We have tried to accommodate the comments of the three reviewers, although in some cases this was not possible. For example, reviewer 2 wanted us to say less, and reviewer 3 wanted us to say more; we obviously cannot do both.

The major changes we have made are detailed in our responses to the reviewers (these are the same as those provided during the open review). Where we have opted not to follow the reviewers' suggestions, we have detailed our reasoning.

We appreciate Anonymous Referee #1's thoughtful comments on our manuscript. Below we respond (in bold type) to the referee's specific comments (in normal type).

The manuscript presents a thorough study of the daily cycles of different hydrological variables during rainless periods in different seasons, reflecting diurnal extraction of shallow groundwater by evapotranspiration and diurnal additions of meltwater during snowmelt. Basis of the study is extensive dataset of diurnal cycles of stream water level, groundwater levels, sap flow measurements, snow characteristics (snow water equivalent) and several other hydrometeorological conditions in the studied catchments (two snow-dominated headwater catchments in California's Sierra Nevada mountains). In the introduction section authors clearly present the basis of the topic. They explain two contrasting concepts, namely, the water table fluctuations (WTF) and missing streamflow approach, which have been traditionally used for analysis of the observed daily cycles. Furthermore, the question of time lags between the daily minimum and maximum ET and snowmelt rates vs. daily stream discharge and groundwater levels cycles is thoroughly explained and gives a reader (even those without strong theoretical background) good insight into the discussed topic.

The manuscript is long; however, I see no other option to present the discussed topic in a such holistic way. Namely, the authors have successfully covered different aspects of the research: (1) extensive field measurements; (2) theoretical background upgraded by a simple, but innovative conceptual model of the riparian groundwater mass balance and (3) presentation of the remote sensing data to support the concept. All 3 parts combined give excellent and holistic picture of the discussed topic.

By using stream levels data directly, authors presented a way how the problem of rating curve uncertainty can be avoided in analysis of daily cycles of various hydrological variables which are usually obtained through different hydrological measurements. This can be problematic especially in the range of extreme values (in this case during low-flow conditions).

In my view, the paper suits well in aims and scope of the HESS journal and I strongly support the publication of the manuscript. I would like to congratulate the authors for their excellent work. Bellow I provide some specific comments which are more or less technical.

We thank the referee for these supportive comments. We understand that the paper is long but, like the reviewer, we think it makes sense to present the whole analysis in one place.

Specific comments: Line 45:

Maybe the role of specific sub-catchment characteristics (the low-land part of the catchment becomes ET dominated before the headwater (high-land part) could be more directly highlighted in the abstract. In the transition period, the temporal prevalence of snowmelt over the ET and vice-versa, strongly depend on the local topography characteristics. This aspect is thoroughly discussed in the manuscript.

We will change the sentence, "Streamflow, however, integrates these transitions over the drainage network" to say instead, "Melt-out, and the corresponding shift in the diel cycle index, occur earlier at lower altitudes and on south-facing slopes, and streamflow integrates these transitions over the drainage network."

Line 144: I suggest changing the sentence: …making these basins, in terms of climate characteristics, ideal…

We will change this to more clearly express the link that needs to be made: "making it relatively easy to see how snowmelt and evapotranspiration are reflected in daily cycles in groundwater and streamflow."

Line 235: If I understand correctly, the "absolute" sap flow values were not directly used (the sap flow instruments were not calibrated) since the temporal changes (daily cycles) of sap flow were used in the study. Could lack of the calibration (drift) also influence the timing of the sap flow daily cycle?

Your understanding is correct. Changes in calibration (mostly due to wound healing in the trees) should affect the amplitude of the observed signals but should not introduce a measurable phase lag.

Line 271: The reported data gaps occurred during the observed 3 years?

Yes, in some cases. Some of the stage recorders had frequent failures, and since they were typically downloaded only a few times per year, the resulting data gaps are sometimes quite long. The results that are shown in the paper are obtained from the sites and time intervals without substantial data gaps.

Line 279: Could the elevation bands limits centered on SNOTEL stations be also shown in Fig. 1 for illustration purposes?

Yes, but this would tend to make it harder for readers to see other essential information in the figure. We will instead prepare a supplementary figure that shows these elevation bands, along with contour lines (some readers find that contour lines are easier to interpret than grayshade, or the other way around).

