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HYDROLAPSE VIDEOGRAPHY: A COUPLED HYDROINFORMATIC STACK FOR IMPROVED VISUAL ASSESSMENT OF RIVER DYNAMICS

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A central problem for managers of river ecosystems is understanding hydrodynamics in an intelligible fashion for effective decision-making. Too often decisions are based on some combination of incomplete hydrologic time series, poorly parameterized models, photographic snapshots of the place in question, and human imagination. Because river ecosystems are dynamic, with ever changing physical dimensions, inferences are made to make up for unknowns, which remain knowledge gaps. This is particularly true in the pursuit of ecogeomorphology, which seeks to understand the interplay between physical processes and ecological responses in river systems over time. Increasing deployment of affordable sensors, however, is beginning to provide information to fill such gaps, but their utility remains constrained by human interpretation. We developed “hydrolapse videography” – a digital, time-encoded coupling of hydrologic information records with corresponding timelapse imagery – as a means to provide river managers a rich, but intelligible, data stream that is both quantitative and qualitative in nature. Hydrolapse videography couples still images from timelapse cameras with hydroinformatical graphs of key monitoring variables sourced from either local instruments or remote data providers (e.g., USGS gages) at a fixed time interval (typically hourly). Video composites are created by a combination of *Python* scripting and *matplotlib* for graphing, *Perl* for data pairing, and *FFmpeg* for video composition (typically 10 fps). Completed videos, typically capturing an entire water year, allow for diagnostic viewing of major hydrologic events, and simultaneous assessment of corresponding environmental variables, such as discharge and stream temperature. Further, the hydrolapse approach allows managers to comprehend river behavior, such as changing habitat dimensions in lateral extent and stage, as function of flow regime. Future versions will include fully automated data retrieval from standard data providers (e.g., WaterML) and processing workflow in a *Python* application stack.

INTRODUCTION

Background

Water resources management is typically focused on two primary environmental conditions: either too much water, or not enough. In California, however, both conditions often prevail, depending on the water year and specific location. Much of California is dominated by a Mediterranean-type climate, with cool, wet winters and dry, warm summers. The characteristic inter- and intra-annual variability and extremes in precipitation combine with mountainous terrain to create complexities in engineered water management and planning operations that aim to minimize economic loss due to flooding and maximize storage and delivery to meet municipal and agricultural demands.

In the broader region, balancing water management demands is further complicated by hydroclimatic alteration created by global warming. Hydroclimate alteration is underway throughout much of the arid and semi-arid western U.S. and future exacerbation is likely to challenge water management schemes as warmer atmospheric temperatures drive alterations in the timing and form of precipitation *Stewart et al. [1]*, *Barnett et al. [2]*, suggesting that major changes in water use and management will be required. In California, for example, projections of decreasing snowpack and increasing population growth will make it difficult to meet municipal demands while maintaining other objectives (e.g., irrigation supply, environmental flows) *Medellín-Azuara et al. [3]*. These hydroclimatic trends are commensurate with global projections for other regions with Mediterranean-type climates *Klausmeyer et al. [4]*, which are also challenged to meet the delivery needs of both irrigated agriculture and domestic supply for high human population densities *Grantham et al. [5]*. Recent studies indicate that California is ill-prepared to adopt water management measures to cope with water scarcity *Hanak et al. [6]* and further that necessary changes in water managed for the environment will require trade-offs between deliveries for human needs, hydropower generation, and ecosystems.

Nowhere else in California are these challenges as problematic as in the vast watershed created by the Sacramento and San Joaquin Rivers and their respective tributaries. This Sacramento-San Joaquin watershed drains 40% of the state into the San Francisco Bay and Pacific Ocean; it generates 43% of the state's surface water runoff, provides drinking water to ~23 M humans, and supports USD $45 B in agriculture annually, which is the economic backbone of the world's tenth largest economy. Formerly comprised of 1.8 M ha wetlands, seasonal floodplains, and riparian areas, these runoff dependent habitats have been reduced to less than 6% of their former extent due to agricultural and urban conversion. Further, all but one of the major rivers in the watershed has been extensively dammed. Increasingly, therefore, modifications to dam operations have been proposed for environmental benefits (i.e., environmental flows) as an approach to mitigate the negative impacts of these operations and habitat loss while preserving essential water management functions *Pittock et al. [7]*. By manipulating the quantity, timing, and quality of water released below dams to mimic natural flow dynamics, it may be possible to restore and maintain ecosystem processes *Poff et al. [8]*. Although structural design and operational purposes of dams, such as to reduce flood damage and increase local water supply, necessarily limit environmental flows, understanding the potential benefits is equally important. Current research indicates that with an improved understanding of these regulated river systems, dams can be re-operated in manners more compatible with natural regimes and buffer against climatic stressors like climate change *Rheinheimer et al. [9]*, *Rheinheimer et al. [10]*.

