measured points to capture the crest elevation. An estimated 800 (range of 600 to 1,200) cubic yards is the approximate volume for the in-channel rock, assuming two 100 ft long sections with a constant crest elevation of 38 ft (NAVD-88). The bank rock volume is estimated at 375 cubic yards, based on GPS survey points. Exposed boulders in the channel had diameters of up to 70 inches. Figure 3 and Figure 4 show the rock in two distinct segments, along with a portion embedded in the right bank. Flow is accelerated through the openings of the rock where deep scour pools have formed. Scattered boulders were observed in the vicinity of the intact segments, which indicates progressive failure of the former revetment over time.

Figure 3. Skiyou rock, view from center of the channel towards the right bank. Flow direction is from right to left of photo. Note that the rock is overtopped at the time of survey during a flow of approximately 13,900 cfs. Bank rock is visible in the background (March 10, 2020).

Figure 4. Skiyou rock, view looking upstream near the center of the channel. Log racked against the rock illustrates the 40 degree angle alignment (0 being upstream) that forms a bend-way weir that sets up a grade line perpendicular to its alignment – directing flow away from right bank. This is the eastern edge of the intact rock segments (March 10, 2020).

HYDRAULIC ANALYSIS

A detailed hydraulic analysis was performed to assess the influence of the rock on the Skagit River and its floodplains within the immediate project area. The primary objective is to quantify the magnitude and extent of the rock's influence both upstream and downstream of its presence, and to identify the range of discharge at which the rock affects hydraulic conditions.

Existing conditions considers the current extent and state of the rock at the time of the survey. A comparison with the hypothetical scenario of full rock removal provides direct quantification of the magnitude and distance upstream and downstream that the rock influences flow patterns in the Skagit River.

Hydraulic Model Development

The analysis relies on a two-dimensional hydraulic model to compute parameters such as depth, velocity, and basal shear stress. Hydronia software, RiverFlow-2D Plus GPU, and Aquaveo SMS v13.0 computer software are used in this study. RiverFlow-2D is a two-dimensional finite volume computer model that provides depth-averaged hydraulic parameters at centroids within an unstructured triangular-mesh model domain. SMS v13.0 is a graphical user-interface for pre- and post-processing hydraulic model input and output data. This analysis utilizes the best available input data and latest versions of software at the time of this study.

Hydrology

Discharge in the hydraulic model is based on the flow record from USGS streamgage 12194000 Skagit River near Concrete, WA. This stream gage is located approximately 30 river miles above the study site and includes regulated Skagit River flows from dam operations in the upper basin. Flows are scaled according to relative drainage areas for input at the hydraulic model boundary, 2,580 mi^2 and 2,300 mi^2 for the project site and USGS stream gage location, respectively.

The hydraulic analysis is primarily focused on low to moderate flows, where the interaction with the rock and streamflow is most pronounced. A flow duration curve is a useful method of providing context to any given discharge in terms of expected probability of exceedance, particularly at lower magnitudes. Figure 5 is the flow duration curve for USGS 12194000, using daily mean flow over the period of record (1924 to present). Flows used in the hydraulic model are listed in Table 2. Note that the flow duration curve is based on daily mean discharge and does not include measurements of peak instantaneous discharge.

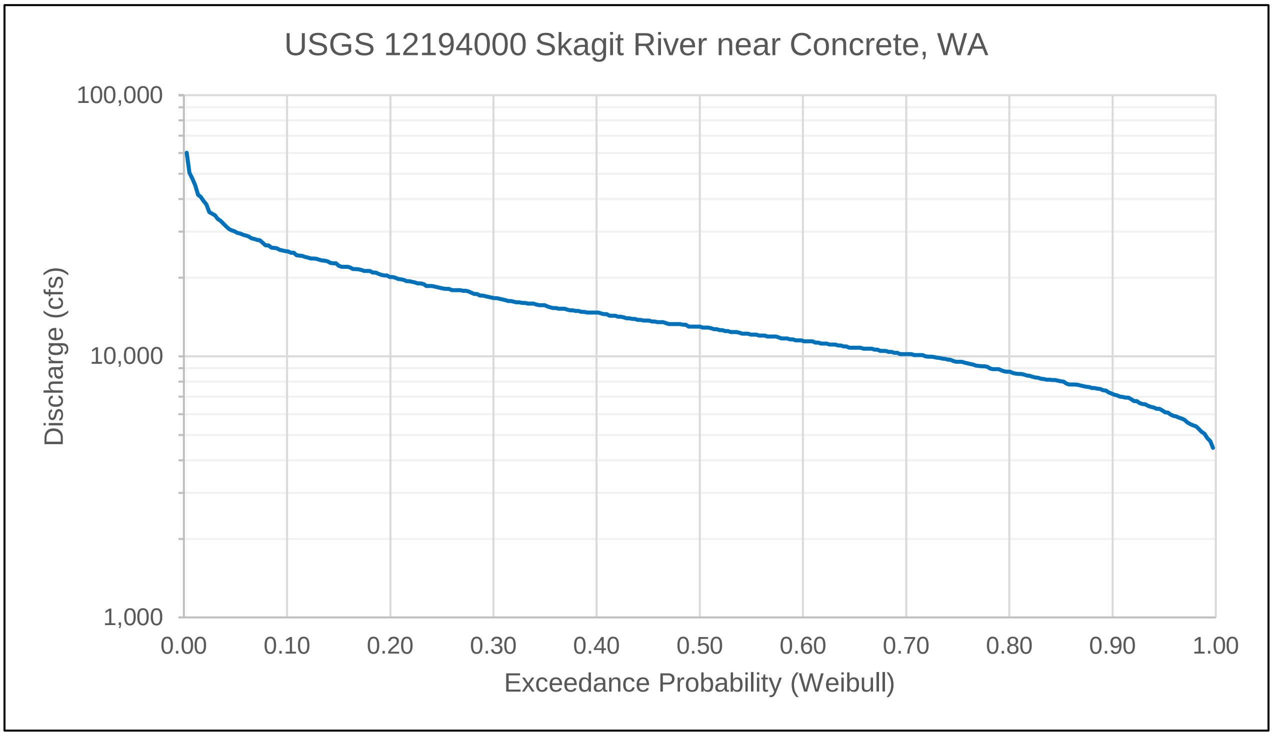

Figure 5. Flow duration curve for USGS 1219400 Skagit River near Concrete, WA. Computed using daily mean flow over the period of record (1924 to present). Note that the y-axis is based on a logarithmic scale.

Table 1. Flood Phase Stage and discharge for USGS 12194000 near Concrete, WA based on published rating curve (shift date June 11, 2020), and study site (scaled by basin area from USGS 12194000).

Flood Phase Stage (cfs)	Discharge for USGS 12194000 (cfs)	Discharge for Study Site (cfs)
28.00	61,992	67,943
32.00	87,087	95,448
37.00	123,200	135,027

Table 2. Summary of inflows used in the hydraulic model. Note that discharge in this table is scaled from the flow duration curve in Figure 1, according to drainage area of the study site. Corresponding stage for USGS 12194000 is shown in the second column, based on the published rating with the latest shift from 08/03/2020. Note that stage refers to a gage-specific height based on the physical characteristics of the gage location and does not directly tie into an established datum for elevation.

Annual Exceedance Probability	Stage for USGS 12194000 (ft)	Discharge for USGS 12194000 (cfs)	Discharge for Study Site (cfs)	Note
90%	15.6	7,100	7,800	-
75%	16.5	9,520	10,400	-
51%	17.6	12,700	13,900	Discharge at time of March 10, 2020 survey
25%	19.3	18,200	19,900	-
10%	20.9	25,200	27,600	-
2%	23.2	~36,500	~40,000	Approximate bankfull flow

The purpose of this study is to identify thresholds at which the abandoned rock produces the greatest effect, minimal effect, and no effect on hydraulic conditions in the mainstem Skagit River. Discharge for the study site is estimated by scaling the discharge recorded at USGS 12194000 according to respective drainage areas, in accordance with published procedures for Washington State Regions (Mastin et al., 2016). Values of discharge hereafter are reported relative to the study site unless specifically mentioned.

Computational Mesh

The model geometry utilizes topographic data referenced from the 2016 LiDAR dataset acquired from Quantum Spatial (QSI, 2017) which covers the main channel, floodplain, and hillsides in the project area. Channel bed topography, rock geometry, bank lines, and gravel bars were surveyed by NSD staff and subsequently processed into a TIN using AutoCAD Civil3D 2017.

This hydraulic analysis assumes a static condition for the streambed and does not consider the evolution of channel forms and associated changes in depth, velocity, and shear stress. The rock is modeled as a solid, elevated mound in the hydraulic model. This is a conservative approach in evaluating hydraulics at low flow.

RiverFlow-2D calculates energy loss in the form of hydraulic resistance, or roughness, and thus, requires the user to delineate surfaces of variable roughness, i.e. forest patches are rougher than short-grass pastures and plane-open channel reaches. Polygons representing differing surface roughness types were digitized using aerial imagery, LiDAR topography, and field observations. Values for roughness coefficients are assigned based on hydraulic literature (Chow, 1959), field observations, and professional judgement. Roughness types and associated Manning's n-value coefficients are listed in Table 3.

Table 3. Manning's n-value roughness coefficients as defined in the hydraulic model.

Surface type	n-value
Forest	0.14
Clearing/Pasture	0.05
Channel	0.034
Slough	0.044
Gravel Bar	0.044
Rock	0.15
Road, paved	0.016
Riprap	0.028
Developed	0.5

Breaklines are digitized by the user to define areas of topographic importance such as grade breaks along channel banks and toes. Node spacing along these breaklines determines the computational mesh resolution, or level of detail. The mesh was created to refine the resolution of the channel and floodplain channels, while reducing resolution in areas either topographically simple (i.e. flat) or outside of inundation (valley walls and high terraces). An open flow boundary condition is defined at the upstream extent of the model domain. A uniform outflow boundary is defined at the downstream extent of the domain, with a slope of 0.00275. No tributaries or additional flow contributions are included in the model.

Calibration and Sensitivity Analyses

A sensitivity analysis was performed to assess the relative influence of channel roughness n-values and uniform outflow slope at the downstream boundary condition on computed water surface elevations. A range of n-values to represent energy losses at the rock were simulated. A value of 0.1 represents a conservative estimate and should be used for low flows. A value of 0.05 should be used for flows when the rock is fully submerged, which assumes that there are lower energy losses when the rock stops acting as a weir.

The hydraulic model is calibrated to surveyed water surface elevations on March 10, 2020, when discharge at the study site was 13,921 cfs. Manning’s roughness n-values are adjusted to best match the measured data with model results. Table 4 summarizes the final calibrated model results. The calibrated model agrees well with measurements at 13,900 cfs.

Table 4. Summary of calibration analysis for 13,900 cfs; measured versus computed model results. Note that a negative downstream distance refers to a distance upstream.

Downstream Distance from Abandoned Rock	Surveyed WSEL (ft, NAVD-88)	Modeled WSEL (ft, NAVD-88)	Difference (ft)
-1,500	40.3	40.6	0.3
0	38.0	37.9	-0.1
1,800	37.7	37.3	-0.4

Existing Conditions Results

Existing conditions represents the topography and hydraulic roughness as of the March 2020 survey, which includes the rock in the Skagit River. Model inflows are “ramped up” in an artificially stepped hydrograph to simulate the full range of low to moderate discharge, and allowed to equilibrate at the values listed in Table 2. Results at significant thresholds are discussed in detail below. Refer to Figure 9 through Figure 11 for model output in the project sub-reach.

Results at 13,900 cfs - Overtopping

At the time of the March 10, 2020 survey, the rock was observed to be in two ~100 ft intact segments within the main channel and a portion of rock located on the right bank. The intact rock segments are angled 40 degrees normal to flow, which acts in a similar manner to a bend-way weir where flow is directed away from the bank and velocities are reduced immediately upstream and downstream of the structure. Theoretically, increased velocity is expected around the tip of the structure where flow converges in a constricted area of the channel. These effects were observed during the field site reconnaissance and verified in the model results.

Figure 6 plots the computed velocity vectors over the 2019 aerial image (flows are 13,900 and 12,900 cfs, respectively). Note the convergence of vectors (black arrows) through and around the openings of the rock. Velocity is highest through these openings where flow is constricted. Low velocity zones are computed immediately downstream of the rock segments where flow is obstructed. The effect of the rock visualized through velocity vectors extends approximately 250 ft downstream, after which the arrows follow a uniform pattern in the downstream direction. Approximately 25% of the flow is conveyed through the right opening (between the bank rock and right rock segment) and 64% through the left opening (between left rock segment and left bank). Since the right opening is only 80 ft wide (compared to 270 ft on the left), shear stresses are generally higher on this side.

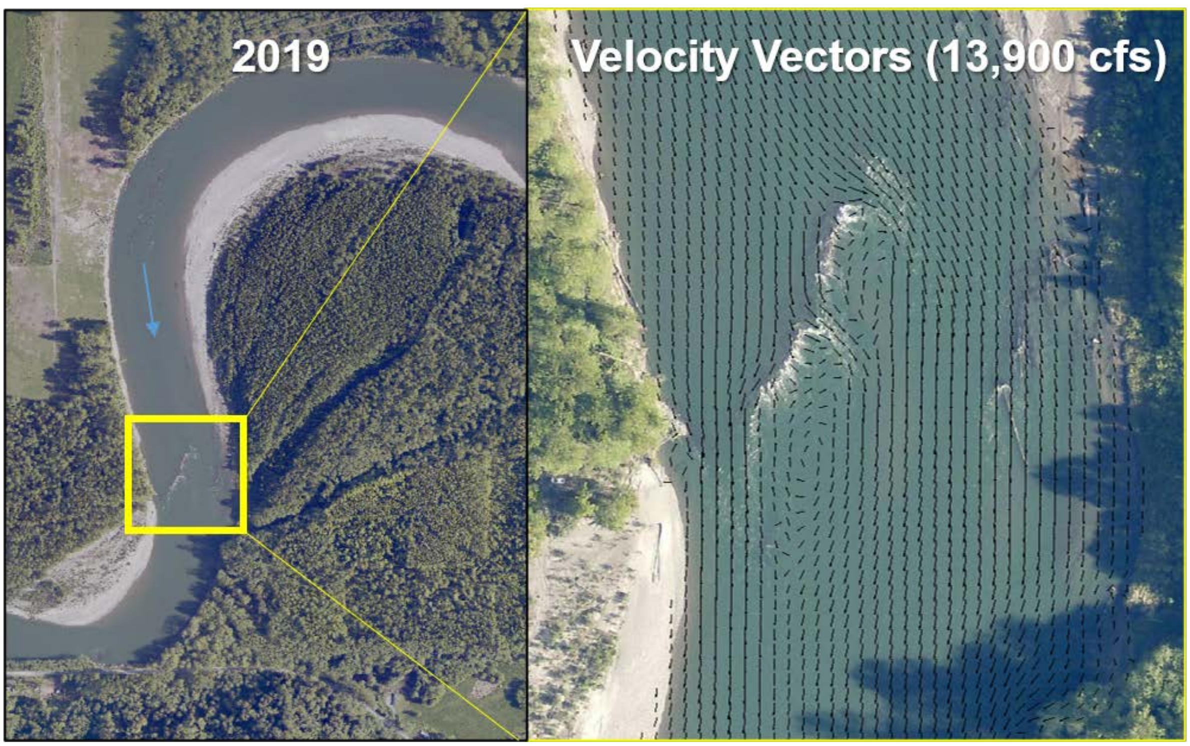

Figure 6. (Left) 2019 aerial image and (Right) computed velocity vectors at 13,900 cfs. Discharge at time of image is 12,900 cfs. Observed flow patterns verify model results during low to moderate flow conditions. Between the bank rock and the right rock segment is the "right" opening, and between the left rock segment and the left bank is the "left" opening.

Model results corroborate field observations of the "flow attraction" effect that rock, boulders, and riprap, can have, which can lead to local scour from accelerated flow around and over the rock. Combined with the physical obstruction of the rock, constriction scour is expected in the high velocity zones (red) shown in Figure 7. The bank rock deflects flow away from the right bank towards the center of the channel. Computed peak velocities are 6-7 ft/s at the right bank rock with shear stresses approaching 1.8 lb/ft^2. At this discharge, shear stresses are capable of transporting cobble-sized, greater than 5 in diameter, material (assuming uniform non-cohesive material, $\tau^*_c = 0.052$). Peak values, computed at the edges of the intact rock segments, reach nearly 9 lb/ft2. This is sufficient to mobilize boulders with a diameter of 20 in. When smaller particles are mobilized and transported away from the intact rock segment, the large boulders become more exposed to flow and prone to scour. When undermined, the boulders roll away and are buried in the river bed. The river has gradually been undermining and tearing apart the original rock revetment and as this process continues, the hydraulic effect of the rock diminishes. Scattered angular boulders were observed during the bathymetric data collection which is evidence toward the gradual failure of the intact rock segments.

Further degradation of both bank rock and channel rock segments is expected to continue. Model results indicate that shear stress is high enough at 13,900 cfs to mobilize gravel-sized particles up to small boulders. This means that on an annual basis, conditions leading to local scour, undermining, and transport of the intact rock segments occurs at a 51% exceedance probability. At flows lower than 13,900 cfs, the rock has an even greater effect on local hydraulic conditions, and a lesser effect at flows over 13,900 cfs.

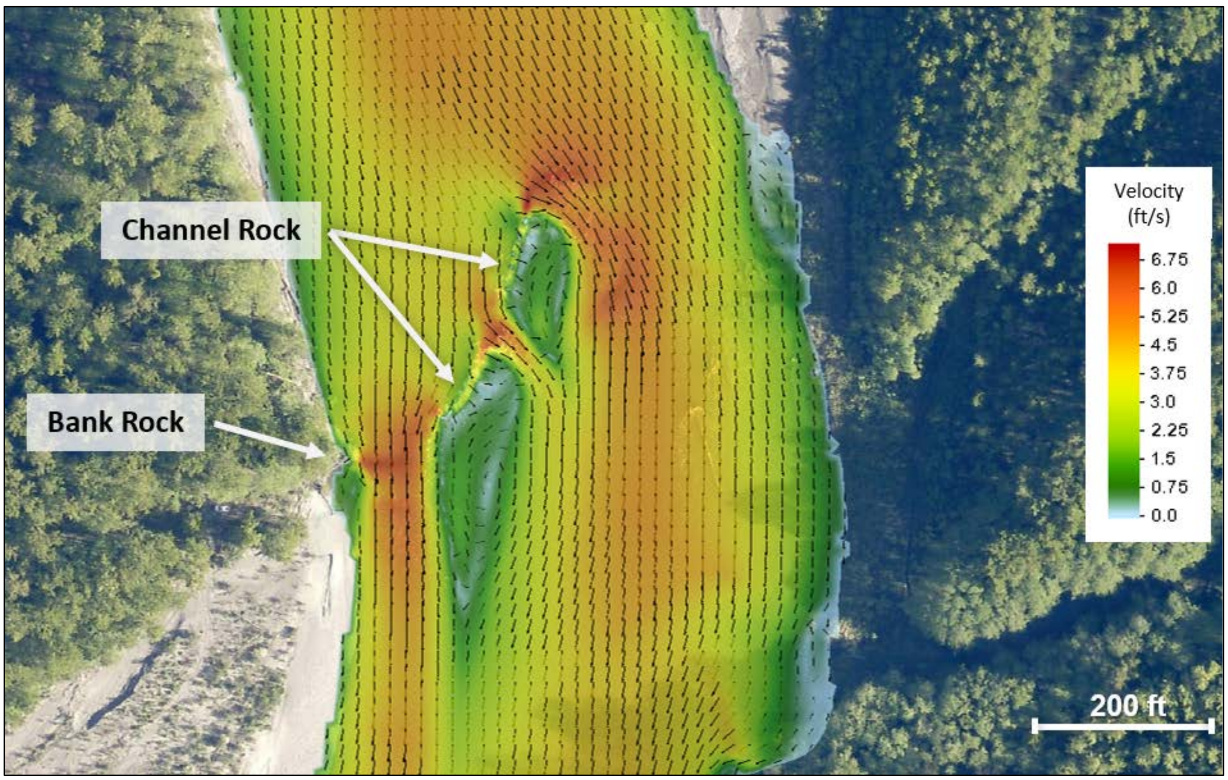

Figure 7. Computed velocity at 13,900 cfs, at which flow begins to overtop channel rock. Peak velocity is 6-7 ft/s. Note that the rock is situated in three distinct sections: right bank and two channel segments. Flow direction is from top to bottom of figure.

An analysis of long term trends of channel migration indicate that the Skagit River will eventually move around the entire sections of bank and in-channel rock before the intact segments are fully broken apart (refer to Channel Migration subsection). When flow moves around the bank rock, accelerated erosion of the right bank and downstream point bar are expected in the short term. Note that the rock is currently providing hydraulic complexity by altering flow and velocity patterns in a channel with otherwise uniform conditions.

Results at 7,800 cfs – Low Flow

Similar flow patterns are observed for discharges below the overtopping threshold. The rock's influence on velocity and shear stress is greater at lower flows since the physical obstruction represents a larger portion of the flow area. Model results are shown in Figure 9. Peak velocity through the rock openings computed between 7-8.5 ft/s. Average shear stress at the rock face is 1.4 lb/ft^2, and is generally between 0.6 and 0.8 lb/ft^2 in the vicinity of the openings. Peak values reach nearly 13 lb/ft^2 which is sufficient to mobilize boulders with a diameter between 20-40 in.

As flow loses energy at the face of the rock, water surface elevation increases in the upstream direction to create a backwater effect (shown in Figure 8). The result is an increase in energy gradient through the rock openings. The pools formed by local scour around the toe of the rock leads to undermining of the intact segments, which are shown in the left window of Figure 9. The 90% exceedance flow at the study site is 7,800 cfs, which indicates that throughout most of the year low to moderate flows will continually undermine the intact portions of the rock.

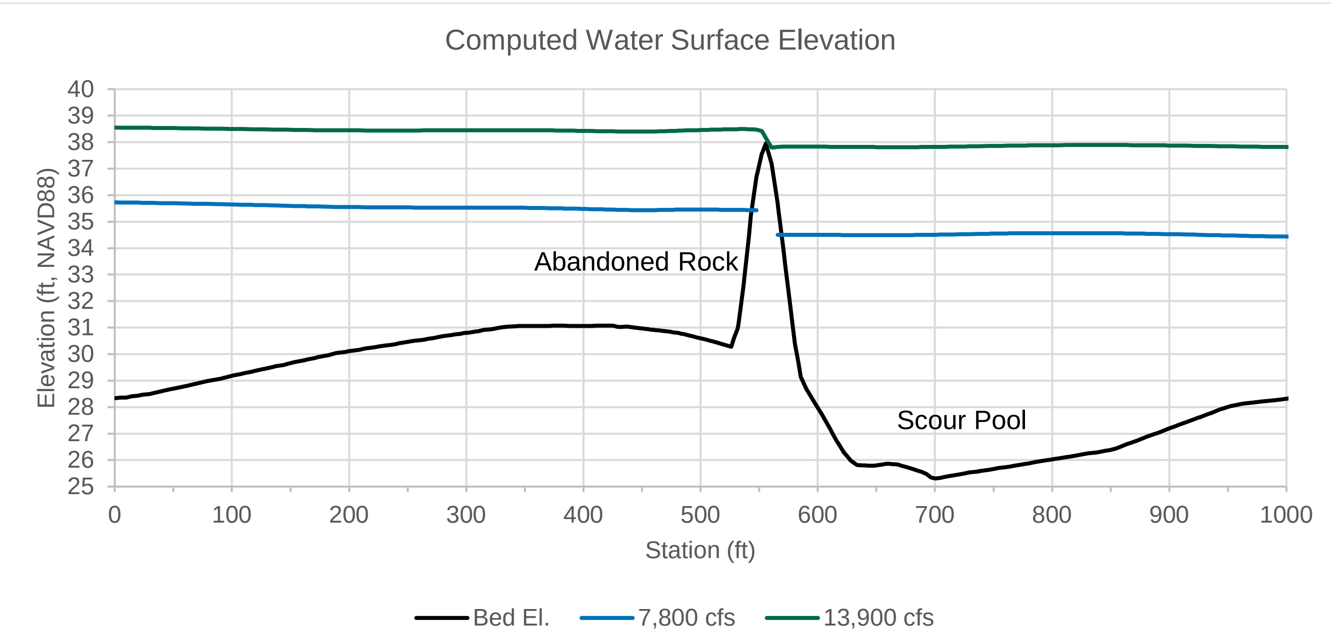

Figure 8. Longitudinal profile of computed water surface elevation and surveyed channel bed topography (NSD March 10, 2020 survey). Water surface elevation drops approximately 1 ft over the crest of the rock at 7,800 cfs. The rock is located at approximately station 500 ft. Stationing increases in the downstream direction.