Figure 6: Groundwater levels shown are absolute values? I would suggest slightly changing the Fig. 6 caption sentence (line 1060): …averaged roughly 200, 1050, 1080, and 950 mm above the Sagehen Creek water level…

We will change the caption to make it clear that the quoted average elevations are above the water level in Sagehen Creek.

Line 369: Is this correct? What could be an explanation for a “static water level of 0.6m above the ground surface”?

Yes, this is correct. The explanation comes a few lines later: "These measurements also demonstrate an upward hydraulic gradient in the valley axis at all three locations, consistent with our hypothesis of groundwater flow from upslope recharging the riparian aquifer during mid-summer, thus sustaining both streamflow and plant water use." We will modify this statement so that it is clearer that by "groundwater flow" we mean bedrock fracture flow.

Lines 405-408: Could authors support their statement with measurements shown in Figs. 3 and 4? This would enable readers to understand the underlying processes more easily.

We will add the statement: "One can see this behavior in Figs. 3 and 4: groundwater levels change fastest near the peak of the solar flux (Figs. 3a and 4a), but the groundwater levels themselves reach their maxima (or, for ET cycles, minima) several hours later (Figs. 3c and 4c), when the rate of groundwater rise or fall changes sign."

Line 422: What kind of water level? Groundwater, streamflow or some kind of “general water level” as an indicator of hydrological state of the catchment?

Sorry, we mean riparian groundwater levels and will modify the text accordingly.

Line 435: What is “A” in the combined forcing $P + M + G – E = A\cos(wt)$?

A is the amplitude of the assumed sinusoidal forcing. We will add this to the text.

Line 515: Were the average lag times for the two stations assessed from low flow discharge conditions (where the diel signal is evident) or using wider range of discharge conditions?

The calculations behind the statement in line 515 were made under average discharge conditions, but the results are not sensitive to the flow regime that is used. The cross-correlation results presented in line 510 are for all three years of data combined.

Figure 9c (lower plot): If the cloudy days and rainy periods were excluded form the dataset, how can detrended stage fluctuations data be continuous (or are they only seemingly continuous)?

Cloudy and rainy days were not excluded from the data set, but rather from the daily correlation analysis shown in Figs. 9a and 9b. That is why blue dots (indicating diel cycle index values) are missing for some of the days in Fig. 9c (and also for some days in Figs. 11, 12, 14, S3, and S4).

Lines 600-601: Since DEMs from Lidar data are available for studied catchments, could authors make their statement more tangible (quantifiable) in terms of the approx. % of slopes (catchment) facing north/south direction?

It is difficult to reliably estimate the catchment area that drains to the two well transects (since they are aligned roughly perpendicular to the stream, and thus parallel to the groundwater flowpath). Nonetheless, at the B transect the stream flows almost exactly from west to east. Thus almost all of the terrain north of the stream faces south, and almost all of the terrain faces north.

Lines 841-843: I would suggest mentioning also the problem related to the fact that diurnal cycles in stream water level in larger catchment (especially during the ET dominated periods) is pretty much undetectable (or unrecognizable) by the waters stage measuring equipment. Of course, this could be related to various lag times to the gauging stations as mentioned by the authors.

We are reluctant to say this because we present no evidence indicating that diurnal cycles are actually undetectable in larger catchments. It seems reasonable that this may be the case, but we would not want to assume it.

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We appreciate Anonymous Referee #2's comments on our manuscript. Below we respond (in bold type) to the referee's specific comments (in normal type).

The manuscript presents a comprehensive study of the hydrological cycle in two montane catchments in the Sierra Nevada, USA. The analysis uses a large dataset to explain how groundwater and streamflow daily fluctuations are dynamically related to transpiration and snowmelt daily cycles forced by solar radiation. A simple and elegant model is used to explain these relationships.

As I understand, the main result of the study is to have identified that in small catchments the links between the daily fluctuations of streamflow (Q) and both transpiration (T) and snowmelt are mediated by the groundwater storage in the riparian zone.

Therefore, the lags appearing between the daily cycles of streamflow and their forcing variables are not due to travel times, but are associated with the dynamics of the whole system with groundwater acting as a buffer that dampens and delays the response of streamflow. This shows that methods to estimate T (or evapotranspiration, ET) using series of Q are not feasible unless characteristics of the riparian aquifer are also known.

Although the manuscript addresses a topic certainly interesting for the readers of HESS, I found it extremely difficult to read. The manuscript is very verbose and I often found myself lost in long explanations about concepts that were not really of interest or strictly relevant.

