James Rees
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Like Water on a Rock:
Correlating Geology and Channel Patterns in the Tuolumne Watershed

Abstract

The channel patterns of the Tuolumne Watershed vary greatly, from the steep reaches of the "Grand Canyon" to the flat meandering channels of Tuolumne Meadows and the Central Valley. Spatial analysis was used to extract stream metrics and channel patterns as they occur over different geologic units. The Tuolumne Watershed was divided into six geologic categories based on age and lithology. Three primary channel patterns, including stream gradient, drainage density, and channel type were determined for the hydrology within each geologic unit. While stream gradient was found to have no correlation with rock type, drainage density and channel type were found to systematically change with rock type suggesting that lithology influences these stream network characteristics.

Introduction

Several distinct geologic units and hydrologic zones are contained within the Tuolumne Watershed. These units are two important factors (but not the only) in determining the channel patterns of the Tuolumne River watershed and its tributaries. This paper uses spatial analysis of hydrologic and geologic data to analyze how different rock types contribute to the overlying channel patterns. Channel patterns, including stream gradient, drainage density, and channel type were compared between different geologic zones to find variation and patterns caused by the watershed's geology. This study aimed to test the hypothesis that underlying lithology plays a fundamental role in dictating fluvial channel patterns.

Geologic Setting

Plutonic rocks formed while subduction was occurring in California during the Mesozoic Era. The Sierran granodioritic batholith was a result of the volcanic arc that existed along the subduction zone. The Jurassic volcanic rock was either a result of local volcanism or accreted from the subducting plate. The Mesozoic meta-sedimentary rock is also exotic, having been accreted to the western margin of California. The Tertiary sedimentary rocks and Quaternary alluvium formed as the Sierran orogeny progressed and erosion carried sediments to the base of the western slopes of the Sierra Nevada. The Tertiary volcanics are a result of regional volcanism that took place over the last 65 million years.

The Upper section, or source zone, of the Tuolumne River flows through the Mesozoic granodioritic intrusion of the Sierra Nevadan Batholith. Downslope of the granodiorite, the watershed is underlain by Tertiary volcanic rocks. Throughout the middle section, or transport zone, of the watershed, the river flows through Triassic and Jurassic volcanic arcs. Just downstream of Don Pedro Reservoir, the river enters its depositional zone, first flowing over Tertiary sedimentary rock, Quaternary alluvial fans that spread out into the Central Valley, and finally ending up in the Quaternary sediment beds of the Modesto Formation, where it converges with the San Joaquin River. Along the river in this zone lie even younger banks of sediment, including mine tailings.

Methods

Data Sources:

Three primary databases were used for spatial analysis, all derived from USGS. These included hydrologic data derived from the USGS National Hydrography Dataset, geologic data from USGS online spatial data site, and elevation data from the USGS 3D Elevation Program (3DEP). Satellite imagery was retrieved from Google Earth.