Results at 26,300 cfs – High Flow

At higher flows, the rock is completely inundated and its influence on local hydraulic conditions decreases. Peak velocity and shear stress decrease as flow is no longer forced to flow through the openings in the intact rock segments. The potential for erosion and mobilization of larger particles at the rock decreases as discharge increases. However, the conditions leading to erosion of the upstream right bank along Parcels P40315 and P40326 increases as flow approaches bankfull.

The discharge at which the rock has no significant influence on local hydraulics is identified when the Froude number is less than 1.0 over the rock (subcritical flow). Though energy losses still persist from the flow obstruction, the rock does not control the flow profile at a discharge of 26,300 cfs. This corresponds with an annual exceedance probability of 12%. For this simulation, the roughness n-value of the rock is decreased to 0.05.

Flow over the rock is between 8-10 ft deep and velocity vectors do not follow local directional patterns compared to existing conditions. Peak velocity occurs over the top of the rock at 5.5 ft/s, compared to 3-4 ft/s on average in the channel. Peak shear stress is computed at 1.1 lb/ft^2 over the rock crest. While shear stress is relatively low compared to lower discharges, overtopping flow can lead to the formation of plunge pools immediately downstream of the rock toe. Over time, the deepening of plunge pools can undermine stability of the intact segments and cause individual pieces to be transported downstream.

The 13,900 cfs threshold represents the condition when the effect of the rock on local hydraulics decreases. By 26,300 cfs, the effect of the rock is drowned out by relatively uniform flow conditions. This flow is similar to the mean June flow of approximately 26,100 cfs at the study site.

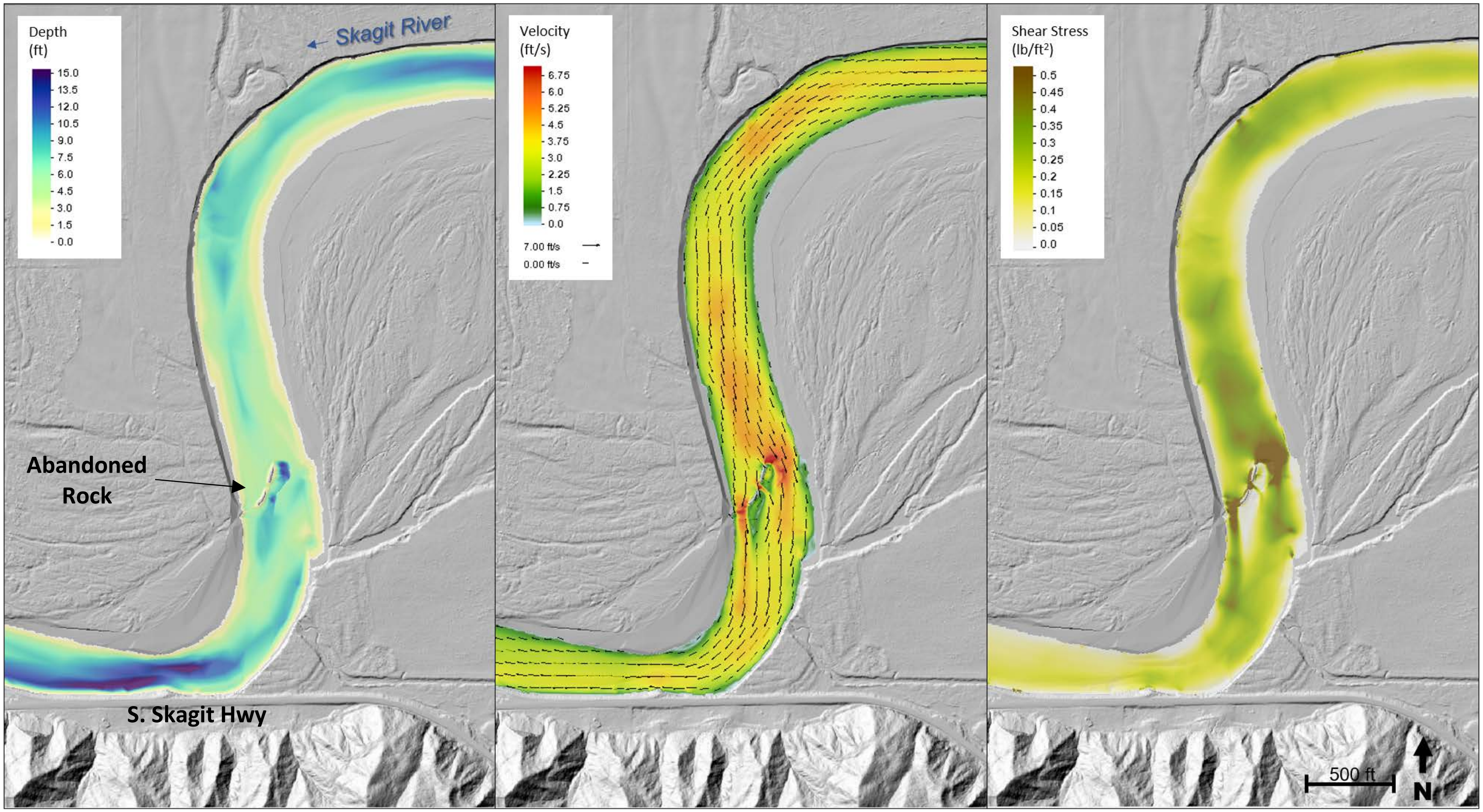

Figure 9. Hydraulic model results at 7,800 cfs (90% exceedance flow), flow is from top to bottom. Pictured from the left to right is depth, velocity, and shear stress, respectively. The top of the rock is exposed and not fully submerged at this discharge. Flow is constricted through the openings in the rock sections, leading to localized increases in velocity and shear stress. Peak velocity is approximately 8.5 ft/s near the outside edges of the rock segments. Shear stress is computed at 1.4 lb/ft^2 in the same areas, with peak values reaching 13 lb/ft^2. The rock has a localized influence on flow patterns which dissipates within 800 ft downstream. The rock has no effect on flows approaching South Skagit Highway or on the right bank of the Benson property (Parcel # P40315 and P40326).

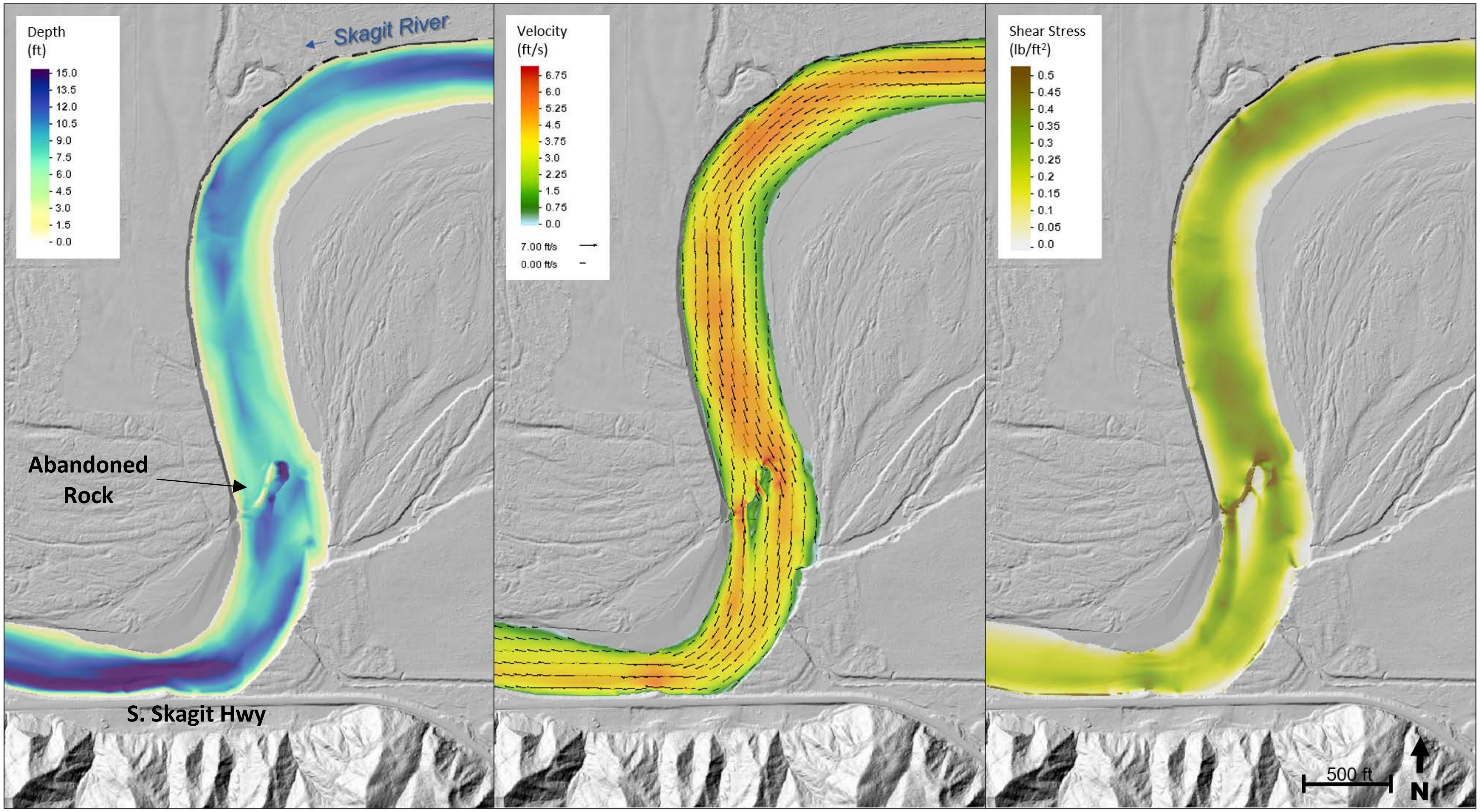

Figure 10. Hydraulic model results at 13,900 cfs (51% exceedance flow), flow is from top to bottom. Pictured from the left to right is depth, velocity, and shear stress, respectively. Flow begins to overtop the crest of the rock at this discharge. Localized increases in velocity and shear stress are also computed at this flow, though to a lesser magnitude and extent than conditions at the 90% exceedance flow. Peak velocity is approximately 7 ft/s near the outside edges of the rock extent. Peak shear stress is computed at 9 lb/ft^2 over the top of the intact rock segments. The rock has a localized influence on flow patterns which dissipates within 800 ft downstream. The rock has no effect on flows approaching South Skagit Highway or on the right bank of the Benson property (Parcel # P40315 and P40326).

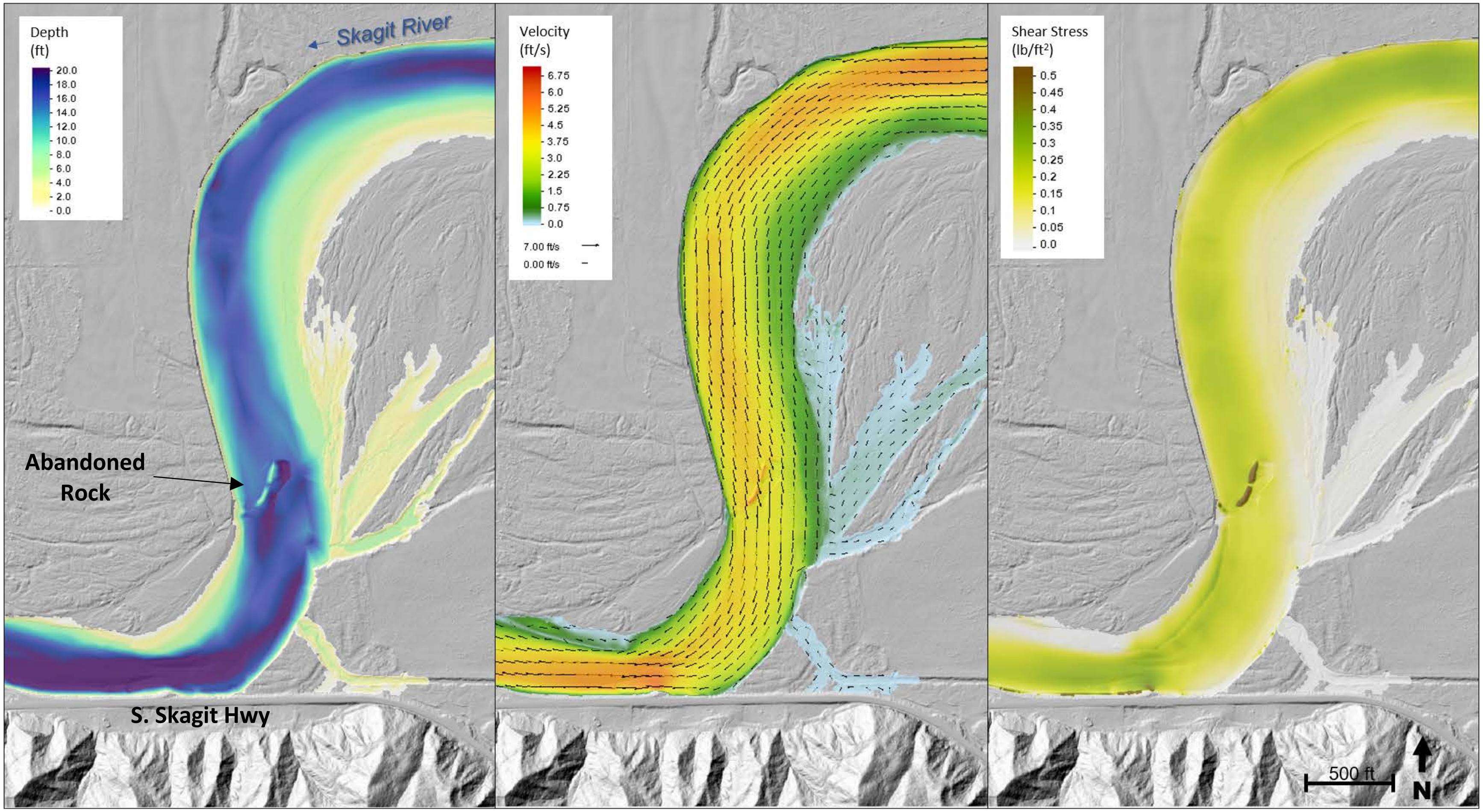

Figure 11. Hydraulic model results at 26,300 cfs (12% exceedance flow), flow is from top to bottom. Pictured from the left to right is depth, velocity, and shear stress, respectively. The rock is submerged by 8-10 ft at this discharge, and subcritical flow is computed through this section of reach. Velocity is relatively uniform throughout the entire width of the channel, shown by the flow vectors. Elevated shear stress is limited to locations over the rock sections, with computed peak value of 1.1 lb/ft^2. The rock has negligible effect on flow patterns and has even less effect at higher flows or on the right bank of the Benson property (Parcel # P40315 and P40326).

Considerations at Flood Flows

NSD constructed a coarse-scale flood model to evaluate high flow conditions at the study site (NSD, 2019). Resulting output indicates that the Skagit River overtops its right bank at approximately 43,000 cfs. The 2-yr discharge is 85,800 cfs and inundates much of the floodplain. The rock has minimal effect at flood flows. The coarse-scale flood model has not been calibrated, and is based on topography strictly from LiDAR (including water surface returns), though results are consistent with findings from previous studies of the Middle Skagit River (Anchor QEA, 2009; PNNL and Battelle, 2009) that show wide portions of the floodplain inundated at the 2-yr discharge.

Full Removal Scenario

The full removal scenario assumes a complete removal of the rock, with no other changes to surrounding channel bed topography or bank alignment. Representation of full removal scenario topography modifies the elevated surface of the rock to a flattened channel bed with a linear grade between the upstream and downstream rock extents. Hydraulic roughness is reduced to a uniform n-value of 0.034 for the Skagit River mainstem channel. Identical flows from the existing conditions run are simulated for full removal scenario.

Full removal of the rock results in a change to more uniform flow patterns in the main channel of the Skagit River. Figure 12 through Figure 14 show model output from full removal scenario through the study site. Table 5 summarizes the computed peak velocity and peak shear stress in the immediate vicinity of the rock.

Table 5. Summary of computed peak values for velocity and shear stress under existing and full removal scenario directly at the rock. Differences in peak values are reported as Full removal scenario minus Existing Conditions results.

Discharge (cfs)	Exceedance Probability	Existing Conditions Peak Velocity (ft/s)	Existing Conditions Peak Shear Stress (lb/ft^2)	Full removal scenario Peak Velocity (ft/s)	Full removal scenario Peak Shear Stress (lb/ft^2)	Difference in Peak Velocity (ft/s)	Difference in Peak Shear Stress (lb/ft^2)
7,800	90%	8.5	13.0	5.6	0.67	-2.9	-12.33
13,900	51%	7.0	9.0	5.2	0.46	-1.8	-8.54
26,300	12%	5.5	1.1	4.2	0.24	-1.3	-0.84

There is a significant reduction in peak velocity and shear stress at the rock under the scenario of complete removal. Note that differences in peak values between the full removal scenario are limited to within the immediate vicinity of the abandoned rock, and beyond 500 ft downstream effects on channel hydraulics are relatively insignificant. Figure 15 through Figure 17 map the relative change between existing and full removal scenario. These maps show the spatial change in hydraulic conditions with complete removal of the rock.

Full removal results in reduced water surface elevations immediately upstream of the rock face and a shift to more uniform flow, with significantly reduced lateral complexity in hydraulic conditions. Maximum differences in water surface elevation, velocity, and shear stress are shown at lower discharges, though the spatial extent of the rock's influence is most pronounced at the overtopping flow of 13,900 cfs. Due to the presence of intact rock segments, modeled increases in flow velocities along the left and right channel margins extend no more than 800 ft downstream. Beyond this distance the effects of the rock are not measurable. Note that the distance to South Skagit embankment toe is approximately 1,200 ft downstream of the rock, which is outside of the zone of hydraulic effect. Approximately 300 ft upstream of the rock, modeled velocity and shear stress is shown to increase in what is currently the backwatered area of the main channel. The full rock removal scenario has an insignificant effect on the actively eroding section of the right bank on Parcels P40315 and P40326.

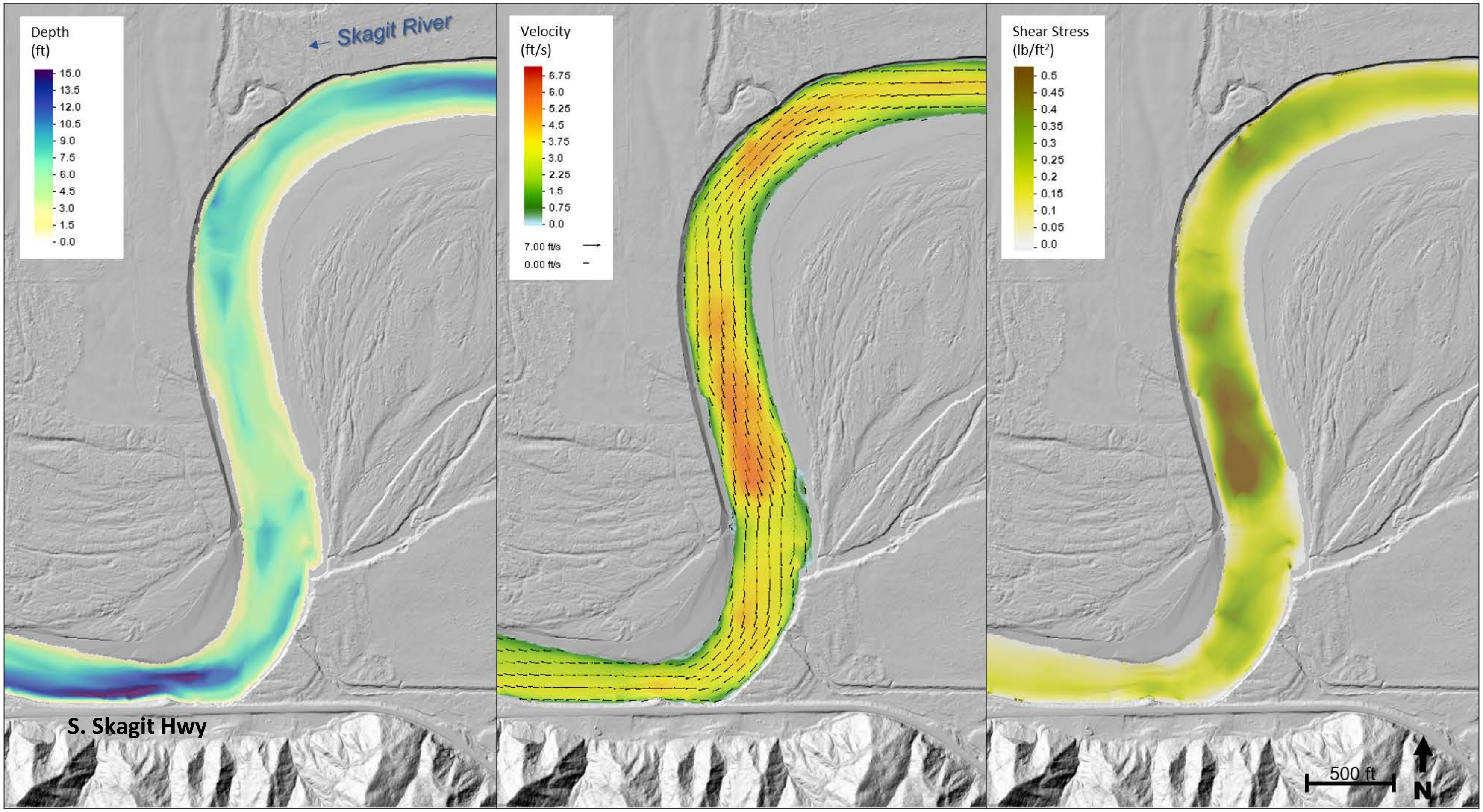

Figure 12. Hydraulic model results at 7,800 cfs (90% exceedance flow) for full removal scenario. Pictured from the left to right is depth, velocity, and shear stress, respectively. Flow moves unobstructed through site. Full removal of the rock would result in loss of deep pools and bed complexity – beneficial fish habitat the rock currently creates.