We understand that the paper may appear long by contemporary standards, in which results from a project are often salami-sliced into as many different papers as possible. Instead of splitting our results into three or four separate papers, however, we have chosen to present them together because they are interconnected. In any case, the manuscript is not that long compared to some others in HESS. It is about the same length as Kirchner and Allen (2020, https://doi.org/10.5194/hess-24-17-2020), for example, and much shorter than Kirchner (2019, https://doi.org/10.5194/hess-23-303-2019).

We disagree with the characterization of the manuscript as "very verbose". Clarity and completeness often require explaining things rather than just asserting them. We also need to allow for the fact that individual readers will have stronger background in some areas than in others. We are aiming at readers who may have some background in one or another aspect of these systems, but may not be experts in all of the topics that we are covering. Readers' points of interest may also differ. Thus each reader may find some "concepts that [are] not really of interest or strictly relevant", but different readers will have different opinions on which specific concepts those are.

Therefore, my suggestions and detailed comments listed below are mainly directed to shorten and hopefully improve the readability of the manuscript.

- Title: already the title seems long. Could it be shortened into something like "The pulse of a montane ecosystem: relating daily cycles of hydrological variables".

We will think about this. Titles always represent a trade-off between the need to be explicit and the need to be concise. "Relating daily cycles of hydrological variables", in our view, is too cryptic (which variables? relating how?). There is also the need to cover the important keywords for search purposes, which is why we have identified the fluxes and storages (snowmelt, transpiration, groundwater, and streamflow), the study sites, and the region (Sierra Nevada).

- Abstract: this is also very long. I would try to shorten it to make the key messages of the study clear to readers.

We will see what we can do. The problem here is that the paper presents many interconnected results. These go well beyond the one that the reviewer has focused on (that riparian aquifer dynamics imply that we cannot infer ET rates from streamflow cycles). If that were the only punchline of the paper, the abstract could end at line 34. But the paper also shows that groundwater cycles reflect the relative dominance of snowmelt vs. ET, and streamflow cycles integrate these signals over the contributing catchment (lines 36-47). We also show that temporal patterns of streamflow cycles are quantitatively consistent with the spatial evolution of snowmelt and ET during the transition from winter to summer and vice versa, as viewed from LANDSAT and MODIS (lines 49-54). And for the abstract to be comprehensible to the reader, the results need to be (briefly) explained, not just asserted. We will see what can be cut or condensed, but we don't want to sacrifice comprehension for the sake of brevity.

- Line 31: "...transiently achieves mass balance." This is not clear to me. The mass balance should be always satisfied.

This depends on whether "mass balance" means "inputs balance outputs plus change in storage" (which is of course always satisfied), or "inputs balance outputs" (which is not always the case). We meant the latter. We can change "solar forcing declines enough that the riparian aquifer transiently achieves mass balance" to say instead "solar forcing declines enough that inputs transiently balance outputs in the riparian aquifer".

- L34: I would not use here "time constant", because that related to the simple model presented in Eq. 5, which assume τ to be constant to obtain an exact solution of the equation. However, as I understood reading the manuscript, the riparian aquifer might have a response time that is not constant.

That is correct. Although "time constant" is sometimes used to refer to a characteristic response time that may not be strictly constant, "response time" would be better here. We will change it.

- L90-91: is integro-differential the correct term here?

We are not referring to an integro-differential equation (that is, an equation with both integrals and derivatives). But, as stated, there is an integro-differential relationship between groundwater levels and ET: groundwater storage integrates ET, and ET is the derivative of groundwater storage, assuming other fluxes are trivial. Integrals introduce 90-degree phase lags, hence we should expect a roughly 6-hour phase lag between daily ET or snowmelt cycles and the resulting groundwater cycles (again, assuming there are no other fluxes; drainage to streamflow complicates this picture, as we describe later). Nonetheless, if the term is confusing we can remove it, and say, "…the WTF method implies that groundwater levels integrate snowmelt or evapotranspiration signals…"

- L108: I believe that the WTF method as defined by White (1932) did not account for Q because the observations were done in a desertic environment where Q was not relevant.

That is correct, but the WTF method is often applied in many situations where Q (or drainage to deeper aquifers) is not zero. In any case, we believe that the statement we made is correct: "Missing streamflow methods assume that the daily cycle in ET results only in a daily cycle in streamflow, and not a daily cycle in groundwater levels, whereas WTF approaches assume the exact opposite. One can of course question whether either set of assumptions is realistic, but they certainly cannot both be correct."