Understanding river dynamics under both regulated and unregulated conditions (i.e., those with dams and those without dams) is necessary to provide scientific evidence for dam re-operation. In this region, for example, improved understanding of flood dynamics on the Cosumnes River has provided insight into water quantity and quality management *Ahearn et al. [11]*, *Ahearn et al. [12]*, as well as cascading effects on floodplain restoration efforts *Jeffres et al. [13]*. Improved understanding of the snowmelt recession period in Sierra Nevada rivers (e.g., American, Tuolumne, and Yuba Rivers) has provided insights into geomorphological response of hydrological dynamism, such as sediment supply and sorting, and cascading effects on flora and fauna alike *Yarnell et al. [14]*. Additional regional insight from operations modeling is now being gained on different types of river regulation, such as hydropeaking events and bypass diversions *Rheinheimer et al. [15]*. However, a fundamental scientific unknown for the alteration of river and floodplain flows – regardless of alteration due to direct human manipulation (i.e., dams) or indirect effects (i.e., climate change) – is the improved understanding of site specific hydrological dynamics at relevant spatial and temporal scales. To help better understand and address these problems, we developed videos of time lapse imagery with time-keyed hydrologic data overlaid for selected rivers and floodplains of the region.

METHODS

In the following section, a method for developing “hydrolapse videography” is described and illustrated (Figure 1). Initial data capture through the deployment of inexpensive remote cameras set to time triggered operation (as opposed to movement detection) was conducted at several locations throughout the Sacramento-San Joaquin watershed (American River n=3, Cosumnes River n=3, Tuolumne River n=2, Yuba River n=2). These remote cameras (Moultrie GameSpy m65) were oriented to capture hydrological dynamics (river stage) as well as longer-term geomorphological and ecological change. While the configurable time step can be set to a 15 minute minimum, a one-hour event trigger provided the best balance for maximizing temporal coverage and battery life. Each camera triggered at every hour, 24 hours a day (Figure 1a). Concurrently, pressure transducers and data loggers (e.g. Solinst Levellogger Edge and Barologger Edge) were deployed to record stage of the adjacent waterbody to couple with the image data. Camera and logger data are retrieved for processing approximately every 6-8 weeks (Figure 1b).

A software package called *StreamLapse* (see *Appendix*: Video links and software for downloads) was developed to process imagery and generate videos. *StreamLapse* uses river stage logger data (or alternately discharge, if available), with any data gaps in the time series reconciled from third parties (e.g., USGS). *StreamLapse* filters out night images and generates a snapshot hydrograph for each image, then creating a composite image from the camera image and the hydrograph. Optionally, *StreamLapse* can pair that frame with a composite from a different site for side-by-side viewing and analysis. Finally *StreamLapse* processes all of these frames into a single time lapse video. These processing workflows can be broken into three broad process segments:

1. Preprocessing and data standardization
2. Graph generation
3. Video generation

Each process segment uses a separate suite of tools, and even programming languages, reflecting the ad hoc nature of the development of this tool. Each time we make a video, we take steps to integrating these tools, but current methods involve significant manual intervention between scripts of varying sources.

Preprocessing and data standardization

In the preprocessing segment, images are filtered and logger data translated to fit desired video format. As the sites for this study are distributed between latitudes 37-40° north, seasonal sunrise and sunset varies approximately 4.5 hours per year. This temporal variance requires choosing an appropriate daily time frame for image selection to filter out unwanted images (i.e., night time). To filter the images, *StreamLapse* employs *Python* scripting to sort images into stacks of daytime and nighttime (Figure 1e). *StreamLapse* uses a solar altitude algorithm from