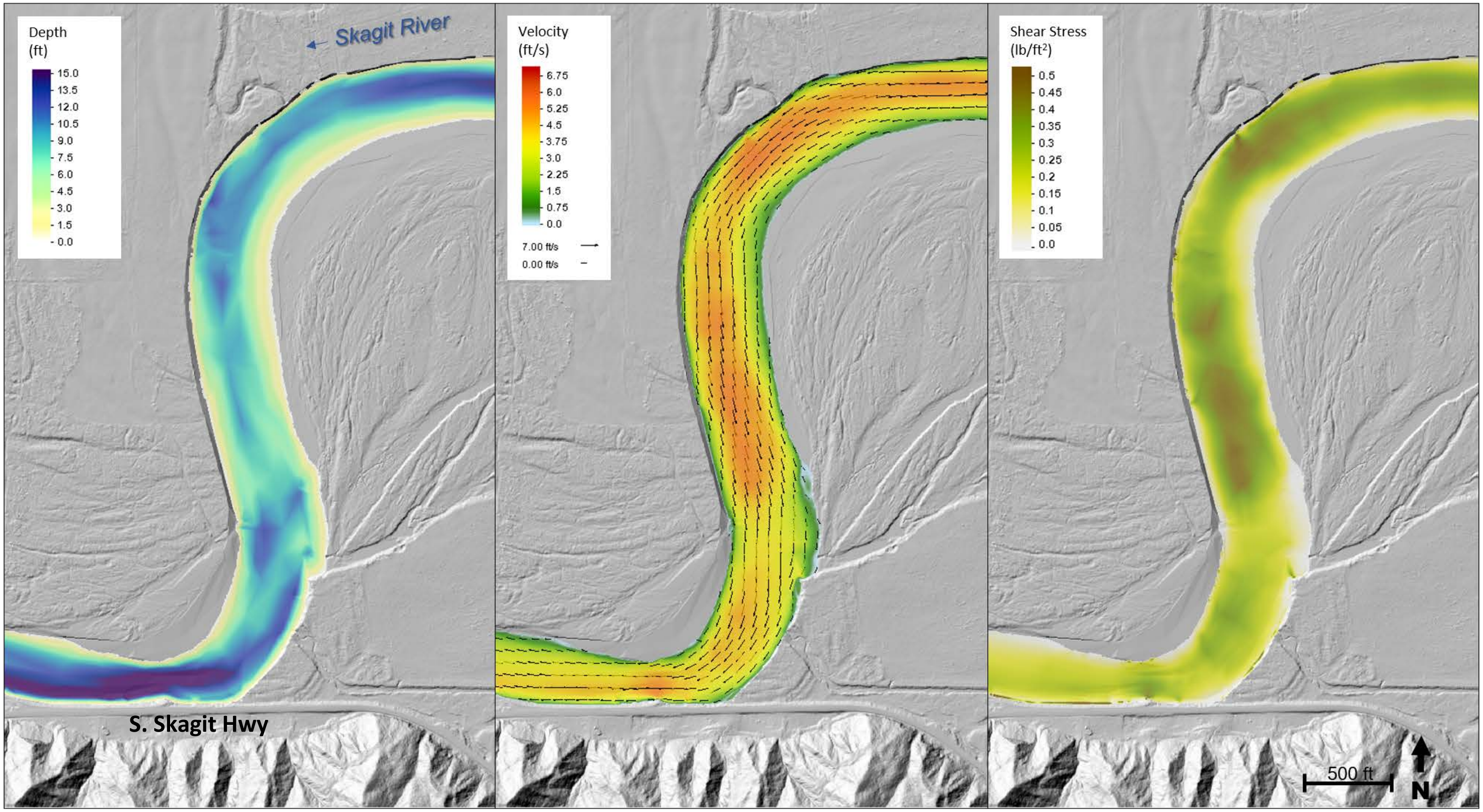

Figure 13. Hydraulic model results at 13,900 cfs (51% exceedance flow) for full removal scenario. Pictured from the left to right is depth, velocity, and shear stress, respectively. Flow moves unobstructed through the site. Full removal of the rock would result in loss of deep pools and bed complexity – beneficial fish habitat the rock currently creates.

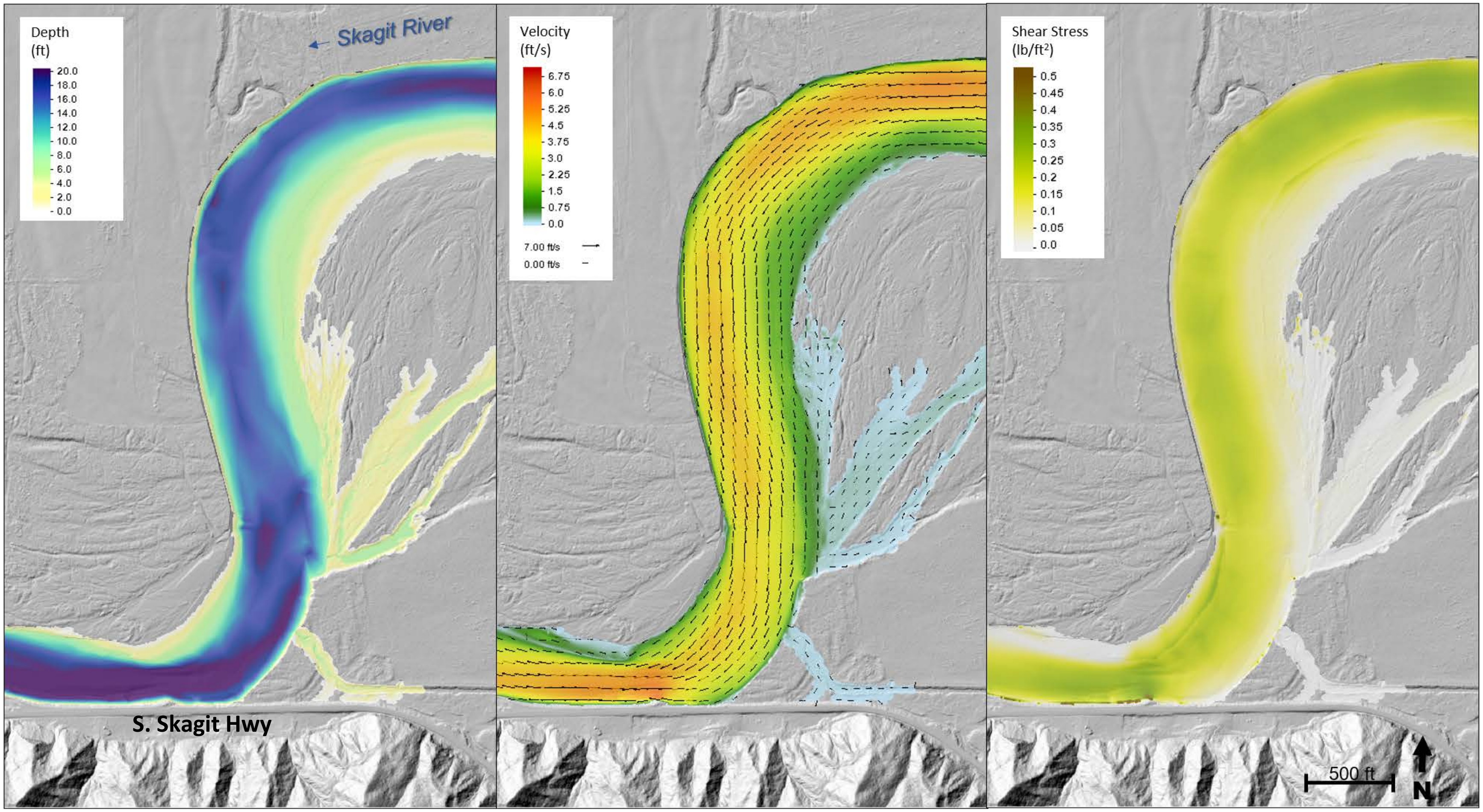

Figure 14. Hydraulic model results at 26,300 cfs (12% exceedance flow) for full removal scenario. Pictured from the left to right is depth, velocity, and shear stress, respectively. At this flow, the wetted channel occupies the entire width from bank to bank but does not inundate the Benson property. Side channels are engaged on the left floodplain through backwater connections with the Skagit River. Velocity and shear stress are distributed uniformly with the primary flow direction. There is a natural flow constriction downstream of the second meander along South Skagit Highway, which is an area of high exposure to erosive forces on the left bank as shown by elevated velocity and shear stress.

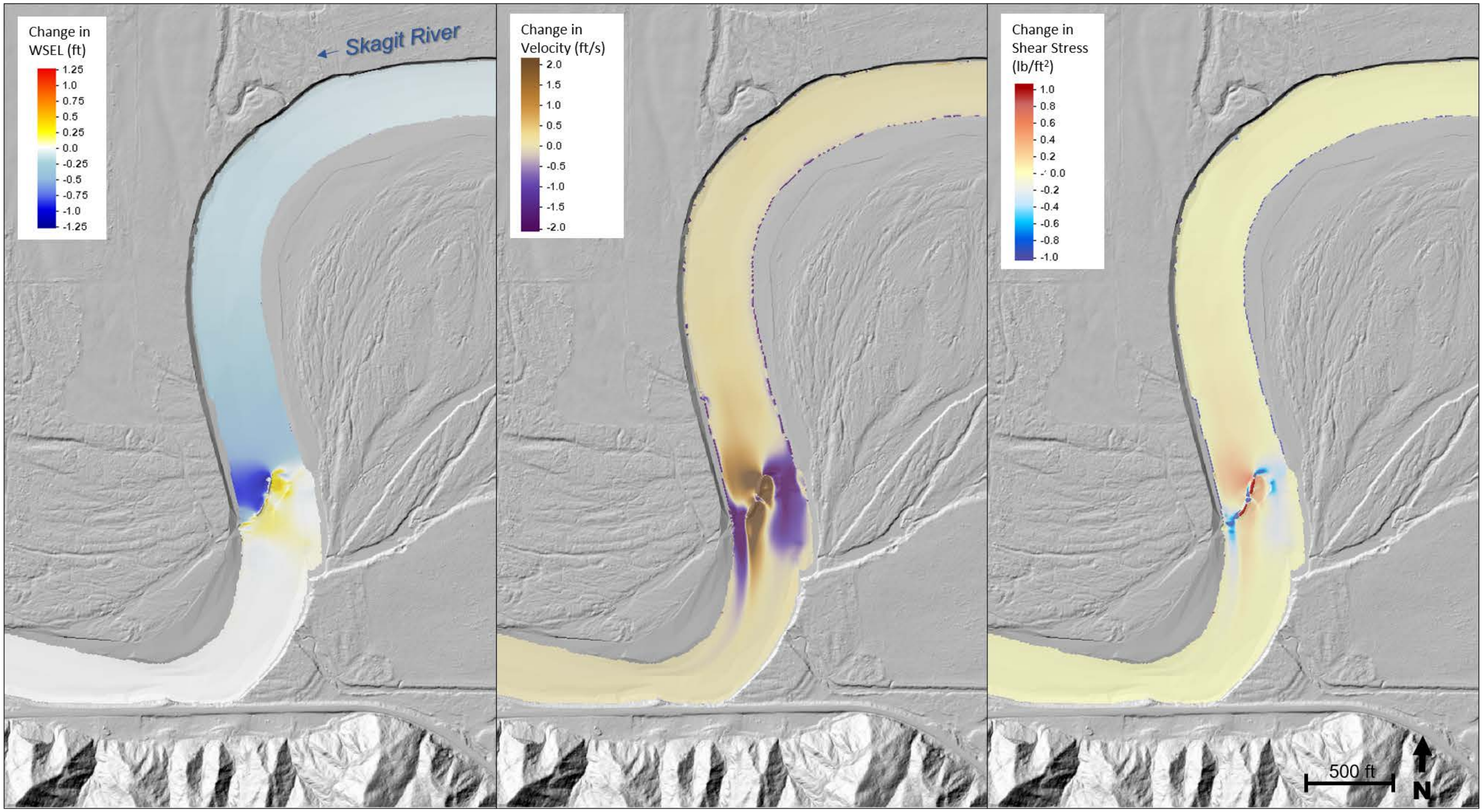

Figure 15. Difference map of water surface elevation (left), velocity (center), and shear stress (right) at 7,800 cfs. Values are mapped for the full removal scenario minus existing conditions. Maximum reduction in water surface elevation is 1.1 ft. Maximum increase and decrease in velocity is 4.6 and 6.5 ft/s, respectively, and average change is generally near 2 ft/s. Maximum increase and decrease in shear is 0.6 and 12 lb/ft^2, respectively, and average change is generally between 0.2-0.4 lb/ft^2.

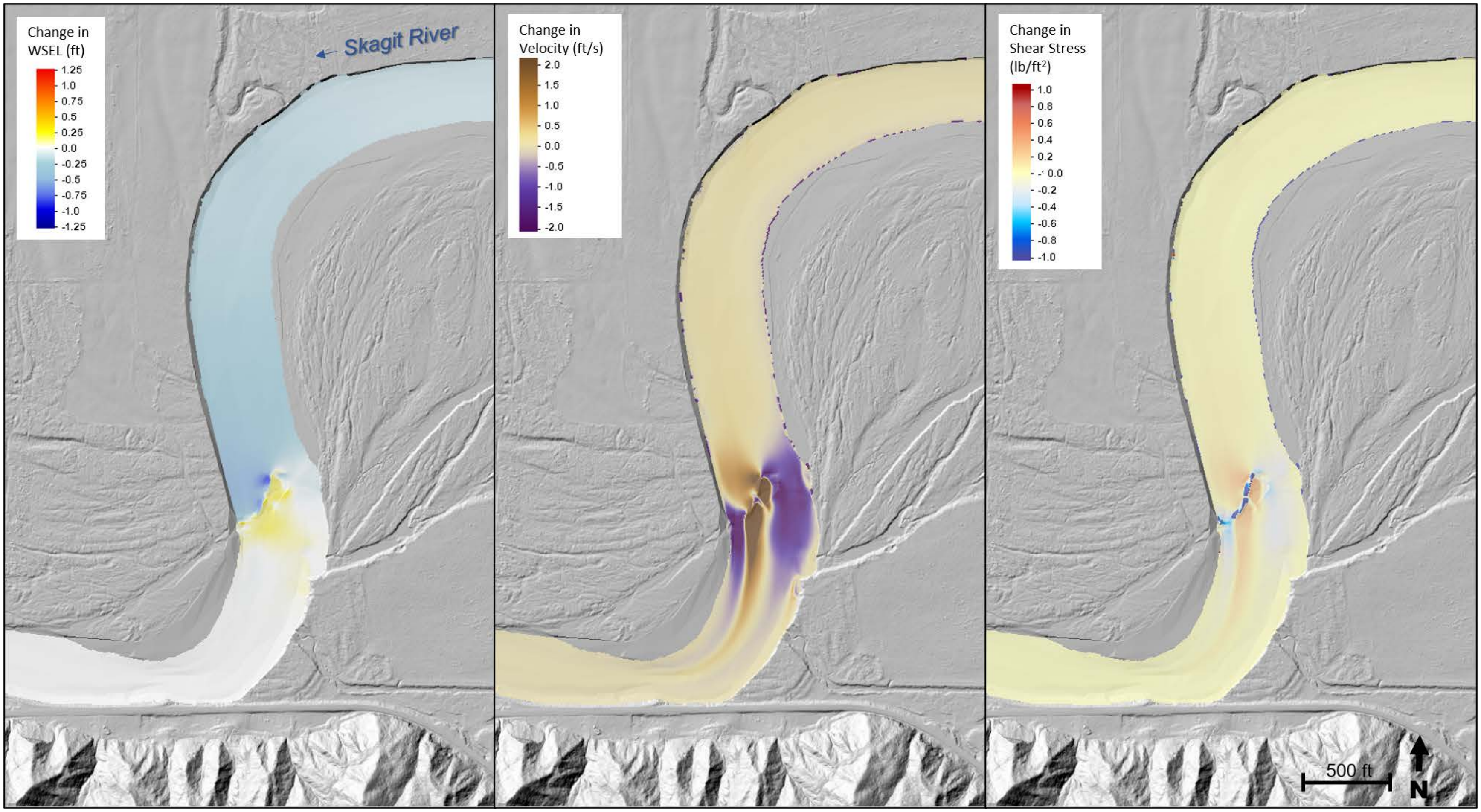

Figure 16. Difference map of water surface elevation (left), velocity (center), and shear stress (right) at 13,900 cfs. Values are mapped for the full removal scenario minus existing conditions. Maximum reduction in water surface elevation is 0.7 ft. Maximum increase and decrease in velocity is 4.6 and 6.5 ft/s, respectively, and average change is generally near 3 ft/s. Maximum increase and decrease in shear is 0.4 and 9 lb/ft^2, respectively, and average change is generally between 0.2-0.4 lb/ft^2.

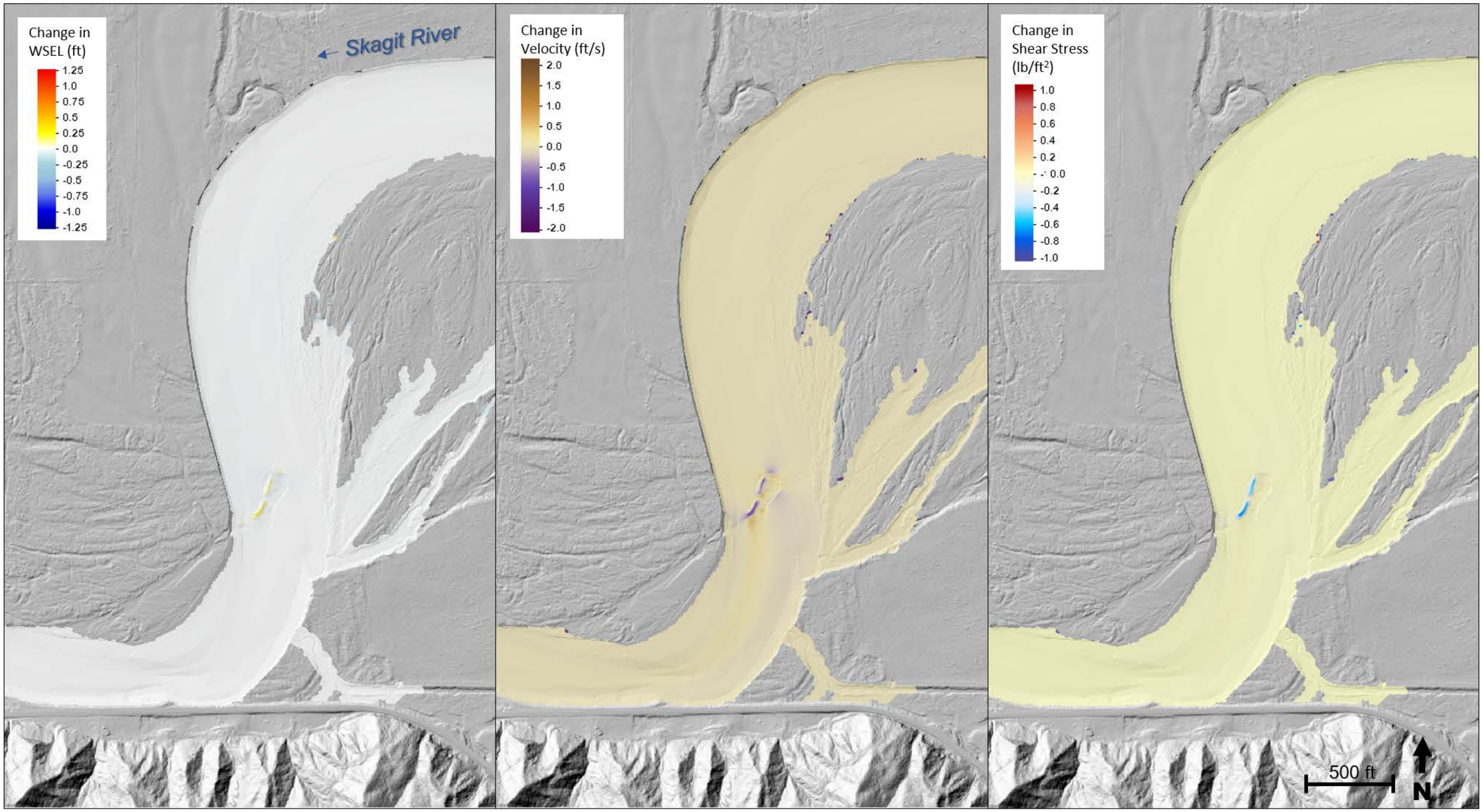

Figure 17. Difference map of water surface elevation (left), velocity (center), and shear stress (right) at 7,800 cfs. Values are mapped for the full removal scenario minus existing conditions. Maximum change in water surface elevation is 0.26 ft. Maximum increase and decrease in velocity is 0.6 and 1.6 ft/s, respectively, and average change is generally between 2 ft/s. Maximum decrease in shear is 0.9 lb/ft^2, with no significant increases computed.

There is a 1,300 ft section upstream of the rock where velocity would increase if the rock were removed. This is attributed to the change in bed gradient at the rock site (Figure 18, orange line). Note that this effect would be temporary and that over the long term, the channel bed gradient would flatten to the reach average, assuming the prevailing geomorphic and flow regimes are constant.

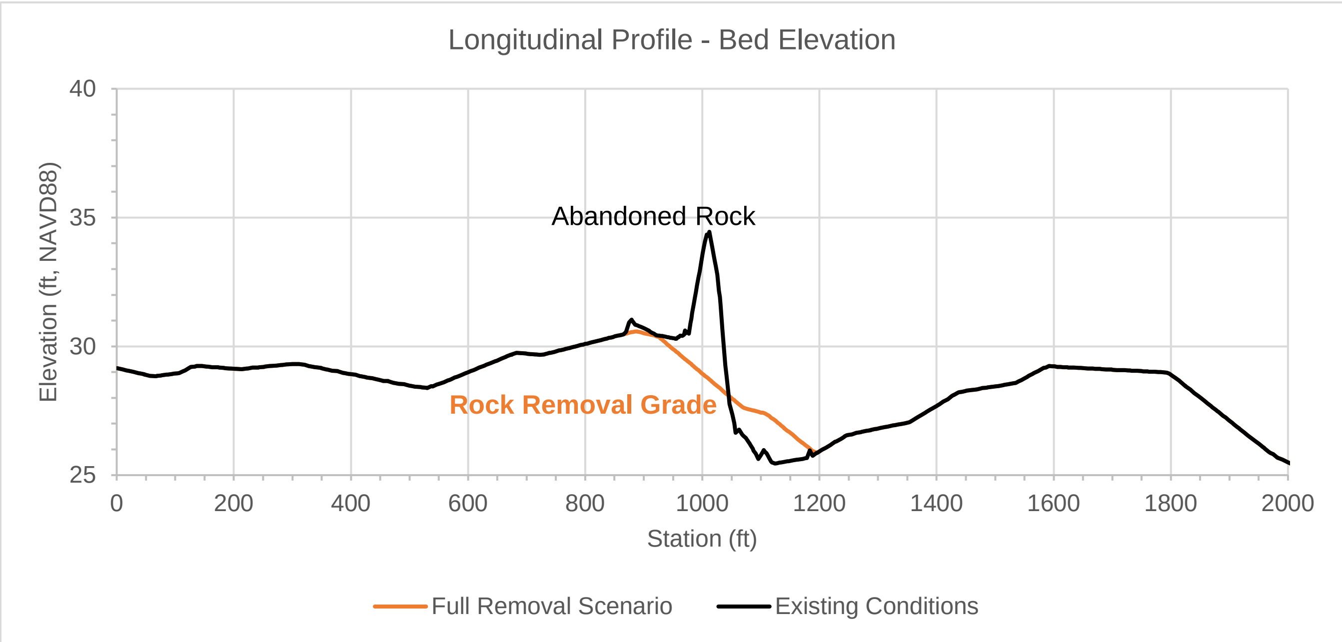

Figure 18. Longitudinal profile of Existing Conditions vs. Full Removal Scenario bed elevation. The orange line represents the complete removal of rock.