- L129: Gribovszki

Sorry! We do know how his name is spelled, and we have no idea how that typo got there. We will fix it.

- Section 2.1: I would erase the pronunciation of the catchments and historical information that is not necessary to understand the analyses presented later on in the manuscript. I don't think information about potential evapotranspiration is provided for the catchments, and rainfall and temperature are not given for the Independence basin.

Rainfall and temperature are not reported for the Independence basin because they are not measured there. (Upper Independence creek is a remote area with no roads and no trails, and we have only measured stream stage variations there. It is nonetheless interesting for our purposes because its bedrock is much less permeable than Sagehen's.) Potential evapotranspiration is not reported because it is not directly measured, and its calculation is assumption-dependent. We mention the pronunciation of "Sagehen" because colleagues have mentioned to us in the past that they don't know how to say it (and because for many readers, hearing words in their heads is important to comprehension). In any case, it's just three added words. Is saving three words really that important?

It would be good if the description of the two catchments followed the same structure to facilitate the reading.

This is not feasible because we have a lot more that we need to say about Sagehen than about Independence.

L191-195 can be erased.

We disagree, because if this information is not provided, some readers may wonder about the possibility of human influences on the phenomena that we report.

- Section 2.2: a lot of details can be removed (e.g., precise location of gages). A lot of this information is already in Fig. 1 (latitudes and longitudes could be reported in the figure or tables instead of the text). I would move the description of the sapflow measurements (L232-239) at the end of this section. At the moment, the description starts with weirs and bores, switches to sapflow, and then goes back to bores. L241-245 can be erased.

Precise locations of gauges are not reported; the lat/long coordinates are those of the snow telemetry (SNOTEL) stations, but we can remove them. We disagree that "a lot of this information is already in Fig. 1". Although of course the *locations* of the various sensors are shown in that figure, the *relevance* of those locations will not be obvious to readers – for example, that the SNOTEL sites span the same altitude range, and the same distances from the Sierra crest, as the Sagehen catchment does – so this needs to be spelled out in the text.

The reviewer is simply incorrect in stating that "At the moment, the description starts with weirs and bores, switches to sapflow, and then goes back to bores". Lines 219-230 describe the weather stations and SNOTEL station (boreholes are not mentioned there at all, and the main gauge is mentioned only as a reference point for the locations of the SNOTEL stations). Next, lines 232-239 describe the sap flow measurements, lines 241-253 describe the water stage recorders and the stream gauging stations, and lines 255-266 describe the borehole transects.

- L256: "To account for the combined..."

Line 256 does not say anything like that. Line 276 does say, "To take account of the combined…". We don't see any difference between "to take account of" and "to account for", besides that one is four characters shorter than the other. Nonetheless, we can change it.

- L345-346: I do not think it is correct to say that solar radiation drives streamflow and groundwater fluctuations. There is an indirect relationship, as also stated at L557-558.

It is broadly acknowledged in the literature of this field that these daily cycles are ultimately derived from the daily cycle in solar radiation. It is not a 1:1 relationship, but that is not what "driver" means.

- L385-389: it is not really clear what an integro-differential system is in this context.

OK, we will change that to "Dynamical phase lags arise whenever one system component integrates another."

- L390-415: this part is rather long and it seems that is repeated more precisely after Eq. 5.

We are trying to build understanding. We want to explicitly link our analysis to the simple dynamical systems approach (lines 390-398), explain how the relationship between storage and discharge arises mechanistically (lines 398-401), give the reader an intuitive understanding of how the phase lag arises from storage integrating its input fluxes (lines 403-409), and then explain that we will be now be analyzing a simple specific example of this more general system (lines 410-415).

I would just introduce Eq. 4, say that Q is assumed to be a linear function of S (i.e., $Q = f(S) = S/\tau$) and then write Eq. 5.

There is a big difference between just assuming that Q is a linear function of S (whereupon readers will wonder, "but what if it isn't?"), and making the point that we make here, namely that even if Q is a nonlinear function of S, it will be approximately linear over small ranges of Q and S, so our analysis still works.

I would avoid mentioning that the solution is well known (erase L434) and provide the solutions in Eq. 6.

We need to mention that the solution is well known, or else readers will think that we are claiming that this is an original result, when instead it can be found (in one form or another) in almost any textbook on linear systems analysis.