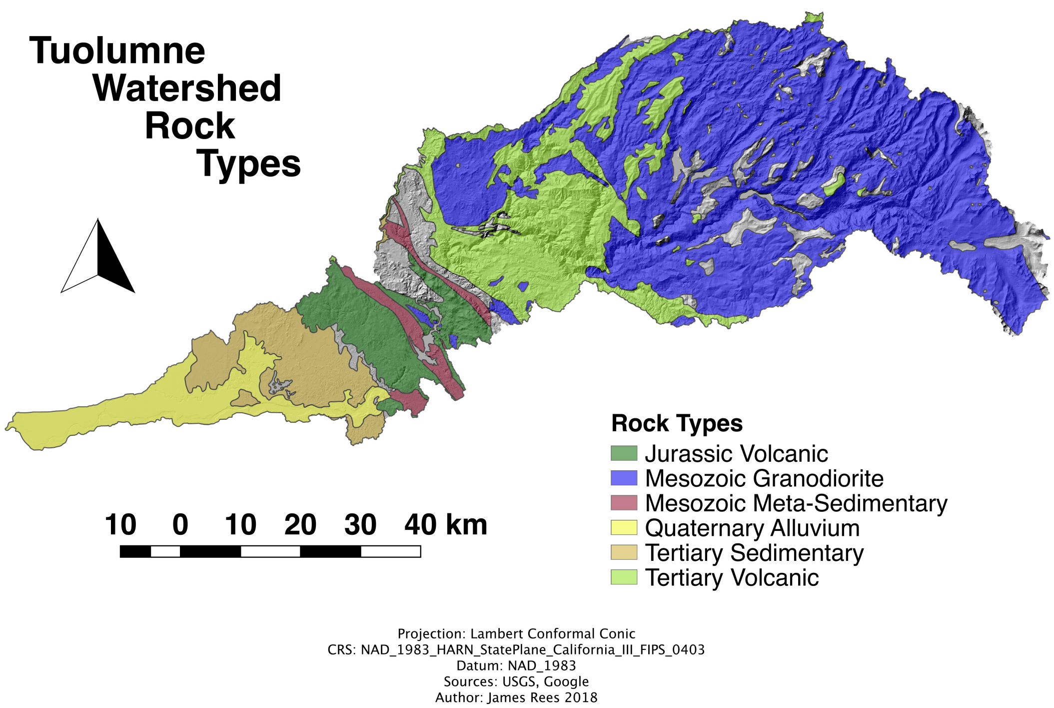

Figure 1: Tuolumne Watershed Rock Types

Spatial Analysis:

Software including ArcGIS 10.4/10.5, QGIS 2.14, and Microsoft Excel (For data analysis) were used. The six most prominent rock types within the watershed were grouped (*Fig. 1*). These include: Jurassic volcanic, Mesozoic meta-sedimentary, Mesozoic granodioritic, Tertiary volcanic, Tertiary sedimentary, and Quaternary alluvial. Channels were created using 1/3 arc-second DEM's for the Tuolumne Watershed.

Stream Gradient was calculated by averaging the slope of all channels within each rock type.

Drainage Density was calculated by dividing the total channel length within each geologic region by the total area underlain by each rocky type within the watershed. For this analysis, Quaternary alluvium was excluded due to issues accurately calculating stream length within this region.

Channel type was found by overlaying the geology of the Tuolumne watershed with satellite imagery derived from Google Earth. NHD HUC 12 sub-basins were identified within each geologic unit. The largest order stream within each sub-basin was examined and categorized based on channel type. The use of sub-basins that excluded the main channel controlled for drainage area and stream order. A definitive channel type could not be established for meta-sedimentary rock because its exposure area was too irregular to entirely cover a HUC 12 sub-basin. The three possible channel types included: braided, straight, and meandering.

Results

Stream Gradient:

Rock Type	Average Stream Slope (degrees)
Jurassic Volcanic	7.14
Mesozoic Granodiorite	17.82
Mesozoic Meta-sedimentary	12.41
Tertiary Volcanic	17.41
Tertiary Sedimentary	1.40
Quaternary Alluvium	1.05

Figure 2: Average stream gradient. Derived from using 3D Analyst tools in ArcGIS 10.4

Drainage Density:

Rock Type	Area of Exposure Within Watershed (km^2)	Total Stream Length (km)	Drainage Density (km^-1)
Mesozoic Granodiorite	2463.8	7204.66	2.92
Tertiary Volcanics	839.90	2030.61	2.42
Mesozoic Meta-sedimentary	111.84	385.65	3.45
Jurassic Volcanics	303.69	816.06	2.69
Tertiary Sedimentary	322.47	929.35	2.88
Quaternary Alluvium	324.40	1204.45	3.71*

Figure 3: Drainage density of each rock type. Derived using geometry calculator in ArcGIS 10.4.

*Calculation does not reflect actual drainage density.

Figure 1: Channel underlain by granodiorite exhibiting straight, poorly incised channels.