Summary of Findings

- The rock is creating two deep pools and riverbed complexity that provides beneficial salmonid habitat in the mainstem Skagit River. This habitat would disappear if the rock were to be removed or when the river migrates past the rock.
- The hydraulic effects created by the rock are most pronounced at discharge under 13,900 cfs, when local flow patterns are influenced by the physical obstruction of the intact segments.
- Under existing conditions, shear stress is sufficient to mobilize small boulder-sized particles within 25 ft of the rock segments. Outside of this distance, boulders are not expected to be mobilized.
- The rock is submerged at flows larger than 13,900 cfs, above which the hydraulic effects of the rock diminish in magnitude and spatial extent.
- Hydraulic influence of the rock becomes insignificant at flows 26,300 cfs and above.
- Hydraulic effects produced by the rock do <u>not</u> adversely impact the right bank of the Skagit River (Parcels P4315 and P4026). The rock creates a backwater zone approximately 300 ft upstream, which currently acts to reduce velocity and shear stress along the right bank.

- Hydraulic effects produced by the rock do not adversely impact South Skagit Highway. The maximum extent of the hydraulic effects is 800 ft downstream of the rock. South Skagit Highway is located 1,200 ft downstream of the rock.

GEOMORPHIC ANALYSIS

A geomorphic analysis was performed from River Mile (RM) 28 near Gilligan Creek to 0.5 RM below the rock, while considering the trajectory of the larger Middle Skagit River flow and sediment transport regimes. Previous geomorphic studies are utilized in conjunction with an analysis of channel migration in recent decades (2007-2019) to characterize historical channel changes and to project future trends in the study area.

Historical Aerial Imagery

The Skiyou reach is a historically dynamic section of the Skagit River, characterized by a pair of meanders with a network of sloughs and overflow channels throughout its floodplain. In contrast to the Ross Island reach upstream, the Skiyou reach has maintained a single-thread channel from early observations in the 19th century. Figure 19 shows the approximate location of the rock with respect to a series of historic maps and images. The Skagit River mainstem has maintained its location along the southern valley hillslope over time.

The amplitude of the meander upstream of the red arrow progressively increases over time and migrates in a down-valley direction. Downstream of the red arrow, Skiyou Island is flanked by the Skagit River mainstem on the north and an overflow channel to the south. Following the image date of 1969, the primary flowpath begins to shift to the south channel, which ultimately reduces channel length and increases the energy gradient through the reach. The 1969 image is the earliest evidence obtained in this study that documents the position of the right bank in alignment with the current rock. It is unknown exactly when the right bank was armored. However, the images from Figure 20 show an armored section that resists erosion in 1993.

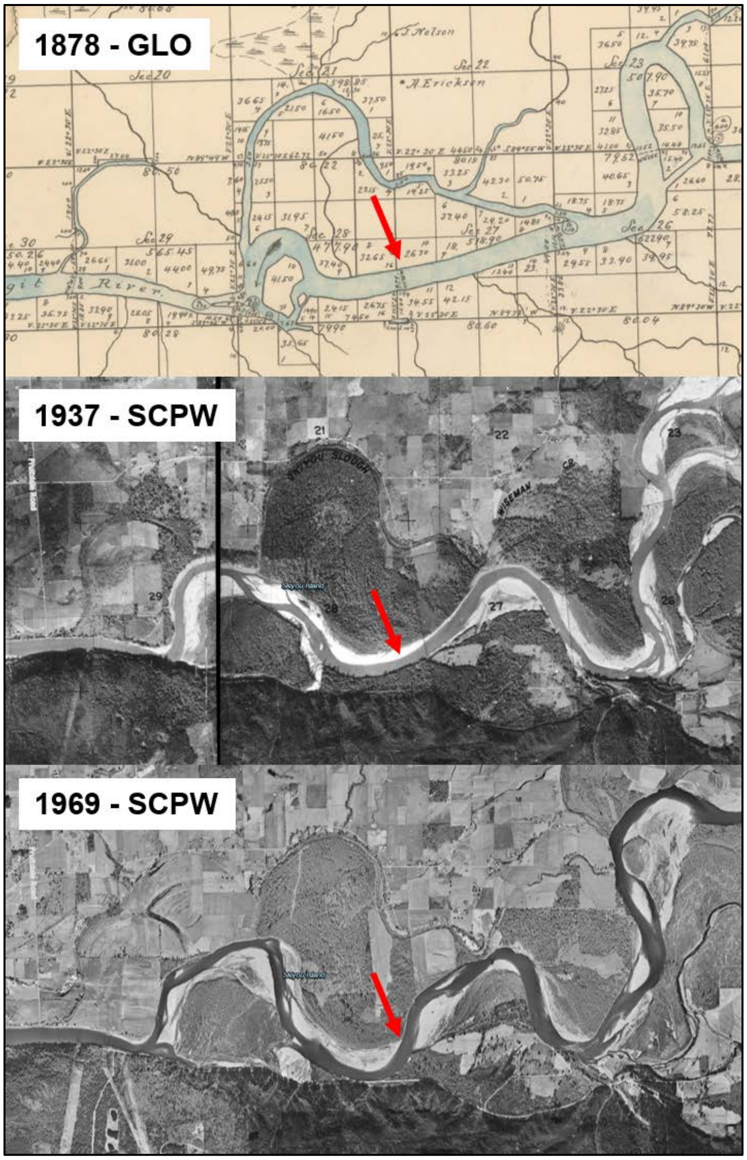

Figure 19. The Skagit River "Skiyou reach" shown, flow direction from right to left of image. The red arrow indicates the approximate location of the rock. The 1878 map clearly shows an anabranching river with two primary channels that formed Skiyou Island within the project area. The north meander channel is now called Skiyou Slough remains a low-lying flow path. Sources are GLO (1878) and Skagit County Public Works (1937, 1969).

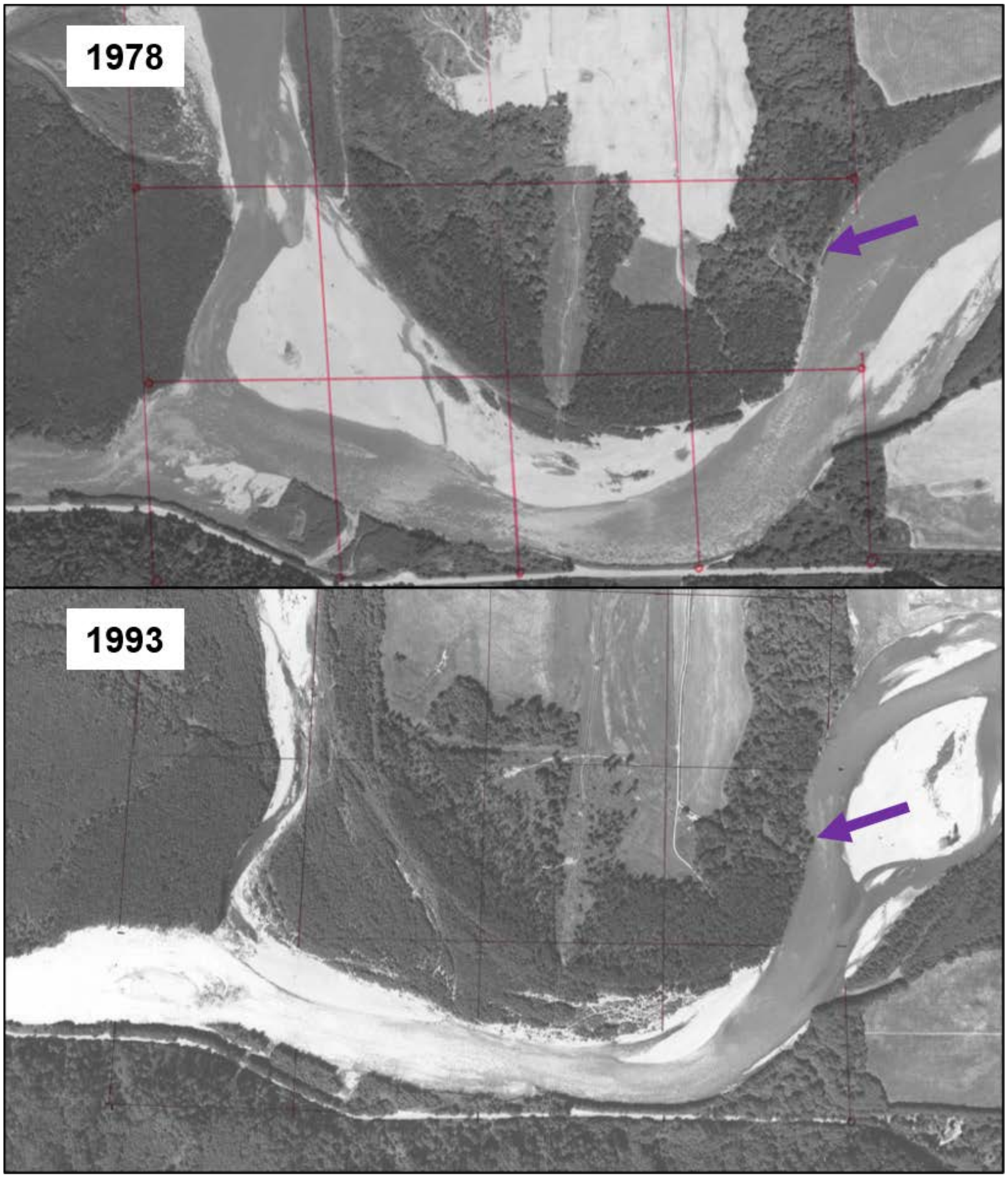

Figure 20. The Skagit River "Skiyou reach" shown, flow direction from right to left of image. The purple arrow indicates the approximate upstream extent of the rock. The upstream meander bend begins to migrate around the revetment on the right bank in 1993. Note that mainstem meander downstream of project site was still active in 1978 but river has moved into secondary channel along South Skagit highway. By 1993 the mainstem had fully occupied its current pathway along southern margin of valley and highway. Images provided by Skagit County Public Works (1978, 1993).

An analysis of satellite imagery reveals that the revetment becomes exposed across the main channel when significant down-valley migration of the upstream meander occurs between 1995-1996. The rock is likely retarding the translation of the downstream meander bend. Refer to Appendix B for the full series of satellite images and plot of the daily mean hydrograph. Visual inspection of the hydrograph shows a relationship between significant channel migration and the occurrence of the 2-year discharge. This observation is consistent with a decadal study of the Middle Skagit sediment budget (Rothleutner, 2017), which finds the highest rates of channel migration are more prevalent during periods of low to moderate discharges when aggradation follows periods of high erosion.

The prevailing flow and sediment transport regime, bar formation during flood events and channel formation during low to moderate discharge, is the primary driver of channel migration in the Middle Skagit River, Skiyou reach included. This strongly suggests that rock is not an underlying control of channel response in the study area due to its localized influence, compared to reach-scale geomorphic processes.

Channel Migration

Channel migration was measured by NSD using the Skagit County iMap service for the period between 1998 and 2019. The apex of the upstream outside meander bend, along the Benson property (P40315, P40326), is measured between available aerial images to quantify maximum down-valley migration. The measured values are then averaged across the period between available images for an average annual migration rate. Table 6 summarizes channel migration measured along the Benson property (P40315, P40326), and Table 7 summarizes rates adjacent to Duffy Rd.

Table 6. Summary of down-valley channel migration rates along the upstream outside meander bend (Parcels P40315 and P40236). Measured distance between meander apex is calculated between consecutive image dates.

Image Dates (yr)	Distance between Meander Apex (ft)	Average Annual Rate (ft/yr)
2019-2017	63	32
2017-2015	69	35
2015-2011	69	17
2011-2009	38	19
2009-2006	112	37
2006-2004	118	59
2004-2001	161	54
2001-1998	42	14
	Average	33
	Maximum	59

Table 7. Summary of channel migration rates along the upstream outside meander bend (Duffy Rd).

Image Dates (yr)	Distance between Meander Apex (ft)	Average Annual Rate (ft/yr)
2019-2017	24	12
2017-2015	51	26
2015-2011	15	4
2011-2009	12	6
2009-2007	20	10
2007-2006	39	39
2006-2004	55	28
2004-2001	50	17
2001-1998	165	55
	Average	22
	Maximum	55

Natural migration of the Skagit River channel will proceed, with the Skiyou meander moving downstream (west) and increasing in amplitude (north and south). The rock has little influence on migration of the Skagit River, though once the river flanks the rock on the right bank, it is likely to result in a short-term acceleration in bank erosion. Based on computed channel migration rates, over the next 30 years, typical channel migration will put the following areas and infrastructure at risk of erosion:

- South Skagit Highway, located 1,200 ft downstream of the rock.
- Private property on the right bank of the Skagit River, Parcels P40315, P40326. Recent migration of the Skiyou meander of the Skagit river is eroding about 1.5 acres a year.
- Duffy Road, located immediately north of Skiyou Slough on the right bank of the Skagit River. Skiyou Slough is within 450 ft from right bank of meander apex of the Skagit river. Based on average and maximum erosion rates since 1998, the Skagit could move into the upper portion of Skiyou Slough sometime between 2028 and 2041, respectively.
- Power transmission towers and lines, running north-south across Skiyou Island and the Skagit River on the right bank. Down-valley migration of the Skagit meander could reach the power line in less than 20 years.

A previous study by Anchor QEA (2009) quantified downstream down-valley migration rates for the meander apex along the Benson Property (Parcels P40315, P40326) between 1937 and 2007. Average and maximum migration rates were computed at 70 ft/yr and 289 ft/yr, respectively (Anchor QEA, 2009). In this study the rate of outward migration of meanders within the Ross and Skiyou Island reaches from 2006 to 2019 range from 14 to 59 ft/yr. Down valley migration rates are higher, ranging from 35 to 123 ft/yr. The Skagit River is approximately 1000 ft from the nearest power transmission line on the Benson property. Based on the recent migration rates, the river will reach the power lines in 17 to 31 years (2037-2051).

Expected Future Trends

Degradation of rock is expected to continue as low flow hydraulic conditions are sufficient to undermine the stability of large boulders and have the capacity to mobilize small boulders, which roll into scour pools and are eventually buried in the river bed. Anecdotal evidence (personal communication with Emily Derenne, 2020) indicates that the bank rock segment has rapidly decreased in extent from recent years. Field observations of individual boulders scattered through the study reach confirm that the intact segments have been progressively failing since being exposed in the main channel. Refer to Figure 21 for a map of erosion risks in the study area.

Continued erosion of the outside meander bend is expected to continue upstream of the rock. Annual average channel migration rates computed for 1998-2019 suggest that the Skagit River will shift around the rock entirely in less than 10 years. When the bank rock is fully exposed to the main channel, accelerated local erosion is expected to occur along the right bank and downstream point bar. Down-valley translation of the meander and point bar is expected over the long term, but its rate may be slowed by the presence of the armored toe along South Skagit Highway. Once the Skagit River entirely moves around the rock, the position and extent of the downstream point bar will be less stable.

Expansion of the outside meander bend will continue to erode property on Parcels P40315 and P40326. At current migration rates, the Skagit River is eroding an average of 1.5 acres per year along the right bank. This assumes a uniform migration rate over a 2,000 ft long section of exposed river bank.

The power transmission towers and lines located immediately west of the Benson property (P40315, P40326) are at risk of erosion. Based on historical average channel migration rates, the Skagit River may reach the nearest transmission tower in approximately 30 years. Note that the land between the current streambank and transmission tower is pastured, likely unconsolidated fine material that is highly erodible. Refer to Figure 22 for an illustration of general trends of channel migration within the study area.

Immediately upstream of the Benson property (P40315, P40326), the right bank is eroding at an average rate of 22 ft/yr. Continuation of this rate will put Duffy Road and nearby inhabitants at direct exposure from the Skagit River in less than 20 years. As the outside meander bend progresses down-valley, it also expands outward towards Skiyou Slough. A direct flow connection here would send a significant portion of the Skagit River into the western floodplain.

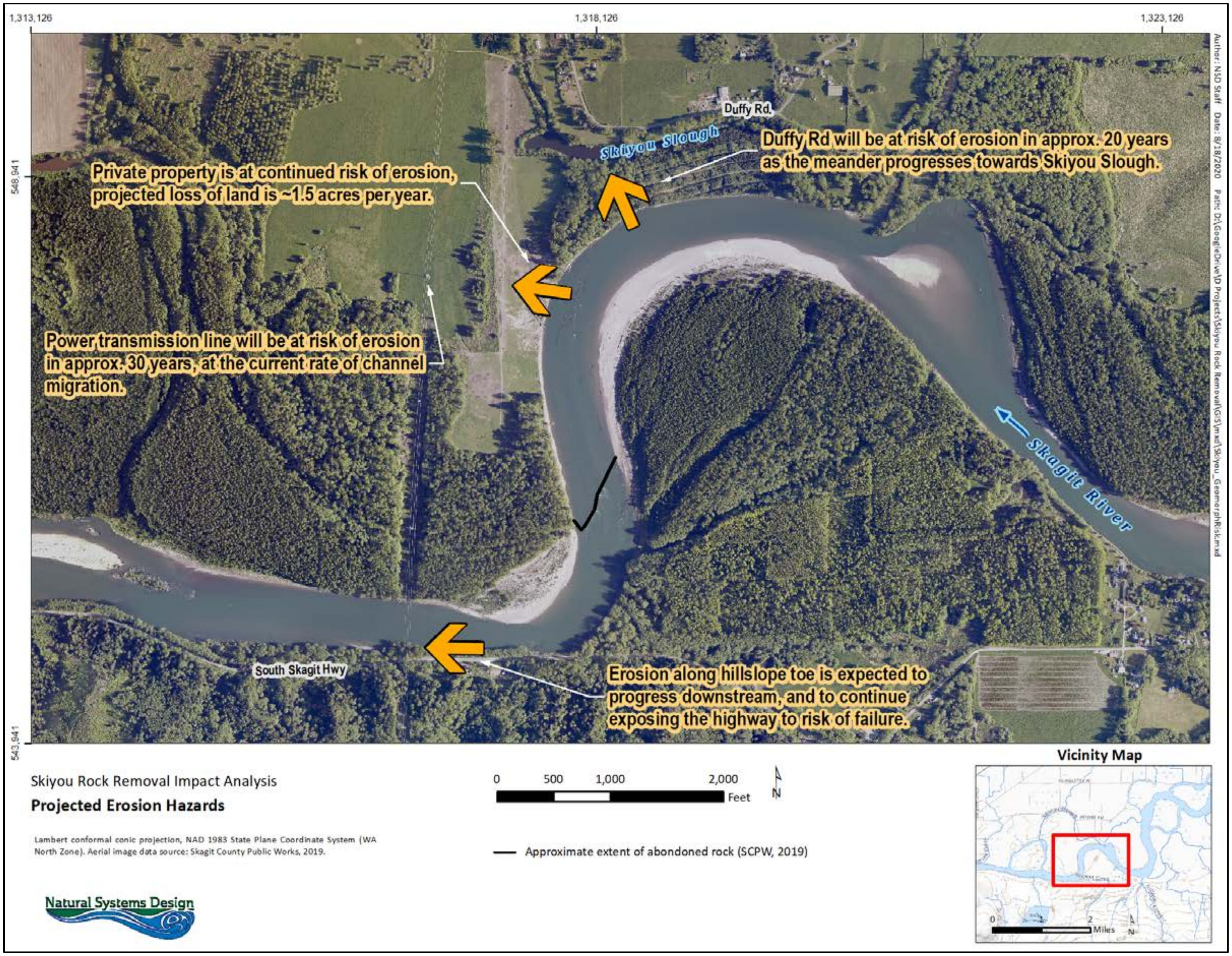

Figure 21. Map of erosion hazards based on historical annual average channel migration rates and expected future trends.

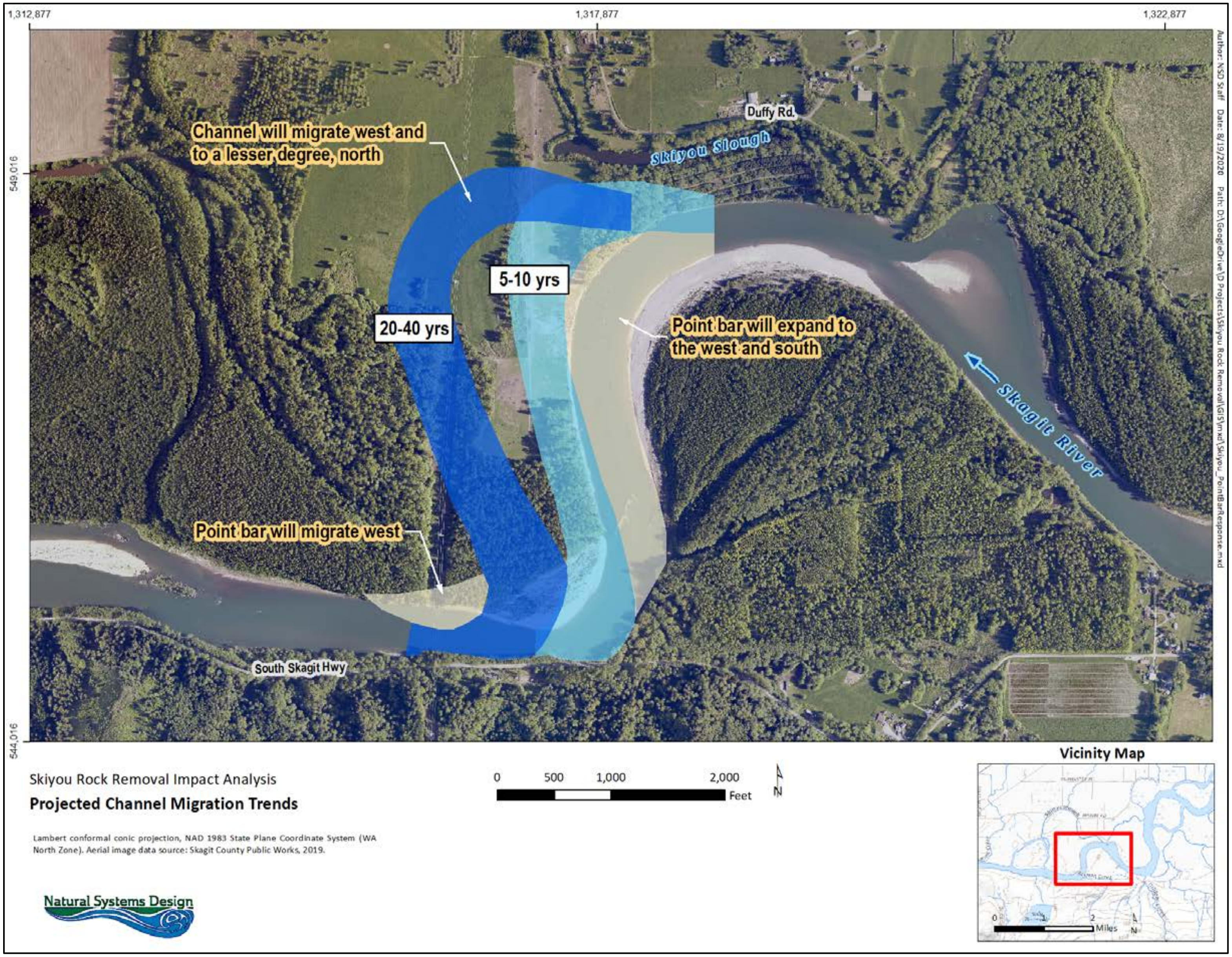

Figure 22. Illustration of general channel migration trends in the Skiyou Reach of the Skagit River.

EXISTING HABITAT

The Skiyou reach of the Skagit River is characterized by a single-thread channel with a relatively straight planform. This differs significantly from its anabranching channels in the 1890s and the current anabranching of the Skagit River upstream in the Ross Island Reach (Figure 22). Typical habitat features such as pools, large wood, and side channels are largely absent in the study area. Furthermore, the quality of available habitat features is low; pools are present along the outer meander bends, but these are areas of high velocity without refuge. Small amounts of large wood are found along the channel margins where erosion and bed scour have exhumed old pieces. Side channels and off-channel habitat are likely the best opportunities in the Skiyou Reach for aquatic species, though the hydraulic model indicates that connection with the floodplain is currently limited below ~26,000 cfs. This means that at flows below the 12% exceedance probability, floodplain habitat along the left bank is not connected with the mainstem.