I think it should be better to say that it is assumed that the period considered is without P; I do not think it is reasonable to assume P with a daily cycle as M, G, and E.

We are not assuming that P has a daily cycle, but rather that P+M+G-E has a daily cycle. Obviously this criterion is met if P is zero and M+G-E has a daily cycle.

Should there be a mention of the initial conditions for these solutions? I understand that the point is to look at cycles and the initial transient is not important; however, in Fig. 7, I found it strange that the initial values of Q were different.

There are no initial conditions, and there is no transient. That is not how Fourier methods work. Equation 6 gives _exact analytical**_ solutions that are valid at _**all values of time**_, from –infinity to +infinity. That's because Fourier methods assume that the cyclic input repeats forever, with no beginning and no end. Equation 6 is neither derived nor solved using numerical integration, so it does not require initialization and there is no transient.**

What the reviewer calls "the initial values of Q" in Fig. 7 are not initial values at all; they are just the values of the solution at midnight (and midnight, every night, is exactly the same, because the cyclic input and the cyclic output go on forever in both directions). Since these are not initial values, it is not "strange" that they are different. They are different because different values of tau yield different amplitudes and phases in Eq. 8.

- L460-479: I would erase this part. In most cases the inversion of the Fourier transform will be done numerically; therefore, one can just solve Eq. 5 numerically to start with.

Yes, but if you solve Eq. 5 by numerical integration, you have to worry about initial conditions and transients (and the comments immediately above illustrate how these can become confusing), and you have to worry about numerical stability. More importantly, if you numerically integrate, you get a numerical answer but you don't get insight, whereas from Eq. 6 or Eq. 8 you can directly see how the amplitudes and phases depend on each of the parameters. (And although this is not important here, Fourier methods can be massively more efficient than numerical integration, which is why they have been extensively used in global circulation models.)

The point about the lags is clear from Eqs. 6 and their discussion.

Of course, but only for an individual cosine wave. In general, the different frequencies are damped and phase-shifted by different amounts. Thus if you have only one cosine wave (Eq. 6), your solution is another cosine wave. The input and the output have the same shape, just with a phase shift and change of amplitude. But if you have an input that is not a pure sinusoid, then _the output cycle will have a different shape**_ from the input cycle. Thus the apparent lag between the peaks will be different than they would be for a pure sinusoid.**

- L501-504: the references to the lines in Fig. 8 do not seem correct.

Good catch! We changed the figure but forgot to update the text. We'll fix it.

- L572-573: I would erase this phrase.

We think it is important, because many colleagues have said to us, "What's diel? You mean diurnal, right?". This indicates to us that the terminology needs to be explained.

- Subsection 3.5: I am not sure this is so important to deserve a full subsection.

Regardless of the question of importance, the material does not fit with the other subsection headings. And we do think it is important. Many colleagues have interpreted the vanishing of the daily cycle as indicating that the snowmelt cycle has ceased (and then later, the evapotranspiration cycle has begun). Instead, the daily cycle vanishes because the snowmelt and evapotranspiration cycles are canceling each other out.

- Subsection 3.7: I do not think this subsection is really necessary. I found that it was not adding much to what already presented and supported by the data. I would recommend to cut this part out.

This section may not be necessary for what the reviewer considers to be the "main result" of the paper. But in our view, that is not the only important result. Another important result is that the diel cycle index reflects the spatial variation in snowmelt and ET throughout the drainage basin, and the only way to directly

visualize (and quantitatively verify) this result is through remote sensing. To the best of our knowledge, an analysis like this has never been done before. Really, who knew that stage fluctuations in streamflow reflected spatial patterns of snow cover and photosynthetic activity that you can see from outer space?

- L724-725: the mismatch between the peaks in radiation and sapflow is not surprising. Vapor pressure deficit (VPD) is usually the variable that mostly drives transpiration, and I believe that VPD would likely explain the timing of the transpiration peak during the year (that's because there appears not to be water limitation).

Although we don't go into this here (because we can't do everything, and the topic is not central to the paper), the data do not support the reviewer's conjecture. VPD remains high until September or October in most years (because the late summer and early fall are hot and dry), whereas sap flow rates begin declining in July. Controls on seasonal patterns in sap flow are discussed extensively in Cooper et al. (in review), which we cite here.

- L773: I would use "changes in storage" instead of "mass balance".