Figure 5: Channel underlain by Tertiary volcanic rock. Well incised, straight channels can be observed.

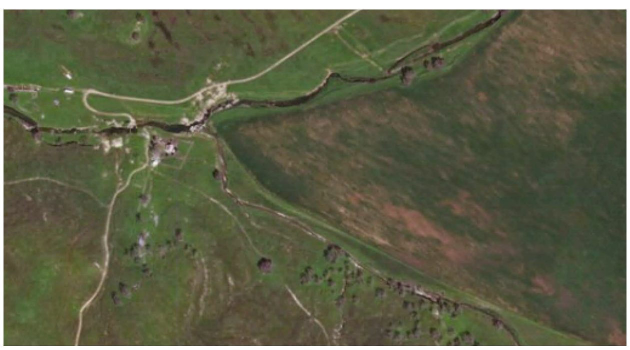

Figure 2: Main channel underlain Jurassic volcanic rock. Exhibits straight channel type and little tributary incision.

Figure 7: Main channel underlain by alluvium and Tertiary sediments exhibiting meandering channel patterns. Extinct channels and oxbow lakes are also visible.

Channel Type

Channels within the watershed exhibit a very straight, unbraided channel type when underlain directly by Mesozoic granodiorite. Reaches tend to cascade or run. Additionally, tributary channels are much less evident within the granodiorite (*Fig. 4).*

The Tertiary volcanics exhibit similar straight, unbraided channels that tend to run rather than create pools. Unlike the granodiorite, tributary channels are much more prominent, exhibiting deep v-shaped incisions (*Fig. 5*).

Jurassic volcanics exhibit straight channels as well, but lack the deep v-shaped erosion of the Tertiary volcanic rock (*Fig. 6*). The Tertiary and Quaternary sediments exhibit mostly meandering channel types. Reaches tend to form pool-riffle-runs. While development around the dam has confined much of this meandering portion, evidence of recent meandering is evident by the multiple extinct channels and oxbow lakes (*Fig. 7*). Meandering channel type is also seen in the flat alluvium of Tuolumne Meadows in the upper watershed.

Discussion

Granodiorite:

The physical properties of granodiorite can be said to influence drainage density and channel type. In a test of 28 rock types' resistance to erosion, granite had the second lowest erosion rate (Sklar and Dietrich, 2001). Sierran granodiorite possesses a dense, crystalline structure that has poor permeability (Selvadurai et al., 2005). This negates the freeze-thaw effect and pore-fluid pressure effects that would normally cause increased amounts of weathering by not allowing water to enter fractures in the rock (Odedra et al., 2001). This high resistance to erosion results in a lower incision rate (Sklar and Dietrich, 2001), which is exhibited in the poorly incised, straight, cascading channels of Sierran Granodiorite. While this would logically result in a higher channelization threshold, low erosion potential creates several important feedbacks that balance out channelization potential. With a low rate of weathering and erosion, granodiorite hosts a thin layer of low-nutrient topsoil that in turn hosts little vegetation (Wolf and Cooper, 2015). Sparse vegetation is a key contributor to increased erosion, as demonstrated by Istanbulluoglu and Bras (2005). Additionally, the poor permeability of granodiorite and the lack of a permeable layer of topsoil results in higher volumes of surficial flow, and a lower threshold of channelization (Carlston, 1963). One final factor is increased precipitation in the upper portions of the watershed, which would result in higher precipitation based erosion relative to the rest of the watershed (Wolf and Cooper, 2015). Ultimately, the low permeability, lack of topsoil, sparse vegetation, and high resistance to erosion that characterizes Sierran granite combine to influence drainage density, as is the case in both the Tuolumne Watershed and other studies of granitic watersheds (Carlston, 1963), which host moderate drainage densities.