The abandoned rock is creating local hydraulic complexity in a channel that is otherwise barren of channel structure. Several deep pools are created downstream of the intact rock segments, and the low velocity zone provided by the flow obstruction acts as refuge for aquatic species. Local accounts report this feature as preferable for fishing (personal communication with Emily Derenne, 2020). A river otter was spotted in the low velocity zone during the field survey.

CONCLUSIONS AND RECOMMENDATIONS

Based on findings from the field survey, hydraulic analysis, and geomorphic assessment, the effect of the rock is limited to low flow conditions and spatially localized. There is no direct impact to South Skagit Highway downstream from the rock and no significant contribution to erosion of the right bank along Parcels P40315 and P40326. Analysis of historical aerial imagery suggests that larger reach-scale processes of the Skagit River are driving channel migration patterns in the Skiyou reach, particularly along the Benson property upstream of the rock. This channel migration will result in further losses of Benson property (Parcels P40315 and P40326) and pose threat to powerlines and South Skagit highway (Figure 23).

Translation of both the upstream and downstream meander bends has historically been trending in a down-valley direction. Continued erosion of the Benson parcel and embankment toe of South Skagit Highway is expected in the immediate and long-term future (Figure 23).

Human disturbances are likely exacerbating flood and erosion issues. Confinement of the main channel through bank hardening and levees increase stream power and the erosive energy of the Skagit River at lower discharges. Disconnection of the floodplain and its sloughs also contributes toward increased erosion potential of the Skagit River.

Recommendations of this study are as follows:

1. The rock should be left in place. Impacts to South Skagit Highway are negligible, and erosion of upstream property is primarily linked to reach-scale patterns of erosion and aggradation. Furthermore, the intact rock segments are creating beneficial in-channel habitat that is otherwise limited in availability. The cost to mechanically remove the rock will provide minimal benefit, and is expected to fail under natural processes in less than 10 years.
2. Continued migration of the Skagit River will result in continued land loss of the Benson family property (Parcels P40315 and P40326) and will put South Skagit Highway, power transmission towers and lines, and other landowners in the area at further risk. Any actions should accommodate the Skagit River's natural processes and align with the prevailing flow and sediment transport regimes of the Middle

Skagit River. Additional study is needed to evaluate the implications of passive (natural channel migration) or active (restoration) reconnection of the Skagit River to Skiyou Slough. Expanding the domain of the hydraulic model used in this study would provide valuable information to evaluate the implications to habitat, South Skagit Highway, critical infrastructure, Duffy and Hoehn Road, and private landowners.

Recommended Next Steps

The Skagit Watershed Council Middle Skagit Reach Assessment (2011) identified the Skiyou reach as a "high" potential for restoration and protection actions, due to the relatively large floodplain areas and their functional capacity. A holistic strategic plan of the Skiyou Island Reach of the Middle Skagit River could help local landowners, address the threat to power transmission towers, improve flood conveyance, and provide large scale habitat restoration. We recommend re-directing funding previously intended to remove the Skiyou abandoned rock to begin a larger scale floodplain assessment of the Skiyou Reach that assesses consequences of Skagit flowing into Skiyou Slough, risk of continued channel migration to infrastructure (South Skagit highway, powerline, Duffy road) and property, and potential habitat improvements of a large-scale restoration project.

Hydraulic modeling begun in this study could be expanded to investigate flood inundation and erosion across and adjacent to Skiyou Island. Restoring an anabranching channel morphology as it once existed in the Skiyou Reach, and presently sustained in the Ross Island reach upstream, could provide tremendous improvements to the quality, quantity, and diversity of aquatic habitat in the Skagit basin. The remaining funding in the Skiyou rock project is sufficient to make substantial progress on these assessments and towards developing a strategic plan for the Skiyou Reach that would include recommendations for restoration, infrastructure protection, and flood relief for affected landowners. Note that a feasibility study was conducted for the enhancement of Hart Slough and Hart Island in 2003, which recognized the potential for fish habitat improvement by increasing connectivity with a historic channel of the Skagit River (Inter-Fluve, 2003).

Understanding the flow and sediment exchange between the mainstem Skagit River and its historic floodplain is critical for long-term planning. This study has identified multiple erosion hazards within a 1.5-mile subreach of the Skagit River, and indicates that channel migration will necessitate protection or repair of critical infrastructure in the next 20-30 years. Restoration of an anabranching reach (Figure 24) would distribute flows and possibly reduce risk of South Skagit highway washouts. Anabranching could also increase salmonid habitat two- to three-fold, as well as creating much needed off-channel habitat. We recommend expanding the spatial extent of the hydraulic and geomorphic assessment to include the Gilligan revetment and floodplain (left bank upstream of rock), Skiyou Slough, Deadman Slough and extends downstream of lower Hansen Creek confluence.

This work would be closely coordinated with regional stakeholders and local landowners. Given the potential of the Skiyou Reach for off-channel habitat improvement and potential flood relief, furthering this work will build upon ongoing restoration efforts towards a long-term master plan of the Skagit Valley.

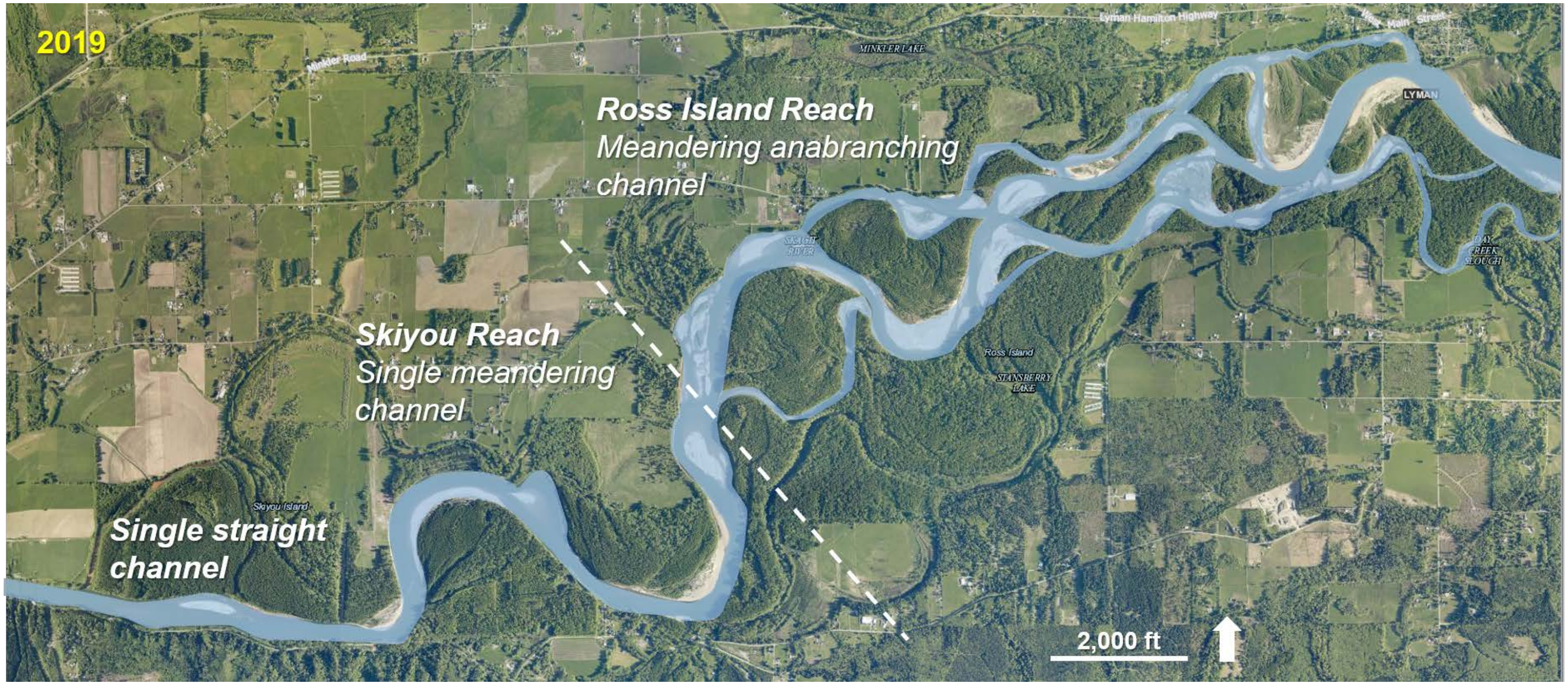

Figure 23. Channel planforms in the Skiyou and Ross Island reaches. Prior to 1890s, the Skiyou Reach had a meandering anabranch planform similar to current conditions in the Ross Island Reach upstream. Existing flow paths are highlighted in light blue according to 2019 aerial imagery.

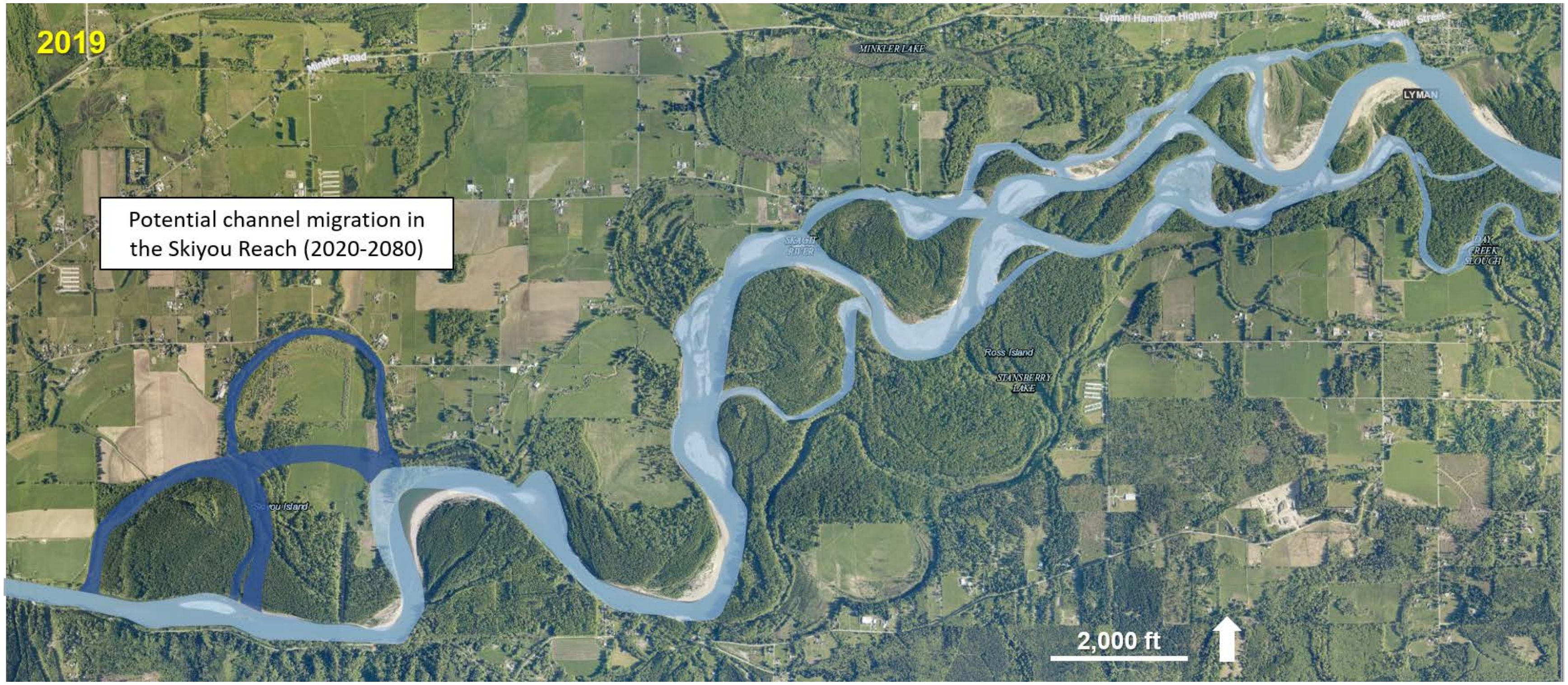

Figure 24. Illustration of one possible restoration scenario of the Skiyou Reach. Over the next several decades, the Skiyou Reach has potential to evolve back into anabranching channel. This could be realized sooner through restoration actions that significantly improve aquatic habitat, increase flood conveyance, and reduce risk to South Skagit highway. Existing flow paths are highlighted in light blue according to 2019 aerial imagery. Potential flow paths from future channel migration, or restoration efforts, are shown in dark blue.

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APPENDIX A – FIELD RECONNAISSANCE PHOTOS (MARCH 10, 2020)

Figure 1. Close view of Skiyou rock looking upstream towards right bank.

Figure 2. Skiyou rock, view from right channel margin. Log is racked on upstream edge of the left rock segment. Flow direction from right to left of photo.

Figure 3. Skiyou bank rock on right bank. Flow direction from right to left of photo. Scour and undermining of the streambank is visible around the rock.

Figure 4. View of Skiyou rock from upstream looking downstream. The weir effect is visible, as flow is overtopping the intact rock segments. Discharge at the site is approximately 13,900 cfs on March 10, 2020.

Figure 5. Left bank along the South Skagit Highway, view looking in the upstream direction. Riprap is visible in the foreground of the photo. Note eroding bank upstream where riprap is not present.

Figure 6. Left bank along South Skagit Highway, view looking in the downstream direction. Riprap is visible in the foreground. Active erosion of the streambank was observed downstream of the revetted bank. Shown in the center of the photo is old wood embedded in the streambank, which has been exhumed by the eroding bank.

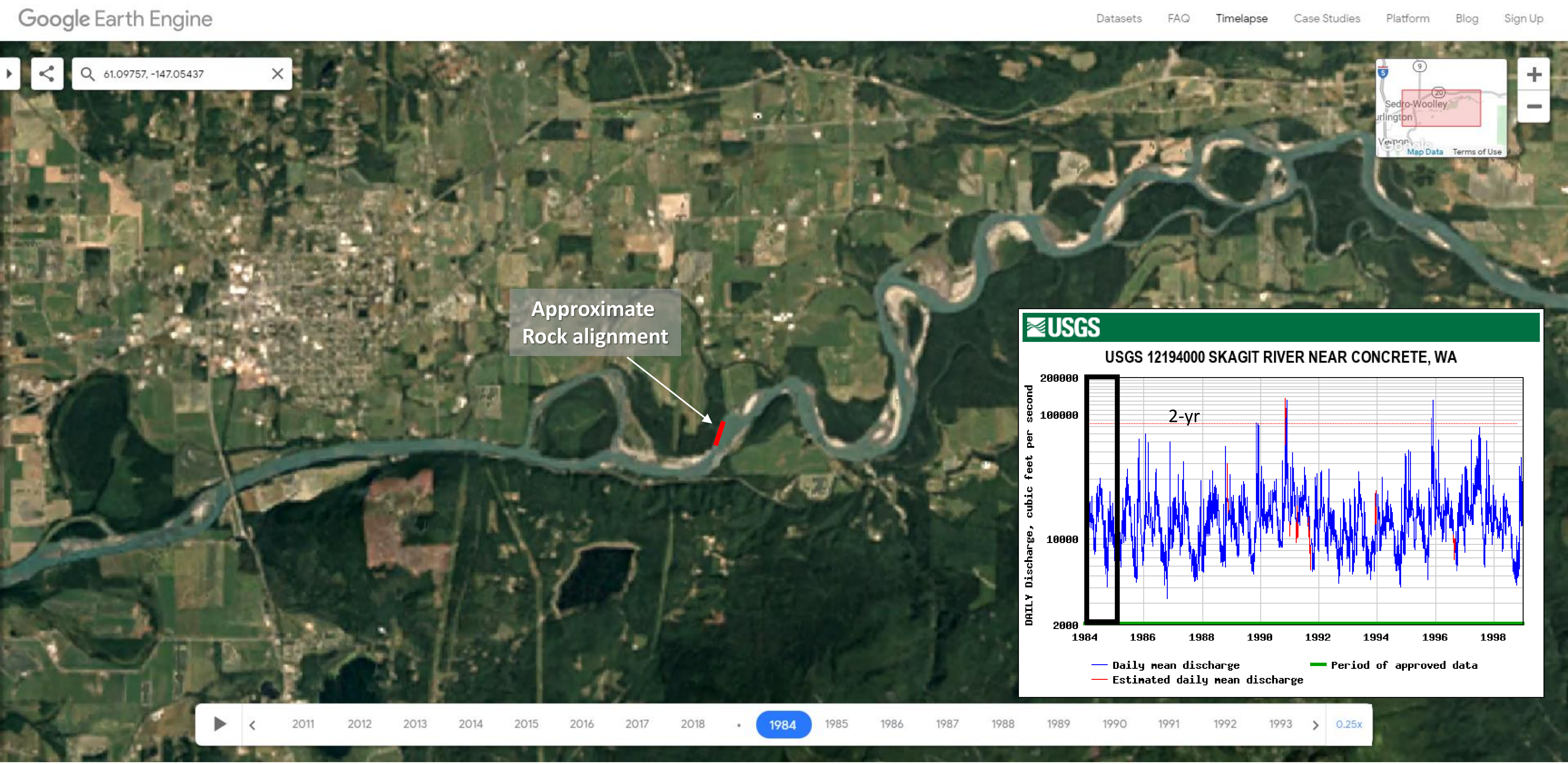
Figure 7. Upstream bank of the Skiyou Slough inlet. Flow direction is from right to left of photo. This entire section of bank has riprap present.

Figure 8. Right bank of the Skagit River immediately downstream of the Skiyou Slough inlet. Flow direction is from right to left of photo. Active sloughing of the streambank indicates undermining of the bank toe.

Figure 9. Right bank of the Skagit River immediately along the Benson parcel and evidence of active erosion, located upstream of Skiyou rock. Flow direction is from right to left of photo. Note that trees on the bank are deposited from recent flood flows (personal communication with Emily Derenne, 2020). Power transmission lines are visible in the background of photo.

Figure 10. Right bank of the Skagit River immediately along the Benson parcel and evidence of active erosion, located upstream of Skiyou rock. Flow direction is from right to left of photo.

APPENDIX B – TIMELAPSE OF SATELLITE IMAGERY FROM 1984 TO 2018 (GOOGLE EARTH ENGINE, 2017)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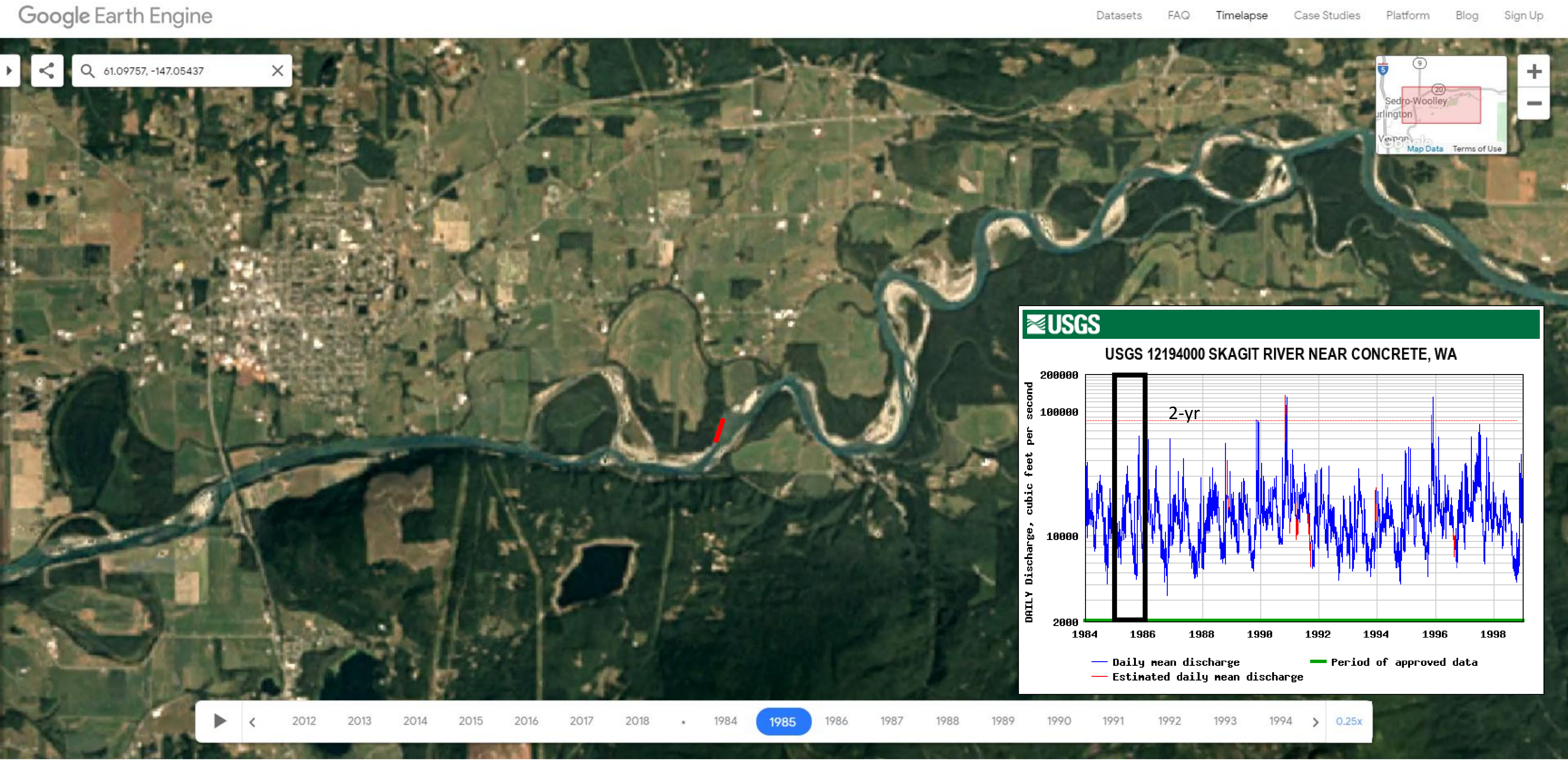
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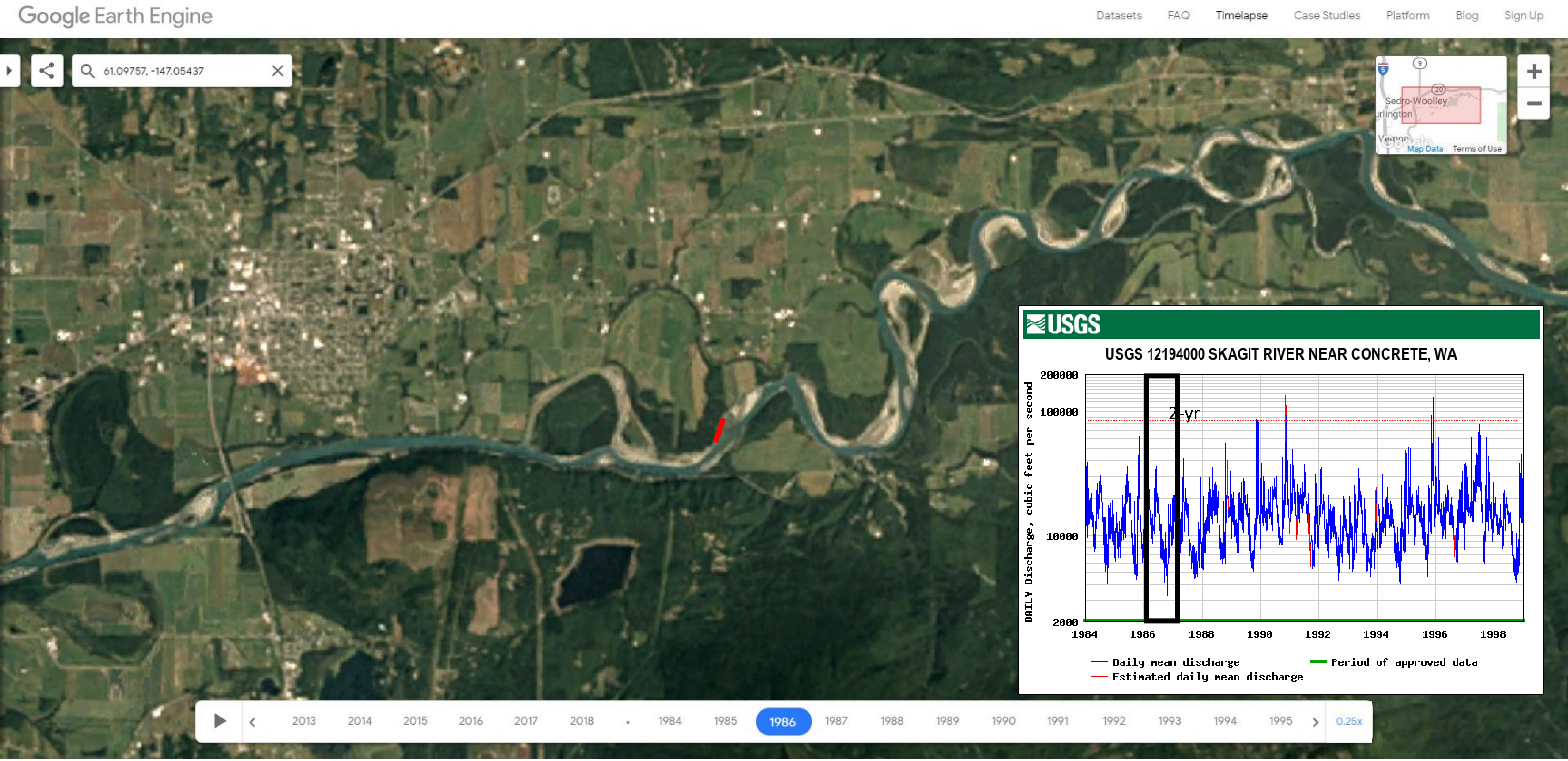