If the reviewer really doesn't like "mass balance" we would suggest "flux balance" instead. "Changes in storage" isn't wrong, but it gives the wrong focus: on the trends in storage rather than the relationships between the input and output fluxes.

- L779-781: erase?

We think it is important to point this out, because otherwise readers could look at Fig. 7 and ask, "yes, but what about storage?"

- Figures: the captions of most figures are very long. Because the figures are explained in detail in the text, I would try to reduce the length of the captions, where a brief description of what the figures show should be enough.

The figure captions are written this way as part of a deliberate communication strategy. Minimalist figure captions often lead to unnecessary workload and confusion for the reader, who must jump back and forth between the figure and the text (perhaps several pages away) in order to understand what the figure says. Furthermore, many readers scan papers by looking at the figures without reading the text, meaning that the figures should be able to stand on their own.

Putting interpretations in figure captions can be a great help to readers, who can thereby get a sense of what the figures *mean* rather than just what they *are*. Experience has shown that authors often think that their figures will be self-evident (which of course they are *for the authors*, who already know what they are trying to say), and fail to comprehend how divergent a reader's understanding may be. Thus it is a smart communication strategy to lean in the direction of over-explaining rather than under-explaining.

- Figure 2: this figure is repeated in a different format in Figs. 11, 12, and 14. I would have these data in a single figure without repetitions.

The whole point of Figs. 11, 12, and 14 is to let readers see the relationships between seasonal patterns of snow accumulation and melt, and patterns in daily cycles of in streamflow. Readers cannot see these connections if the things that they are supposed to connect are in different figures, many pages apart from one another.

- Figure 10: if Subsection 3.5 is reduced or removed, perhaps this figure can be removed as well.

For the reasons that we explained above, we think it is important to keep subsection 3.5.

-Figure 11: because sapflow and groundwater are related in this figure, I wonder whether it would be better to report the depth to the water table from the surface to show that the water table is within reach of the root system. In the caption, it is said that signals were detrended but it is not explained how.

Unfortunately we don't know the depth of the rooting zone. The detrending procedure is documented in Eq. 3 at the end of section 2.3.

- I would consider removing Figs. 13 and 14 along with Subsection 3.7.

As we explained above, section 3.7 presents a novel analysis that draws connections that have never been drawn before. We believe that this section, and the corresponding figures, should be kept.

We thank Jessica Lundquist for her comments on our manuscript. Below we respond (in bold type) to Prof. Lundquist's specific comments (in normal type).

Review Summary: Overall, I'm very happy to see this paper. The authors have done a nice job using an integrated and well-measured field site to present the inter-relations between multiple aspects of diurnal cycles in both streams and groundwater in a setting experiencing both snowmelt and evapotranspiration. This is a solid contribution to the field, and I recommend it be published after revisions, particularly addressing my major comments, as follows:

We thank Prof. Lundquist for these supportive comments.

1. While the authors have done a wonderful job integrating and presenting their results, most of what they show is not new.

We disagree with the claim that "most of what they show is not new".

Specifically, Figures 3, 4, and 5 illustrate the strong hour-by-hour coupling between the solar flux and the rate of rise and fall of riparian groundwater tables, during both snowmelt and ET cycles. Most of this is new. Our Figure 5 somewhat resembles Figure 6 of Loheide (2008), but that only concerns evapotranspiration cycles, and compares derived estimates of ET and potential ET, not solar flux and the rate of groundwater rise/fall (although these are obviously related).

Our conceptual model analysis presented in Section 3.3 and illustrated in Figures 7 and 8 is also new. Although the conceptual model makes broadly similar assumptions to those of Gribovzski et al. (2008), as we acknowledge on line 426, we apply our model in different ways and reach new conclusions. In particular, our analysis leads to two conclusions that are new, and in our view, significant:

> **1) The commonly observed lags between peak snowmelt or peak ET and the daily peak or trough in streamflow are largely dynamical phase lags, not travel-time lags, at least in small catchments. This result challenges the assumptions underlying decades of prior work, including Wicht (1941), Jordan (1983), Bond et al. (2002), Lundquist et al. (2005), Lundquist and Dettinger (2005), Wondzell et al. (2007), Barnard et al. (2010), Graham et al. (2013), and Fonley et al. (2016); see the manuscript for the full citations.**
>
> **2) The amplitude of the daily cycle in streamflow cannot be quantitatively linked to the daily ET or snowmelt flux, unless the time constant tau of the near-stream groundwater system is quite short. This result also calls into question over 50 years of prior studies, including Tschinkel (1963), Meyboom (1965), Reigner (1966), Bond et al. (2002), Boronina et al. (2005), Barnard et al. (2010), Cadol et al. (2012), and Mutzner et al. (2015).**

We also note that this conceptual model also explains the asymmetry in snowmelt and ET cycles in streamflow, which were pointed out by Lundquist and Cayan (2002).