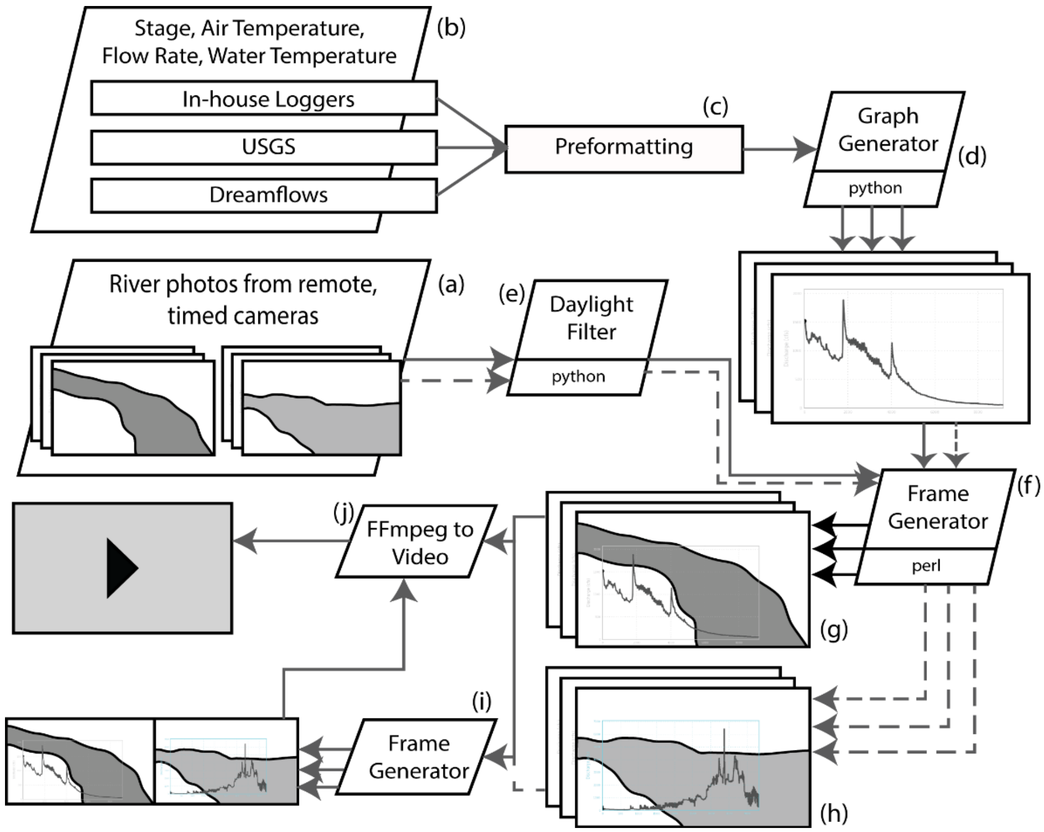

Figure 1: Illustration of the flow of data and code during video generation

module *Pysolar* to determine the height of the sun at the time each image was taken based on the latitude and longitude of the camera's site and the timestamp embedded in the image EXIF data. Using the solar altitude and a configurable offset parameter for each site to account for localized variations in brightness due to topography, *StreamLapse* filters out nighttime images and stores daytime images for further processing.

The next step in the *StreamLapse* workflow is data translation (Figure 1c). As typical field deployment for hydrological monitoring uses a heterogeneous set of loggers from differing manufacturers and generations, with a variety of output formats, and further that many such deployments operate at fine time steps (<15 minute), *StreamLapse* parses data streams to achieve 1:1 synchronization with the daytime image stack. Optionally, *StreamLapse* can utilize other discharge or stage data, such as those available from USGS or encoded with WaterML. This alternative data translation step is currently a sequence of manual actions, depending on the specifics of the data stream. For example, if a study site uses USGS gage data, *StreamLapse* uses the "Water Data for the Nation" API using a *Python* wrapper package. For logger data, *StreamLapse* incorporates tabular results as comma separated values (CSV) from other data manipulation packages, such as *R* or Microsoft Excel, which are often used to standardize data (e.g., timestamp format) and synthesize timeseries to standard intervals (e.g., hourly).

Graph Generation

The next process is the generation of the overlay hydrographs for each video frame (Figure 1d). *StreamLapse* uses a Python script to generate a graph for each moment in time, pulling data from the CSV output in the previous step. This script uses *scipy* and *matplotlib* packages to iterate over timeseries values, generating a stack of graphs where graphic elements in the future ($> t_i$ where i is the present timestep) are semi-transparent and values in the past ($\leq t_i$) are opaque, such that perception of timeseries progression is easily achieved when viewed sequentially. For data with large, regular fluctuations, *StreamLapse* can apply a moving average to the values to make it easier to view in the video. The composed graphics are output to PNG image format with a timestamp filename to enable image ordering and stack development.