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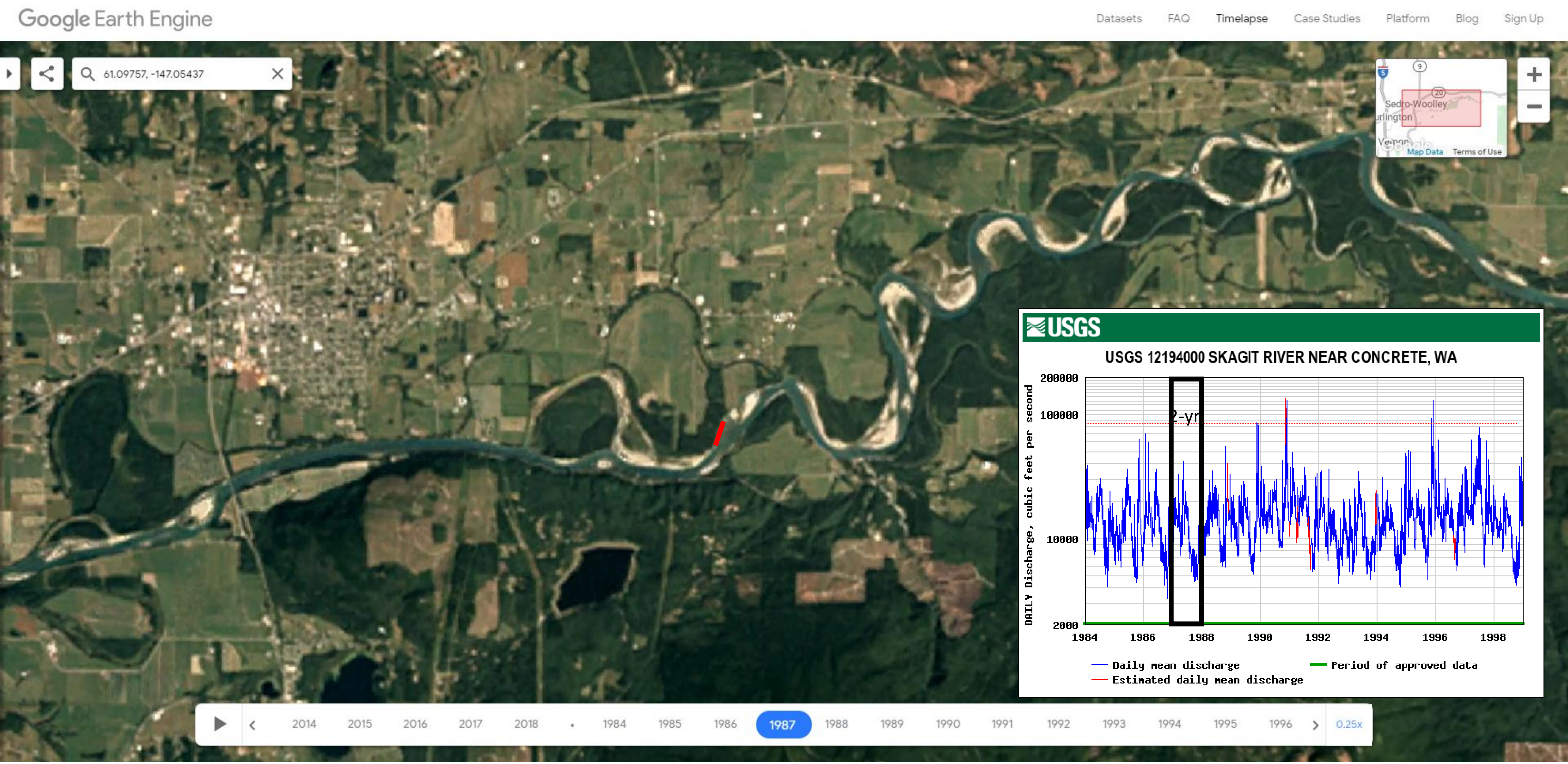

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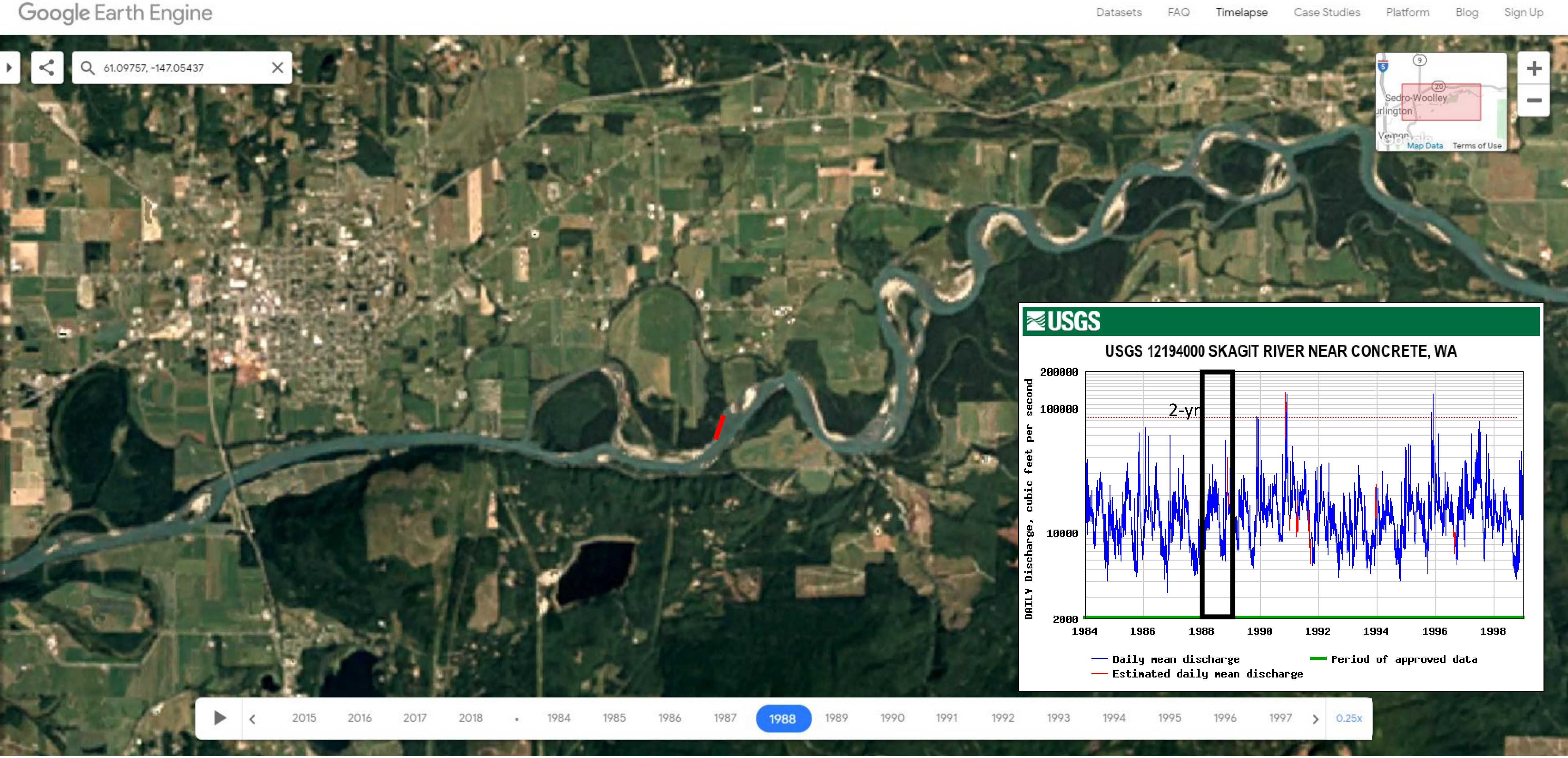
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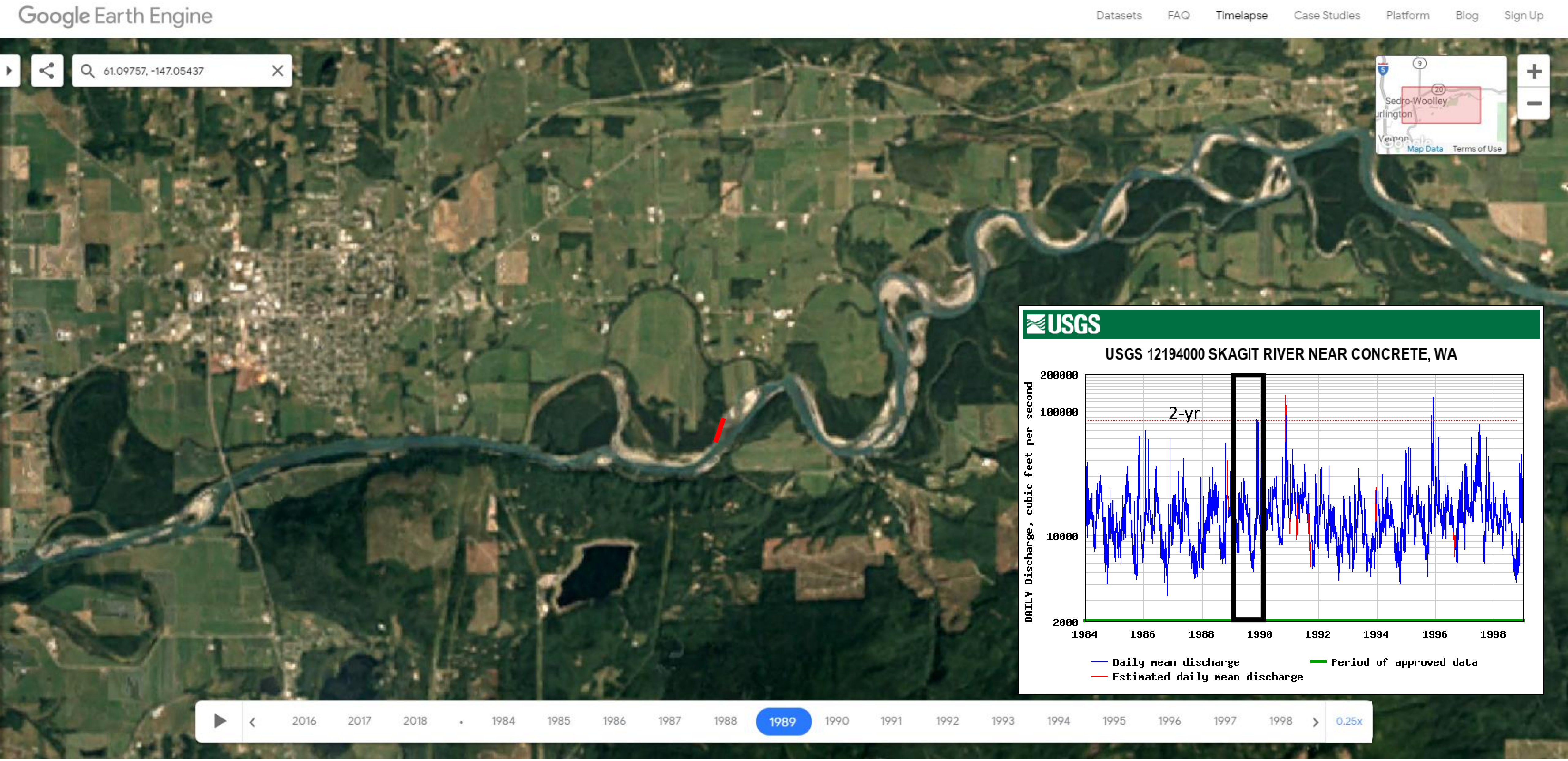
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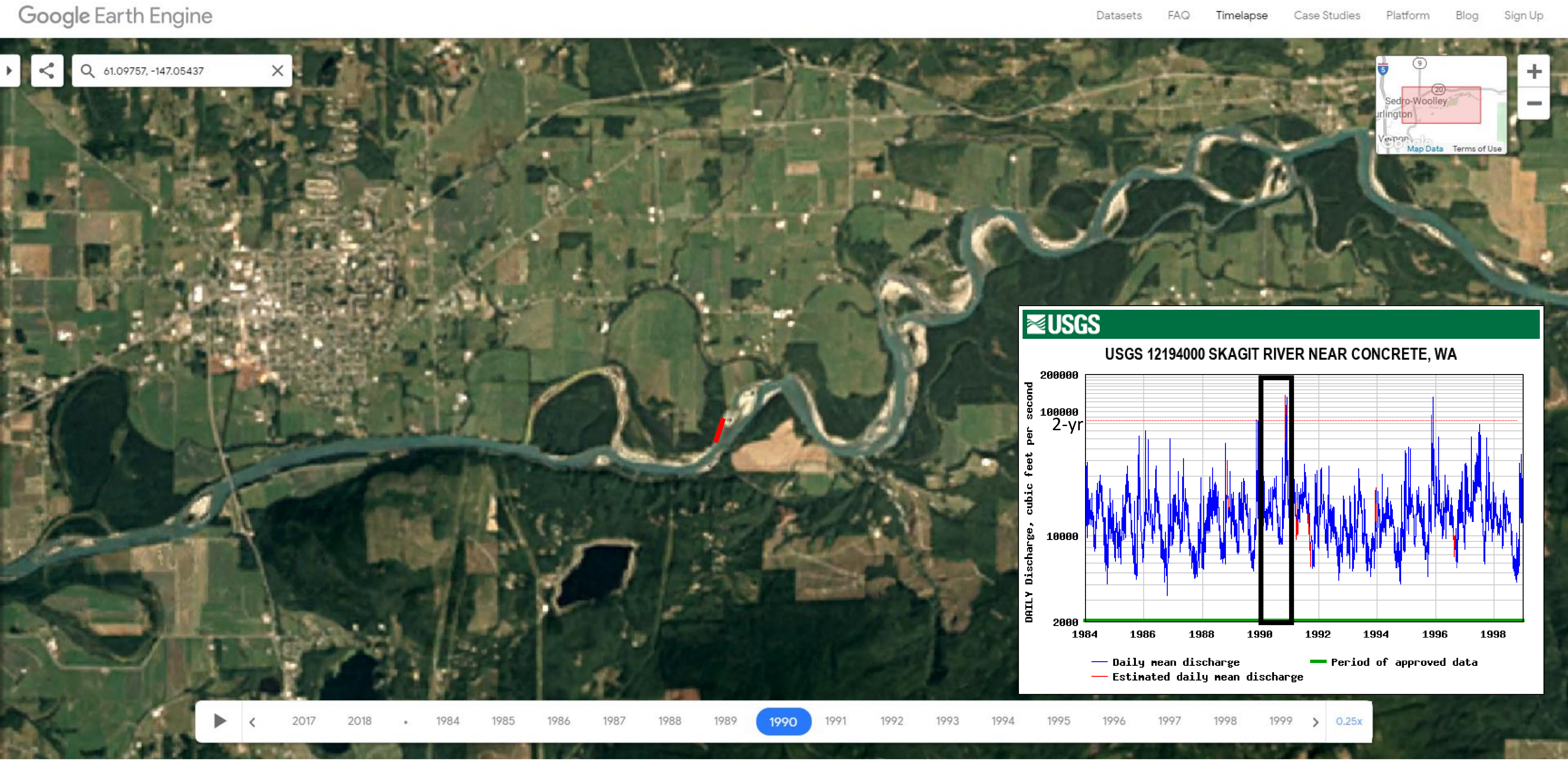
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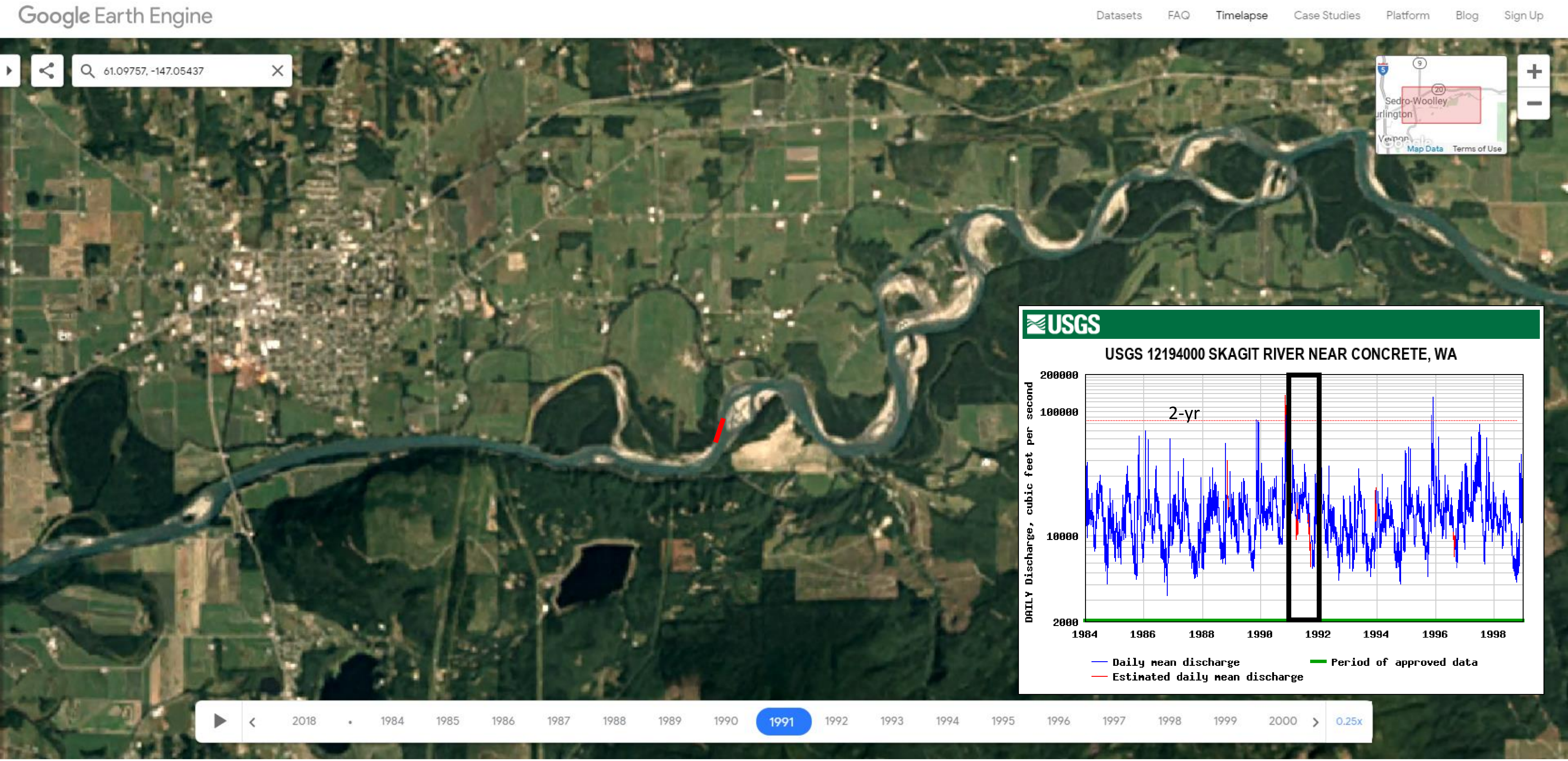
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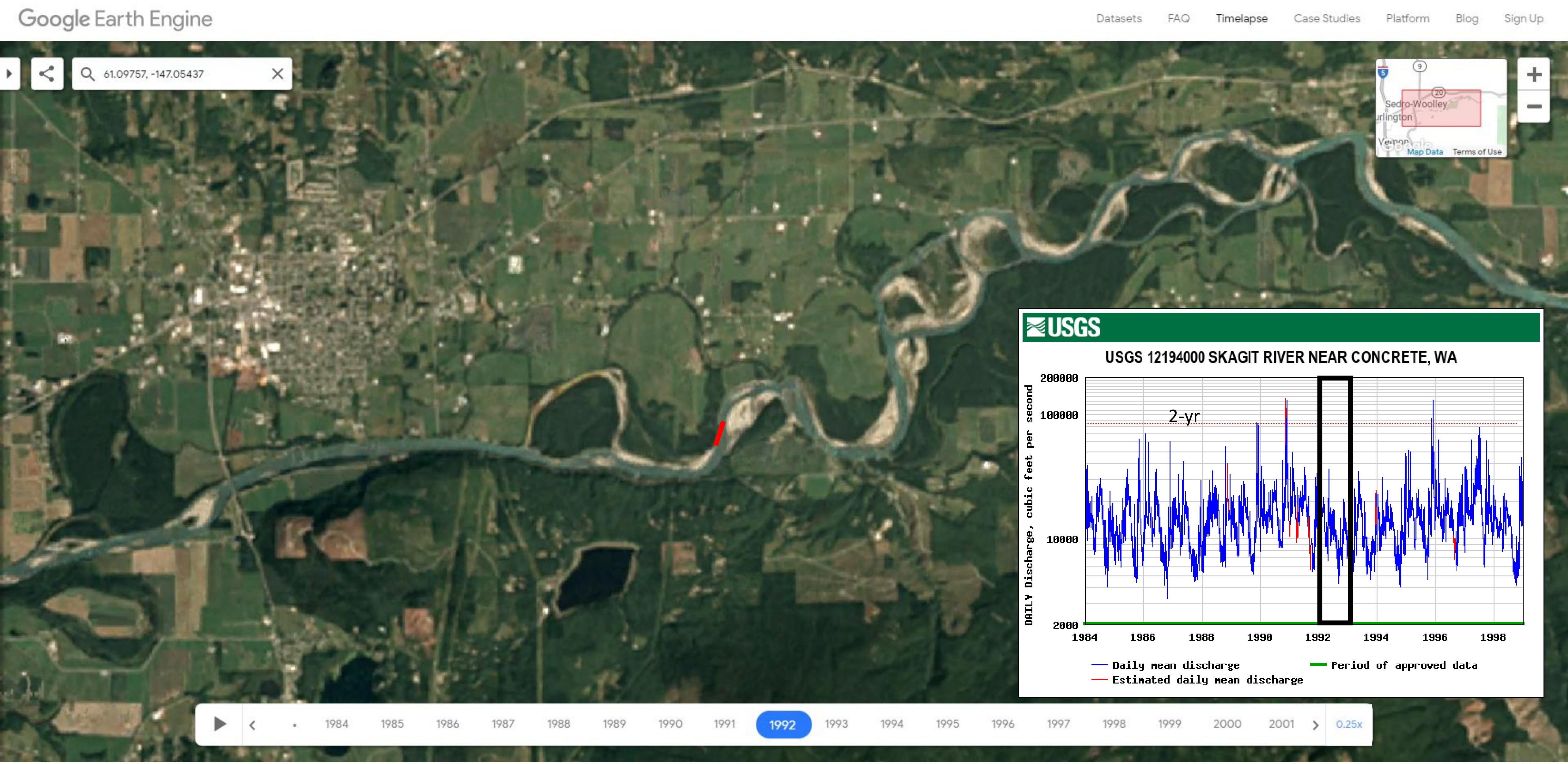