The diel cycle index developed in Section 3.4 and illustrated in Figure 9 is also new. This provides a new tool for characterizing seasonal transitions between snowmelt and evapotranspiration cycles in small basins.

In Section 3.5 and Figure 10 we observe that, as snowmelt cycles give way to ET cycles, the amplitude of daily cycling in the stream nearly vanishes. We also infer that this results from destructive interference between the snowmelt and ET signals originating from different parts of the catchment. These points are also, to the best of our knowledge, new.

We also observe that the transition between snowmelt and evapotranspiration cycles occurs differently in groundwaters and streamflow, due to the fact that groundwater cycles mostly reflect local forcing and streamflow integrates that forcing over the drainage network (Section 3.5 and Figures 11 and 12). This transition occurs earlier or later at different points along the drainage network (Figures 12 and S3), reflecting differences in snow accumulation and melt (and also in the onset of evapotranspiration) from place to place depending on altitude and aspect. This is all, to the best of our knowledge, new.

We also show that the spatial pattern in daily streamflow cycles is consistent with the spatial evolution of snow cover and vegetation activity as seen from space (Figures 13 and 14). This is also, to the best of our knowledge, new.

These new observations and inferences comprise almost the entire manuscript, whether measured by number of figures or length of text. Thus the claim that "most of what they show is not new" is factually incorrect.

Lundquist and Cayan (2002), see Figures 12-14, clearly illustrate the presence of both snowmelt and ET driven diurnal cycles in river basins.

Of course, and we say almost exactly this in the second sentence of the manuscript, "Both snowmelt and evapotranspiration cycles result from daily variations in solar flux, but are of opposite phase (Lundquist and Cayan, 2002…" We certainly do not want to give the impression that we are claiming to have discovered snowmelt and ET cycles in streamwater (indeed, these were known in the literature for decades before Lundquist and Cayan's work, as section 2 of their paper makes clear).

Lundquist and Dettinger (2003), which I have also attached here, with citation below*, as it's hard to find, takes this concept further (see Figures 5 and 6) by using the diurnal cycle switch to highlight inter annual variations in water supply and climate. The paper here builds nicely on this work, but it would be better to present the information as a development and illustration of already published ideas rather than a new idea.

Figure 5 of Lundquist and Dettinger (2003) is a verbatim copy of the previously mentioned Figure 14 of Lundquist and Cayan (2002). Figure 6 of Lundquist and Dettinger (2003) makes the point that snowmelt cycles switch to ET cycles earlier in drier years, based on what appears to be a preliminary analysis of daily cycle asymmetry in four years at one river. We don't think it is correct to say that our manuscript "builds nicely on this work", given that neither the methods nor the questions are similar: we use the diel cycle index rather than daily cycle asymmetry to measure the transition from snowmelt to evapotranspiration cycles, and we do not focus on year-to-year variations in the timing of these transitions, but rather the spatial evolution of those transitions in a catchment context.

2. At multiple points in the paper, the authors seem to dismiss earlier literature as missing key physical concepts and as being incomplete. At times the tone is dismissive and gives the impression of lacking respect for the earlier work.

We certainly do not mean to be dismissive or disrespectful toward prior work. However, in some cases it is unfortunately necessary to point out where the assumptions or conclusions of these previous studies are

contradicted by our data, or by accepted physical principles of water flow in hydrologic systems. For example, nearly every paper that discusses the propagation speed of snowmelt or ET cycles assumes that this propagation speed equals the flow velocity of the water itself, but that is simply not correct. It has been known for decades that changes in flow rates in hydrologic systems propagate at the kinematic wave speed, not the bulk flow rate. We have tried to point this out as gently as we can, but we cannot avoid the fact that it needs to be said.

The paper would be a much stronger contribution if the authors instead addressed why the earlier work took different approaches than here.

We do not want to speculate about why earlier studies took the approaches that they did. Obviously it is a different situation if the papers themselves reveal their motives, but that is rarely the case.