Video Generation

The final processing segment is the generation of sequential frames from the composited data components (Figure 1f). *StreamLapse* creates final video frames via a Perl program that uses the module Image::EXIF to load metadata, including timestamp for each image. *StreamLapse* then sorts the images for each stack by time and assigns each image a range of time it represents, starting with the timestamp time and ending with one second before the next image in the sequence. Next, *StreamLapse* loads the times for each graph by site location using the timestamp encoded in the filename and then matches to each image frame (Figure 1g) based on the valid time range. Once all non-duplicate pairs are made, *StreamLapse* creates a virtual data stack of time synchronized images and overlay graphs that is passed to *ImageMagick* to create the composite frames for a video. Variations for multiple sites can be made by assigning primary and secondary status to multiple locations (Figure 1h). These two frames using the same time matching method to create a single video frame (Figure 1i). The data stack from *StreamLapse* is ultimately pushed through *FFmpeg* to generate video at high quality (Figure 1j). Output hydrolapse videos run at 10 frames per second, which results in approximately a day of real time per second of video.

RESULTS

To date, *StreamLapse* has been used to generate six videos for study rivers in California, four of which are publicly available online (See *Appendix: Video links and software*). These videos include study locations at the North Fork American, Cosumnes, and Rubicon Rivers for the 2011 water year. Site comparison videos showing two rivers side by side in each video were created for the North Fork American (unregulated) and South Fork Yuba (regulated) rivers during water year 2011. The second site comparison video shows the Tuolumne (regulated) and Clavey (unregulated) rivers at their confluence during water year 2012. These graphs also include air and water temperatures for additional data synthesis.

StreamLapse videos have enabled direct visualization of both habitat availability and hydrologic change over time. Camera deployment for these initial studies has been at long term monitoring locations, which has allowed for direct observation of dynamic geomorphic activity (channel bar formation) and ephemeral hydrologic events (snow fall, snow melt, and localized freshets). Side-by-side site videos (see Figure 2 for sample), enable direct comparison of geographically similar locations, but with specific disturbances that make them differ. We observed two primary effects:

1. Water temperature alignment in unregulated rivers and divergence in regulated systems (Tuolumne and Clavey).
2. Unnatural flow changes in regulated systems, including hydropeaking and drops from moderate flows to base flow in under 24 hours (North Fork American and South Fork Yuba).

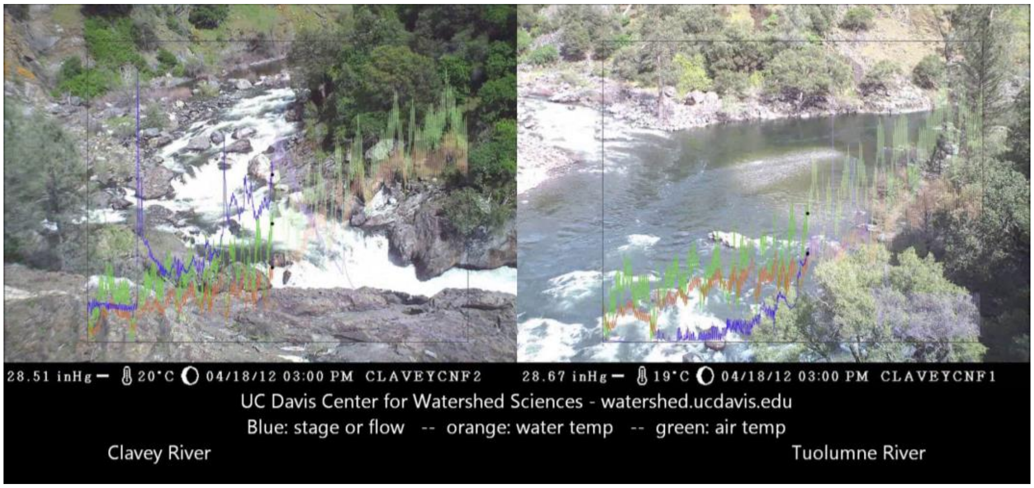

Figure 2: Sample output frame showing Clavey River (left) and Tuolumne River (right) with stage/discharge, air temperature, and water temperature.

CASE STUDIES

We highlight three videos as case studies of the utility of *StreamLapse* software. Links to all videos are available in *Appendix: Video links and software*.