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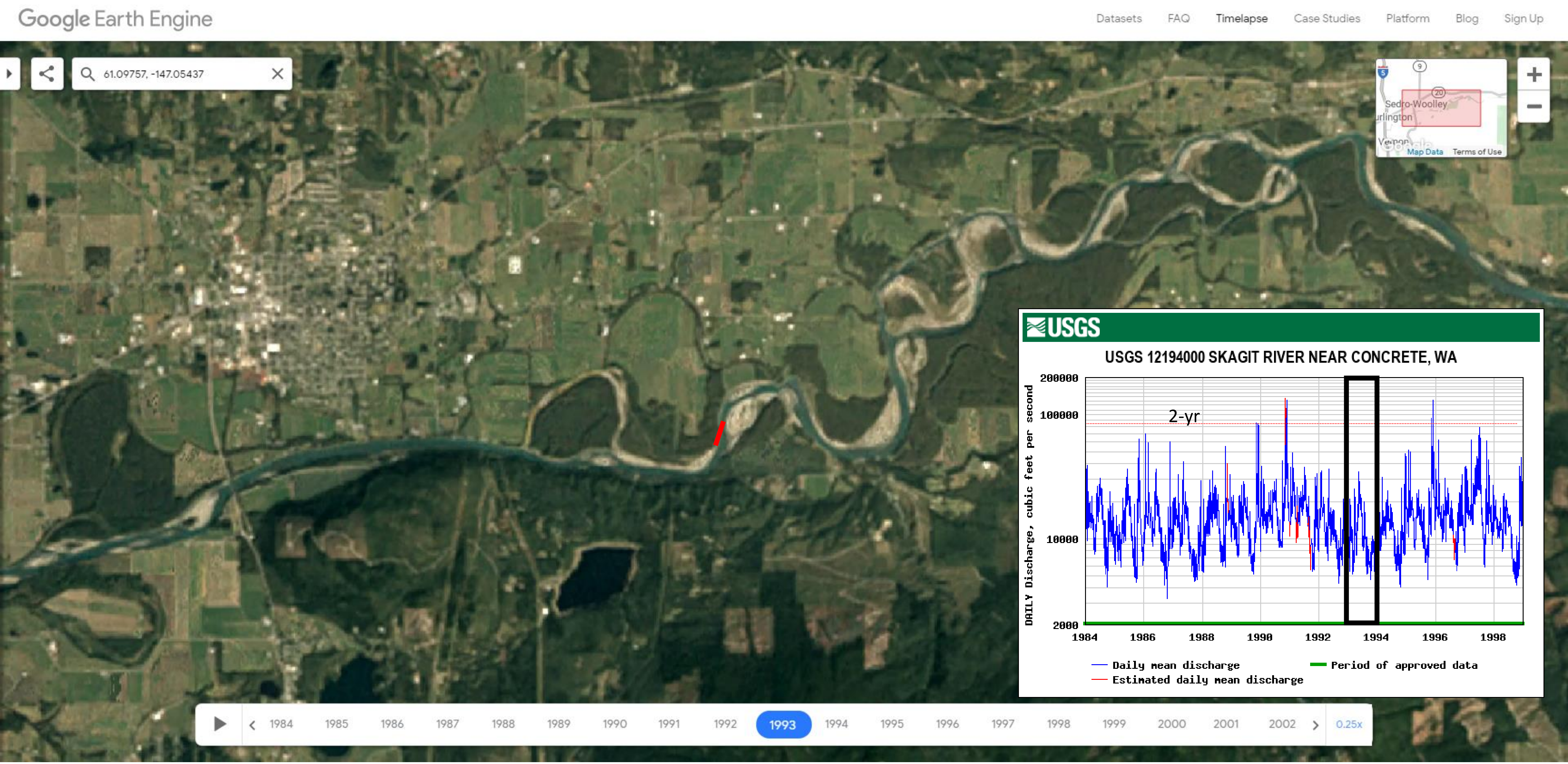
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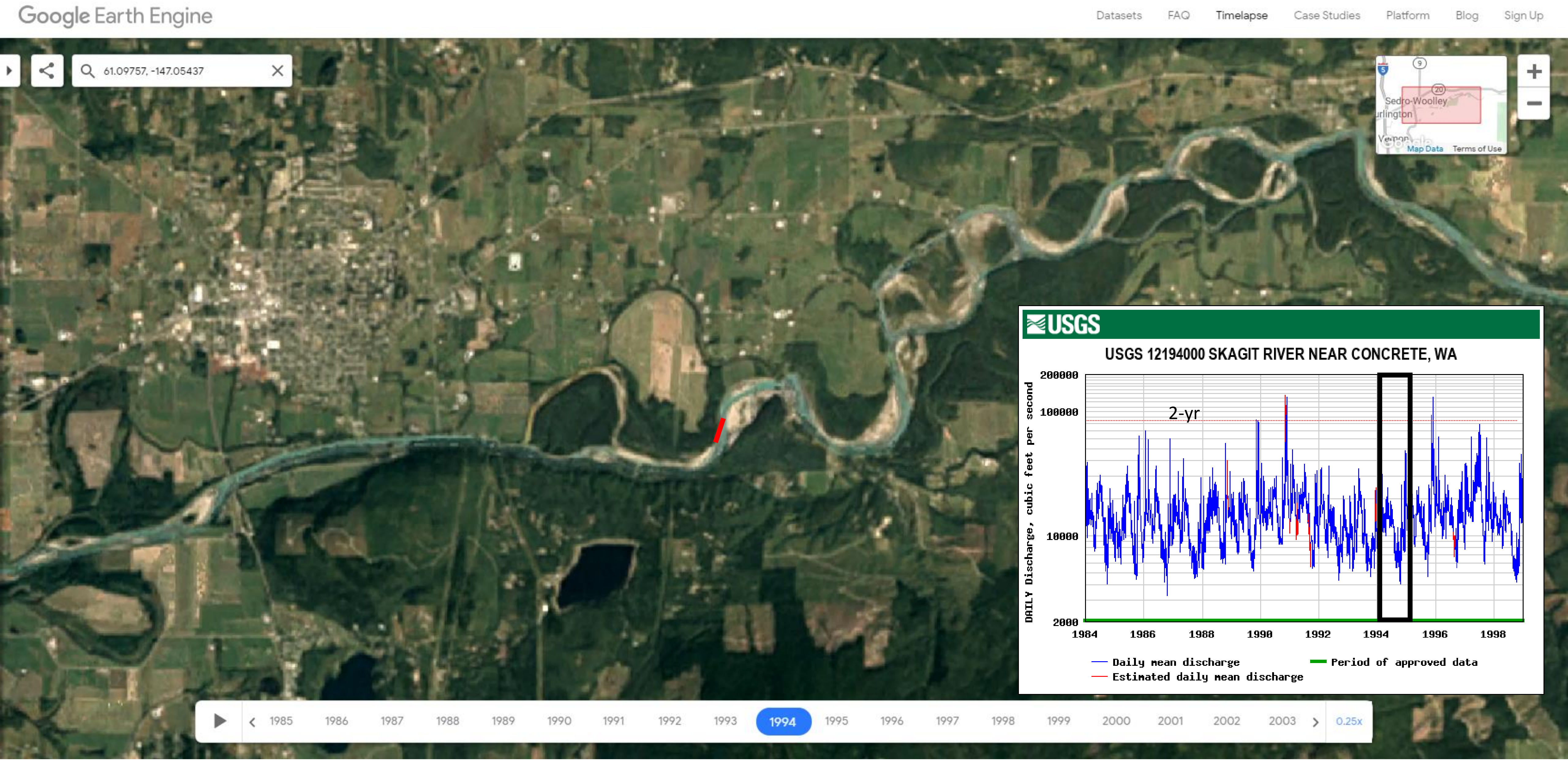
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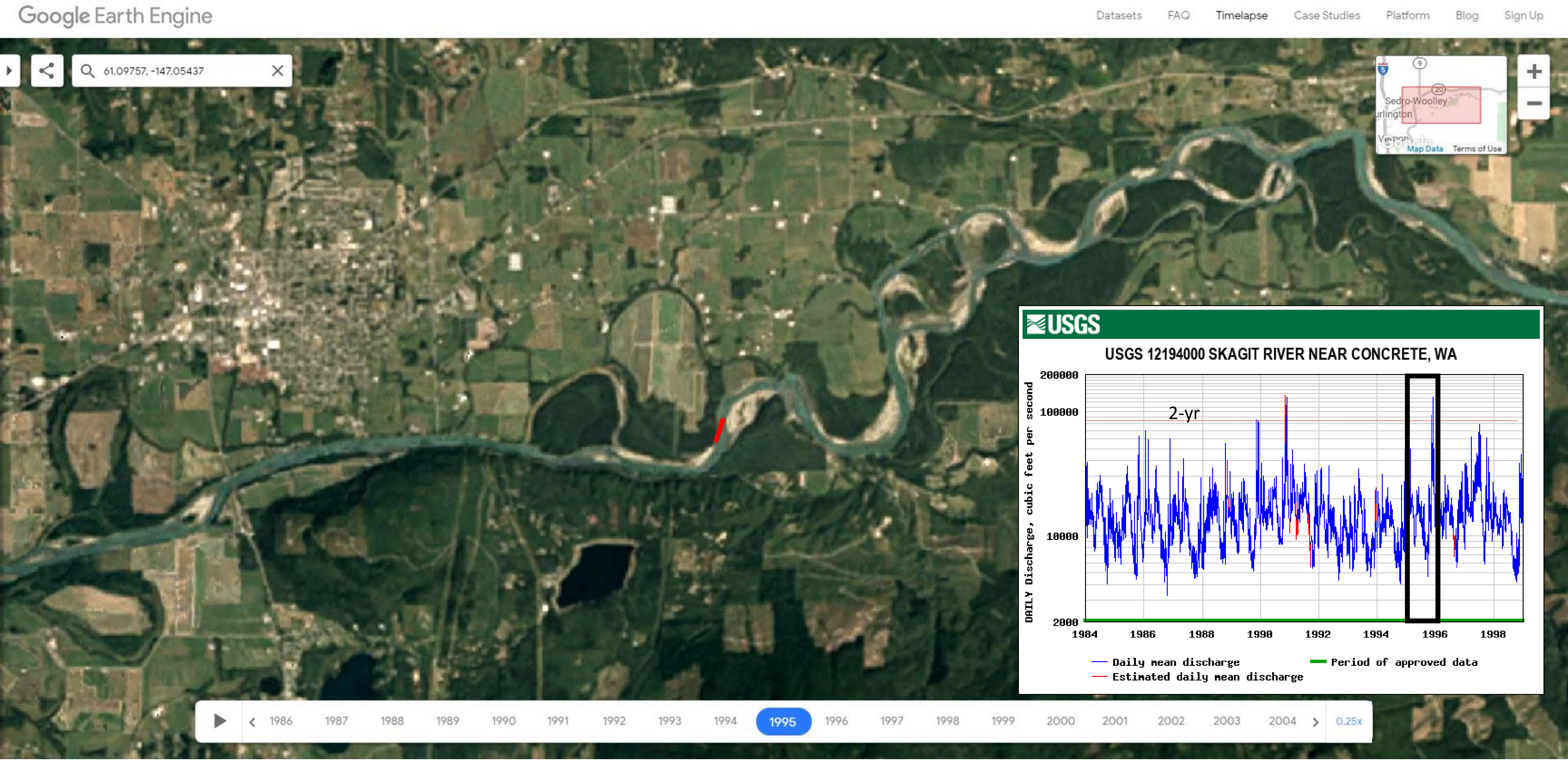
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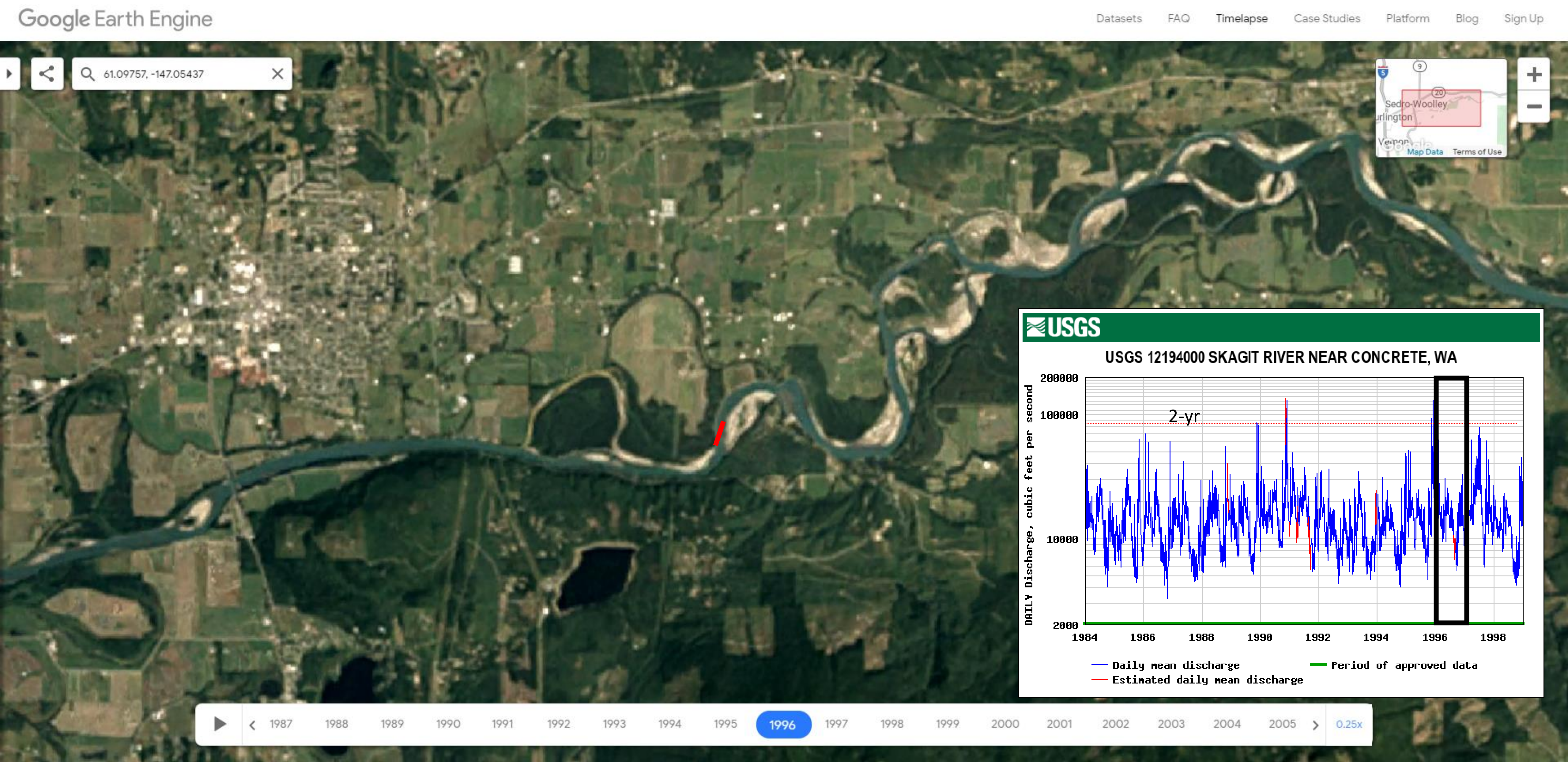
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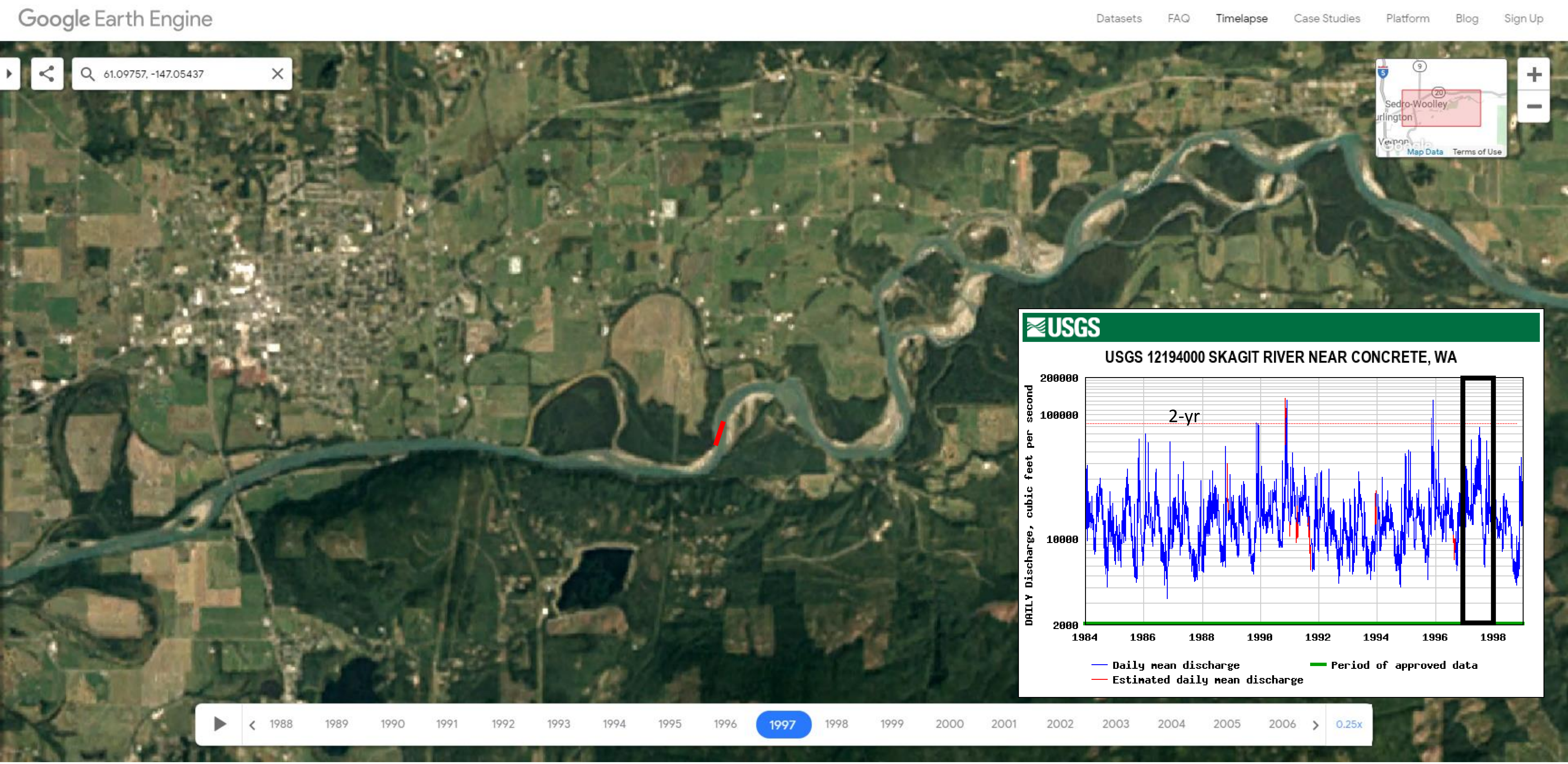
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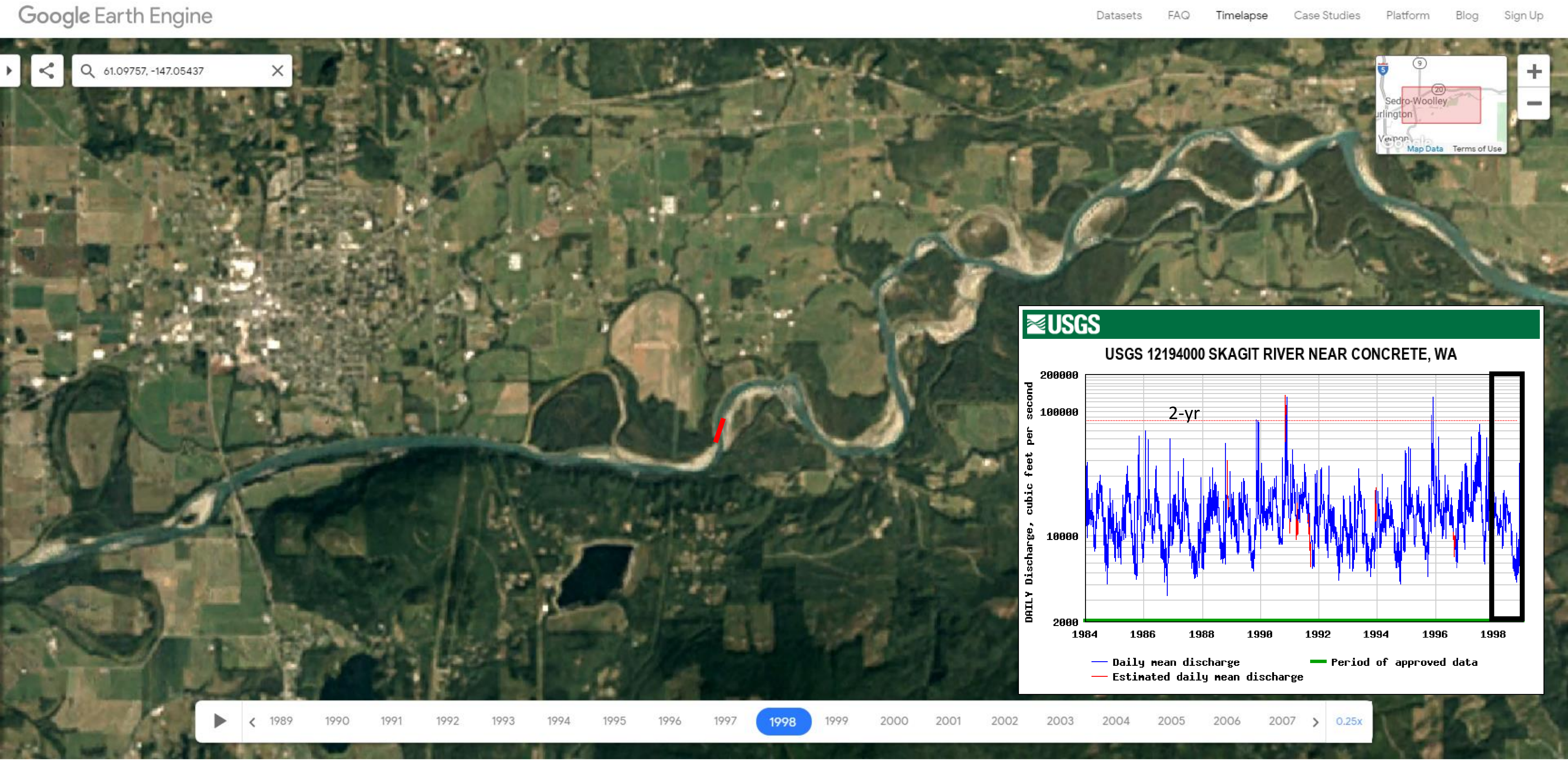