Volcanics:

The Tertiary volcanic rocks have evident incised tributary channels (Figure 5), suggesting a slightly greater erosional tendency than the granodiorite. Volcanic rocks form with high porosity, which allows greater permeability (Sruoga et al., 2004), and more subsurface flow (Carlston, 1963). This negates the amount of surficial flow, lowering the amount of channel incision that would normally occur in a saturated system (Dietrich et al., 1993). In addition, volcanic tuff has a high resistance to erosion (Sklar and Dietrich, 2001). This lowers the incision rate (Sklar and Dietrich, 2001), and results in a higher threshold of channelization (Dietrich et al., 1993). This low incision rate is reinforced by the tendency of volcanic rocks to host a high pH, nutrient rich layer of topsoil that promotes vegetation growth (Wolf and Cooper, 2015), which serves as another impediment to erosion (Istanbulluoglu and Bras, 2005). These low channelization rates, combined with the greater volume of subsurface flow, explain the low drainage densities for the volcanic regions of the Tuolumne Watershed. The older Jurassic-age volcanics in the lower area of the watershed have a slightly higher drainage density than the Tertiary volcanics, a result of greater aggregate welding, which lowers porosity and permeability (Sruoga et al., 2004) and slightly increases drainage density as a result.

Meta-sedimentary:

Paleozoic meta-sedimentary rocks could not be examined for channel type, but the thin section present within the watershed was selected to host the Don Pedro Reservoir. Slate and greywacke has an intermediate erosion potential (Sklar and Dietrich, 2001), as well as low permeability (Foyo et al., 1991). Additionally, metamorphic rocks generally create low pH, low nutrient topsoil that limits vegetation growth (Wolf and Cooper, 2015), which in turn promotes more erosion (Instanbulluoglu and Bras, 2005). This leads to higher incision rates (Sklar and

Dietrich, 2001) and more surficial flow (Carlston, 1963), which in turn promotes higher channelization rates (Dietrich et al., 1993) and ultimately greater drainage density. This reinforces earlier studies that suggested a correlation between slate and high drainage density (Carlston 1963).

Tertiary and Quaternary Sedimentary:

The channel types that flow over Tertiary and Quaternary sedimentary rocks shows virtually no incision. The high permeability of alluvium and poorly lithified sediments allow for high volumes of subsurface flow and thus less incision occurs on the surface (Dietrich et al., 1993). Additionally, the flat topography occupied by such lithology causes the soft alluvial and sedimentary banks to erode laterally, causing stream migration and thus meandering channels (Sklar and Dietrich, 2001). The Quaternary alluvium and Tertiary sedimentary rocks have an unusually high drainage density, probably a result of how ArcGIS 10.4 builds steam channels. Further analysis of this phenomenon is needed.

There is no evident correlation between rock type and average stream gradient. Stream gradient increases without exception as you move eastward and into higher elevations of the watershed. This is consistent with previous research that shows hill-slope to be proportional to rainfall in the Central Sierra Nevada (Wahrhaftig, 1965).

Conclusions

- There is no correlation between rock type and average stream gradient. Rainfall is the primary determinate of average stream gradient.
- Drainage density and channel type are both influenced by lithology within the Tuolumne watershed.
- Volcanic rocks have the lowest drainage density, a result of their high permeability and higher channelization threshold.
- Meta-sedimentary rocks have the highest drainage density of the studied lithologies due to their low permeability lack of plant bearing topsoil, and average resistance to erosion.
- Mesozoic granodiorite has a moderate drainage density due to a combination of low permeability, lack of plant bearing topsoil, and a high resistance to erosion.
- Flat topography and extremely high permeability should result in a low drainage density for alluvium and fan deposits, but ArcGIS processing algorithms create multiple channels where none exist, resulting in an erroneously high drainage density. Further analysis of this unit's relationship to drainage density is needed.
- Straight channel patterns dominate the sub-basins of the middle and upper zones of the Tuolumne watershed. Sub-basins underlain by Quaternary alluvium and Tertiary sedimentary rocks exhibit meandering stream channels.
- Further analysis is needed to determine the effects of anthropogenic sediment transport on channel patterns in the lower regions of the watershed.

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