Cosumnes River Flooding, 2011

The Cosumnes River is a relatively low elevation catchment in California's Sierra Nevada and the only undammed drainage of significant yield in the region. Because the river is unregulated, it has become an important study system to examine flood dynamics. For this case study, a camera was mounted adjacent to an experimental floodplain to quantify peak stormflows and floodplain inundation (depth and residence time). This video, produced from water year 2011 data, shows brief floodplain connection during a high flow event (at 0:27), most of which appears to peak overnight according to the hydrograph and the video. The hydrograph can be seen to track river stage. Starting at 1:04, on July 1, 2011, the Cosumnes River site also experiences a near perfect spring snowmelt recession (the gradual tailoff of spring flows to summer baseflow).

North Fork American and South Fork Yuba – 2011

The North Fork American River and the South Fork Yuba River sites were used for comparative purposes. These two sites are separated by approximately 25 km, their catchments are of comparable sizes (~500 km^2) with near identical land cover, and their stream reaches are at similar elevations (~500 m) and gradient (~1%). Thus, they receive many of the same precipitation events and respond similarly hydrologically in unregulated periods. However, a key difference is that the South Fork Yuba has a regulating dam at Lake Spaulding, upstream of the study site. As a result, despite the atmospheric comparability, the experienced flow and rates of change vary between the two sites over the course of the water year.

The comparative hydrolapse video shows the unregulated North Fork American site (left) and regulated South Fork Yuba (right). Key hydrologic differences in the sites include:

1. The diurnal snowmelt fluctuation in the North Fork American drainage that is absent in the South Yuba drainage.

2. The storm responses in the North Fork American and the buffered response of the South Fork Yuba.
3. The rapid rates of flow change at the end of the season in the South Yuba drainage compared with the North Fork American's smooth recession.

Tuolumne and Clavey Rivers – 2012

The second comparison video condenses eight months of time into four and a half minutes of video. This hydrolapse video was the first to track three variables: stage, air temperature, and water temperature. The Clavey River is an undammed tributary to the Tuolumne in the Sierra Nevada. The frame on the right is at their confluence, while the other is ~500 m upstream on the Clavey River. The Tuolumne River is regulated upstream by multiple dams, including O'Shaughnessy Dam that created Hetch Hetchy Reservoir. Discharge data for the Tuolumne River comes from an upstream USGS gage and stage on the Clavey River comes from a logger.

Observational differences are apparent in the hydrolapse for the two rivers. The most obvious is the summer hydropeaking of Tuolumne River discharge as a result of river regulation and hydropower. These pulses show up readily in the video and hydrograph, though they are somewhat obscured in the video due to diurnal fluxes. The hydrograph alone clearly illustrates hydropeaking, but value addition of the video provides direct insight to lateral and vertical habitat affected by hydropeaking operations – in other words, the hydrolapse data stack shows definitive high and low water lines created by hydropeaking.

Two other highlights are apparent. First, water temperature diverges from air temperature in the mainstem Tuolumne during the summer, which is consistent with the effects of dam regulation and cold water releases from the hypolimnion of upstream reservoirs. The Clavey River hydrolapse, on the other hand, shows a tight coupling of air and water temperatures due to its unregulated status. Second, the high flow event that occurs at 0:29 appears in the Clavey logger data, but not the Tuolumne USGS gage data. While this issue is unexplained by the hydrolapse data stack, it is potentially due to a localized low elevation rain event and resulting freshet.

Due to the volume of data for this video and the significant diurnal fluctuation, *StreamLapse* was configured to produce moving averages for the timeseries to smooth rapid fluctuations in temperature compared to lower frequency changes in river stage and thus uses a much larger graph display to make the data more easily assimilated. Feedback has suggested that the graphs obscure the river too much and therefore future versions of *StreamLapse* may generate a four panel video (2x2 frames, with graphs on top and rivers on the bottom).

CONCLUSIONS

A central problem for managers of river ecosystems is understanding hydrodynamics in an intelligible fashion for effective decision-making, especially under operational constraints such as flood and drought. Too often management decisions are based on some combination of incomplete hydrologic time series, poorly parameterized models, photographic snapshots of the place in question, and human imagination. Because hydrologic systems and river ecosystems are dynamic, with ever changing physical dimensions, inferences are made to make up for unknowns, which remain knowledge gaps. Increasing deployment of affordable sensors, however, is beginning to provide information to fill such gaps, but their utility remains constrained by human interpretation. The use of "hydrolapse videography" – such as that created by *StreamLapse* – can provide river managers a rich, but intelligible, data stream that is both quantitative and qualitative in nature. Hydrolapse videography allows managers to better understand river behavior, such as changing habitat dimensions in lateral extent and stage, as a function of flow regime that in turn may result in improved river management.