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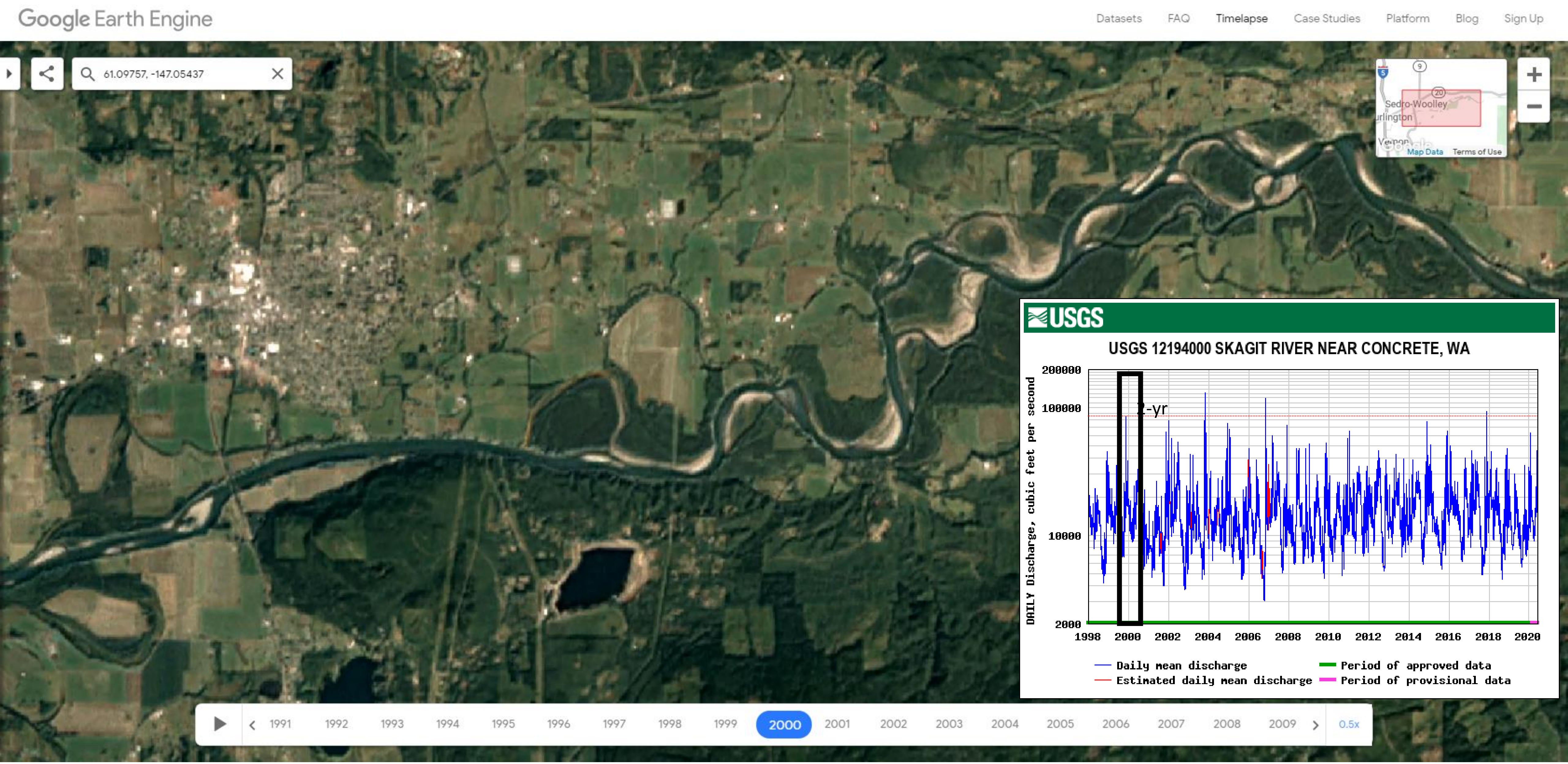
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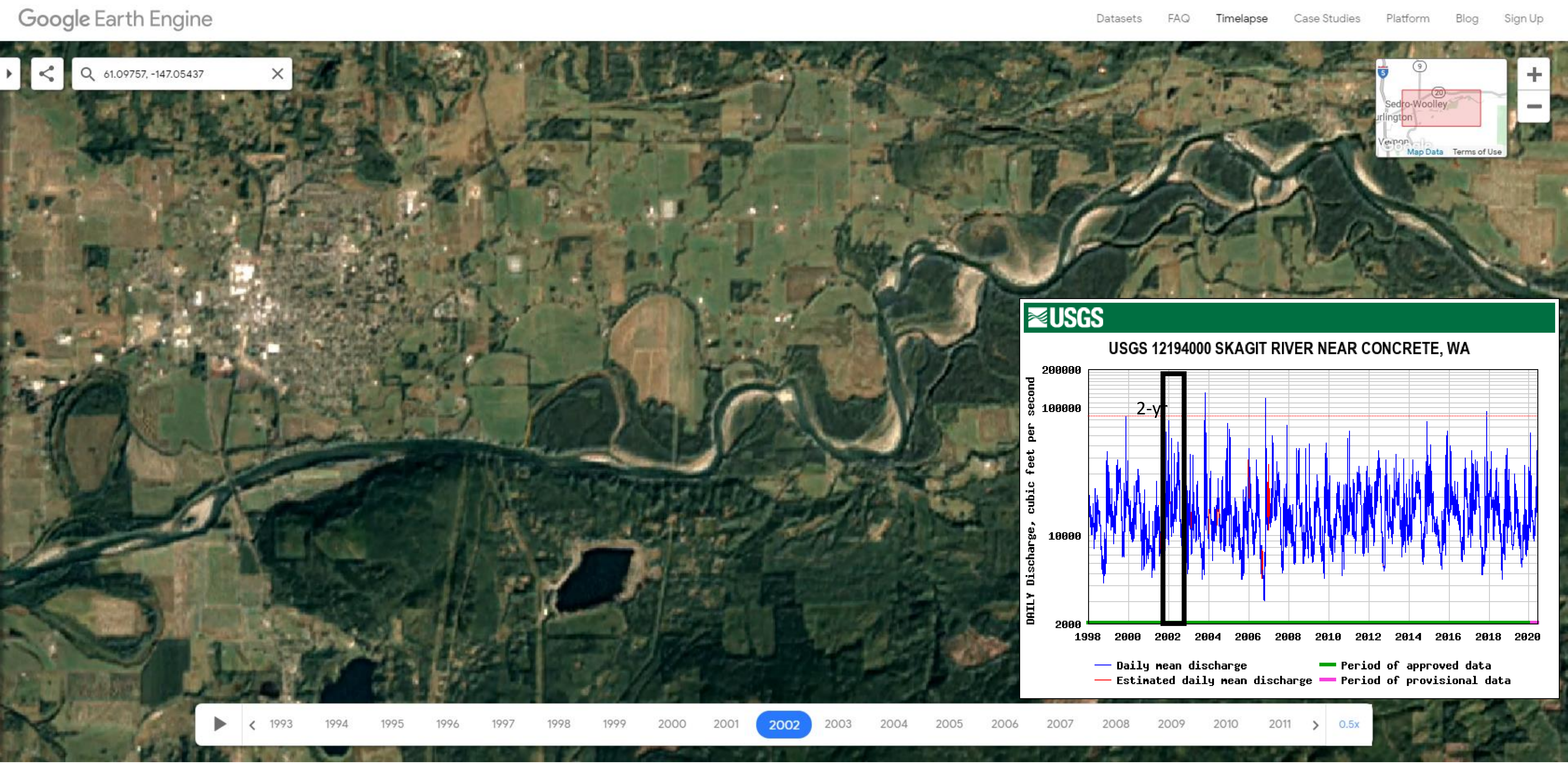

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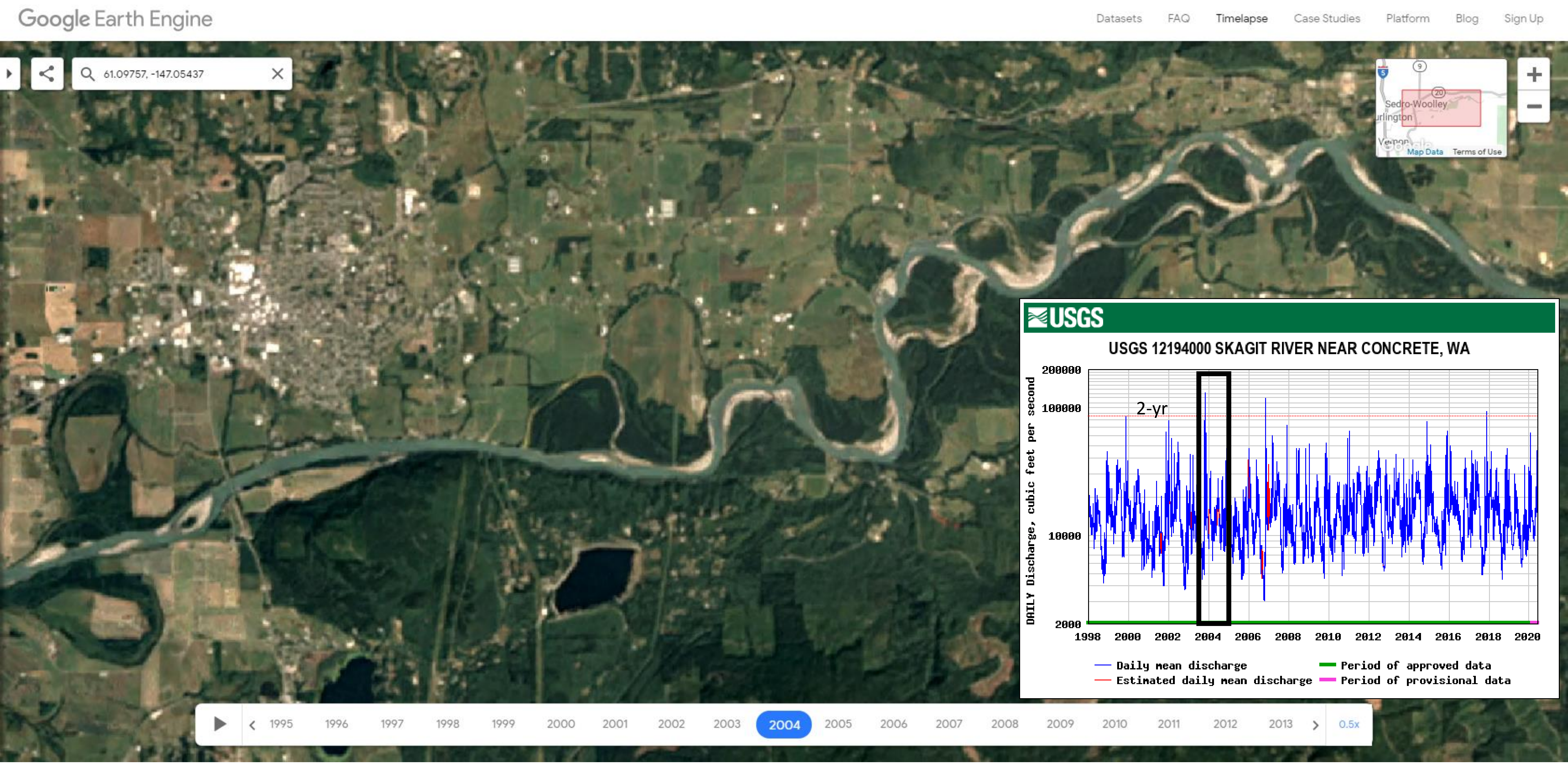
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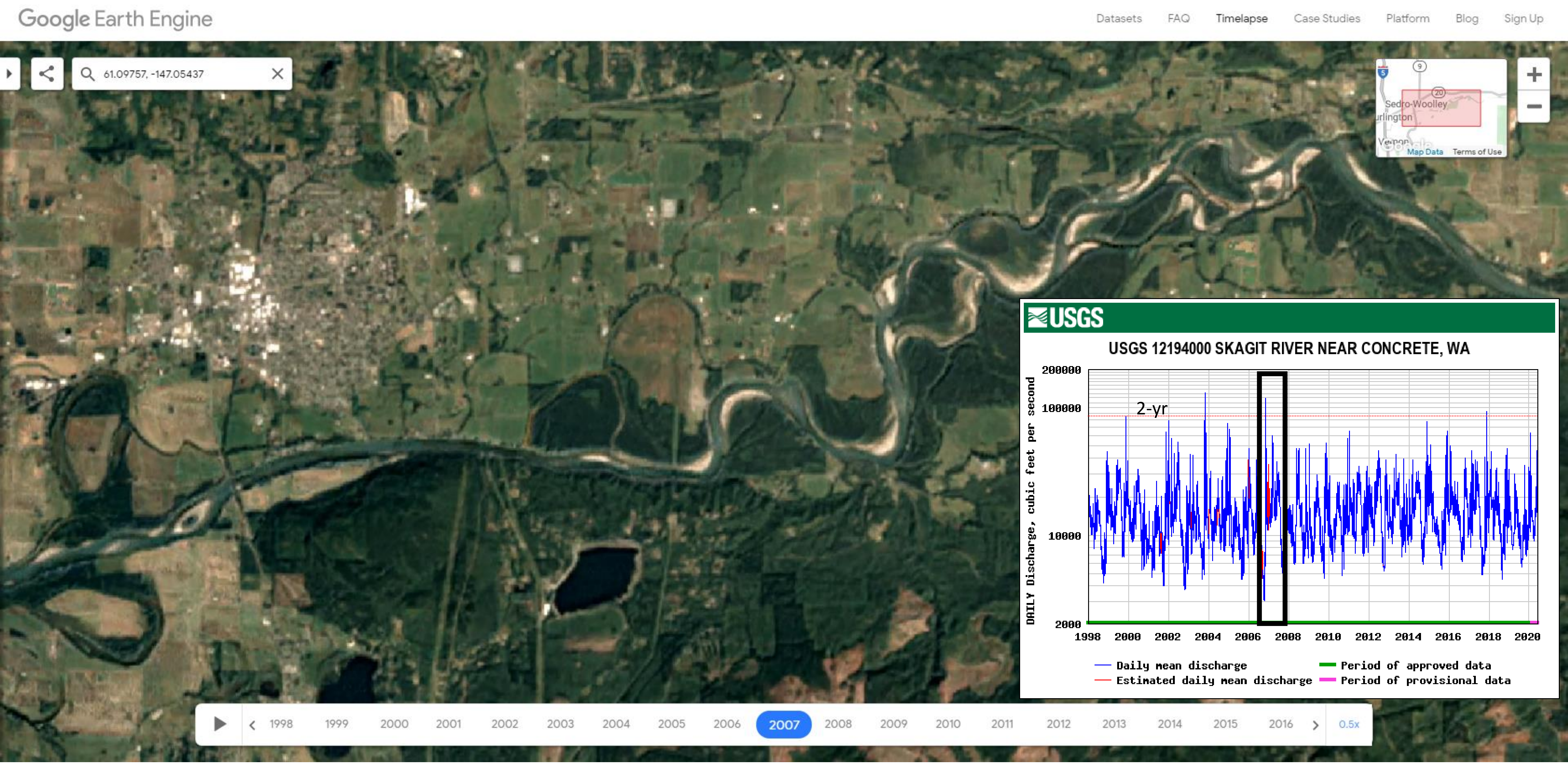
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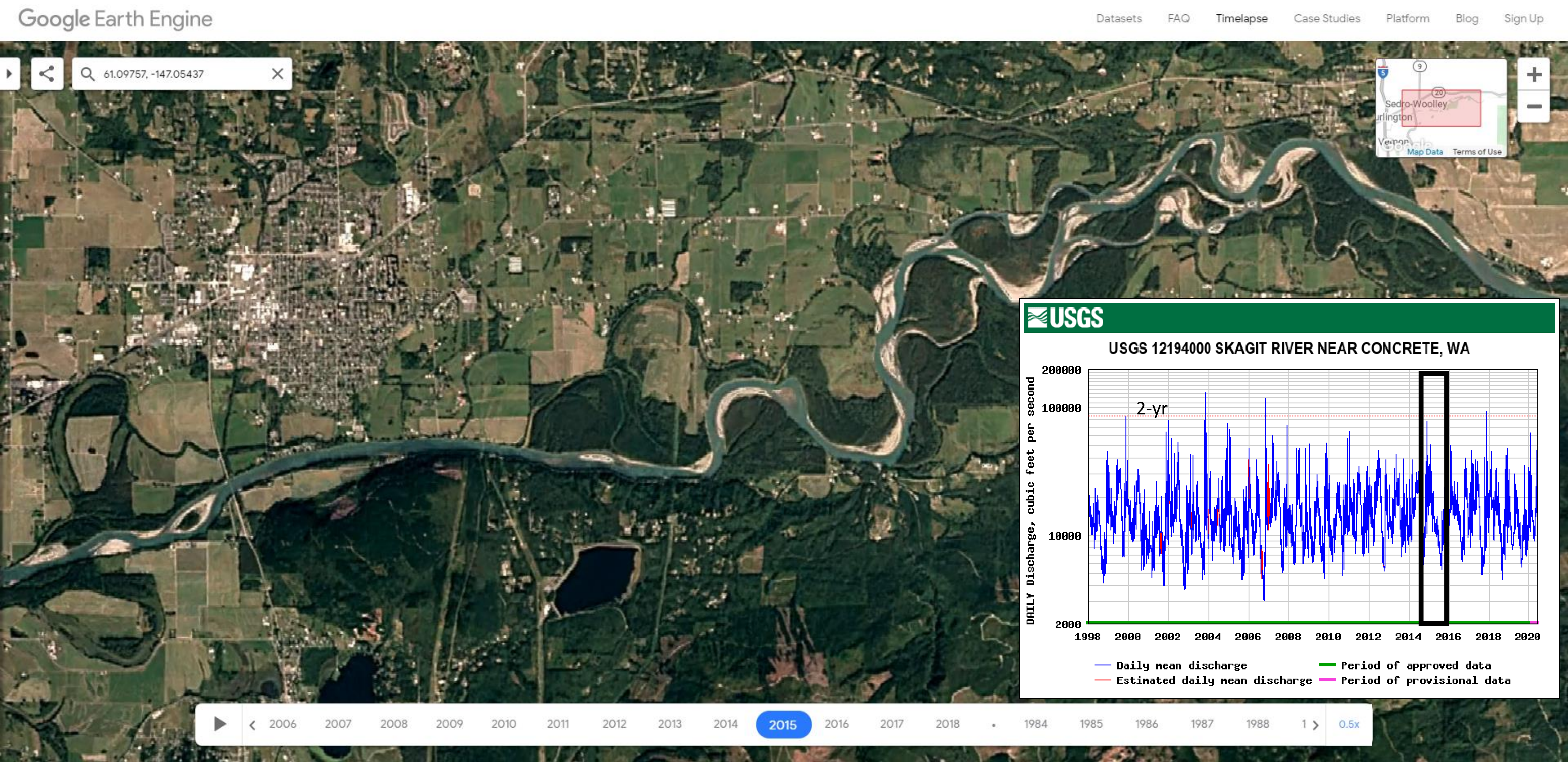
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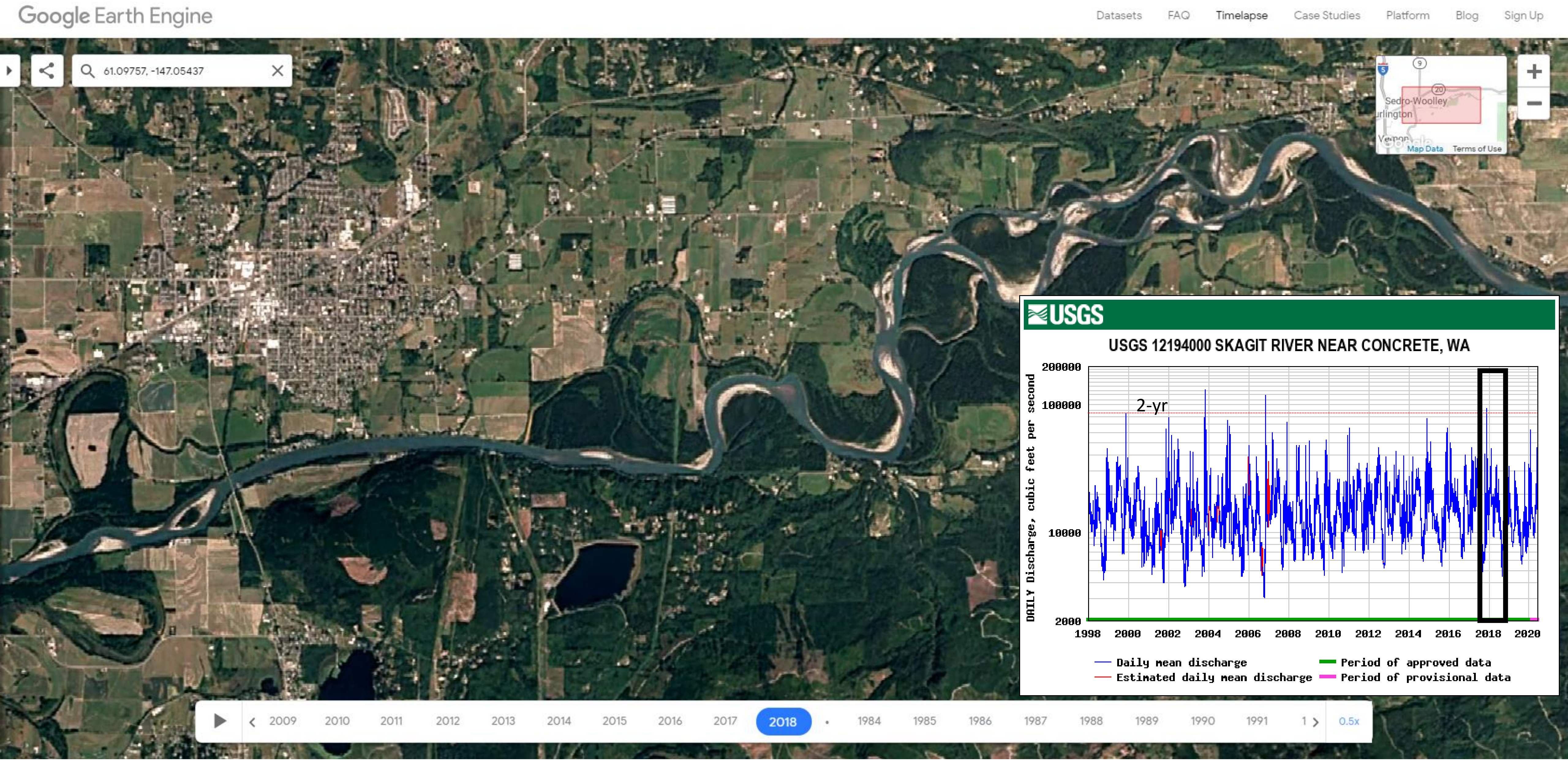
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