APPENDIX: VIDEO LINKS AND SOFTWARE

StreamLapse is available at http://watershed.ucdavis.edu/streamlapse. See webpage for details. The software does not contain documentation, and new versions are under development. Videos created by StreamLapse can be found at https://vimeo.com/channels/streamlapse

Case Study Videos:

1. Cosumnes River, 2011: https://vimeo.com/49867017
2. Tuolumne and Clavey Rivers, 2012 with temperatures: https://vimeo.com/51708563
3. North Fork American and South Fork Yuba Rivers, 2011: https://vimeo.com/46239865

REFERENCES

[1] Stewart, I. T., Cayan D. R. and Dettinger M. D., "Changes toward earlier streamflow timing across western North America", Journal of climate, Vol. 18 (2005), pp 1136-1155

[2] Barnett, T. P., Pierce D. W., Hidalgo H. G., Bonfils C., Santer B. D., Das T., Bala G., Wood A. W., Nozawa T. and Mirin A. A., "Human-induced changes in the hydrology of the western United States", Science, Vol. 319 (2008), pp 1080-1083

[3] Medellín-Azuara, J., Harou J. J., Olivares M. A., Madani K., Lund J. R., Howitt R. E., Tanaka S. K., Jenkins M. W. and Zhu T., "Adaptability and adaptations of California's water supply system to dry climate warming", Climatic Change, Vol. 87 (2008), pp 75-90

[4] Klausmeyer, K. R. and Shaw M. R., "Climate Change, Habitat Loss, Protected Areas and the Climate Adaptation Potential of Species in Mediterranean Ecosystems Worldwide", PLoS One., Vol. 4 (2009), pp e6392-e6392

[5] Grantham, T., Figueroa R. and Prat N., "Water management in mediterranean river basins: a comparison of management frameworks, physical impacts, and ecological responses", Hydrobiologia, Vol. Online First (2012), pp 1-32

[6] Hanak, E., Lund J., Dinar A., Gray B., Howitt R., Mount J., Moyle P. and Thompson B. B., "Managing California's Water: From Conflict to Reconciliation", Public Policy Institute of California, (2011)

[7] Pittock, J. and Hartmann J., "Taking a second look: climate change, periodic relicensing and improved management of dams", Marine and Freshwater Research, Vol. 62 (2011), pp 312-320

[8] Poff, N. L., Allan J. D., Bain M. B., Karr J. R., Prestegaard K. L., Richter B. D., Sparks R. E. and Stromberg J. C., "The natural flow regime: A paradigm for river conservation and restoration", BioScience, Vol. 47 (1997), pp 769-784

[9] Rheinheimer, D. E. and Viers J. H., "COMBINED EFFECTS OF RESERVOIR OPERATIONS AND CLIMATE WARMING ON THE FLOW REGIME OF HYDROPOWER BYPASS REACHES OF CALIFORNIA'S SIERRA NEVADA", River Research and Applications, Vol. (2014), pp n/a-n/a

[10] Rheinheimer, D. E., Yarnell S. M. and Viers J. H., "Hydropower Costs of Enviornmental Flows and Climate Warming in California's Upper Yuba River Watershed", Vol. (2012)

[11] Ahearn, D. S., Sheibley R. W., Dahlgren R. A. and Keller K. E., "Temporal dynamics of stream water chemistry in the last free-flowing river draining the western Sierra Nevada, California", Journal of Hydrology, Vol. 295 (2004), pp 47-63

[12] Ahearn, D. S., Viers J. H., Mount J. F. and Dahlgren R. A., "Priming the productivity pump: flood pulse driven trends in suspended algal biomass distribution across a restored floodplain", Freshwater Biology, Vol. 51 (2006), pp 1417-1433

[13] Jeffres, C. A., Opperman J. J. and Moyle P. B., "Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river", Environmental Biology of Fishes, Vol. 83 (2008), pp 449-458

[14] Yarnell, S. M., Viers J. H. and Mount J. F., "Ecology and Management of the Spring Snowmelt Recession", BioScience, Vol. 60 (2010), pp 114-127

[15] Rheinheimer, D. E., Null S. E., Liu P., Akhbari M. and Viers J. H., "Optimizing Hydropeaking with Variable Electricity Prices in a Daily Time Step Water Management Simulation Model", Journal of Water Resources Planning and Management, Vol. (In Review)