In many cases, this can be addressed by the different hydrogeologic settings of the basins, which fundamentally changes how the different processes interact and which matter the most. The Tuolumne studies (including many of the papers by Lundquist and by Loheide) are in a granitic basin with very shallow soils, which is quite different from the groundwater dominated Sagehen basin. This fundamentally changes the role of diurnal fluctuations in groundwater on the overall stream signal. (In the detailed comments below, I have called out places in the paper where this contrast could be addressed.)

We agree that different hydrologic settings could be important, but we are not aware of evidence that supports the statement that "this fundamentally changes the role of diurnal fluctuations in groundwater on the overall stream signal." Indeed, our data suggest the opposite, because daily snowmelt and ET cycles in our granitic Independence Creek drainage are strikingly similar to those in the more groundwater-dominated Sagehen Creek basin. We believe this is because the transmission of daily cycles depends on how groundwater and soil water respond to incremental additions and subtractions of water from the surface, not on the total volume of water in storage. Note that, for example, S in Eq. (4) is transient storage (or, as the manuscript puts it, "storage above the stream"), so whether there is a large volume of water stored below the stream does not change the behavior of our conceptual model. And again, the field data support this view, because the daily cycles in Independence Creek and Sagehen Creek are similar, even though one basin is granitic and the other has an extensive groundwater system.

To make this point clearer in the manuscript, we will add the following figures and text:

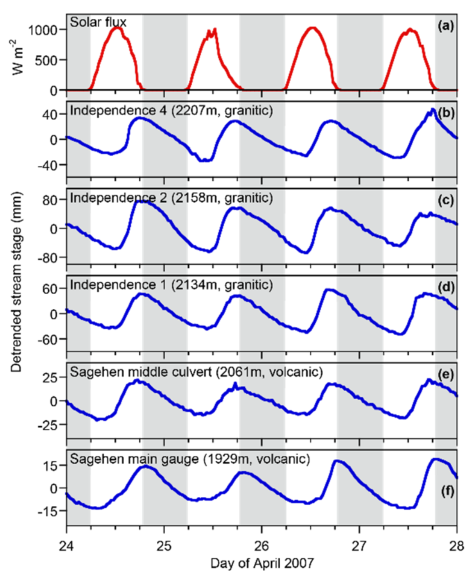

Figure A. Snowmelt-driven daily cycles in stream water levels measured in April 2007 at three locations along Upper Independence Creek, underlain by glaciated granodiorites, and two locations along Sagehen Creek, underlain by thick volcanic and volcaniclastic deposits. Stream stages were detrended using Eq. (3).

The shapes and phases of the daily cycles are similar, and all exhibit similar lags relative to the solar forcing, despite the marked geological differences between the two catchments.

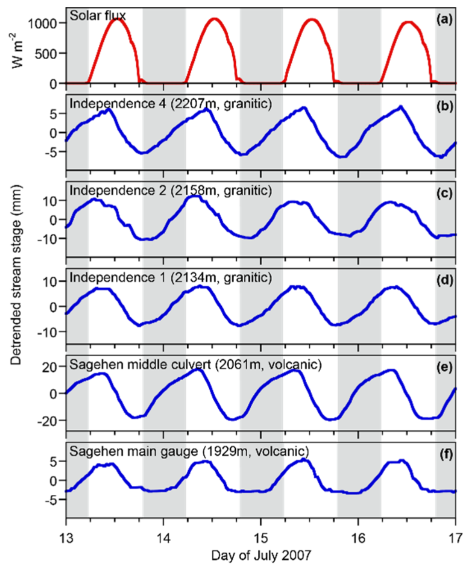

Figure B. Evapotranspiration-driven daily cycles in stream water levels measured in July 2007 at three locations along Upper Independence Creek, underlain by glaciated granodiorites, and two locations along Sagehen Creek, underlain by thick volcanic and volcaniclastic deposits. Stream stages were detrended using Eq. (3). The shapes and phases of the daily cycles are similar, and all exhibit similar lags relative to the solar forcing, despite the marked geological differences between the two catchments.

Although this conceptual model has been developed in the context of Sagehen Creek, which has an extensive groundwater aquifer, the mechanisms described here do not require substantial aquifer storage. In the model, changes in storage equal changes in discharge multiplied by the characteristic response time τ. This directly implies that the daily range of storage also equals τ times the daily range of discharge. At the Sagehen main gauge, where we can measure daily cycles in units of discharge (at the other stations we lack rating curves and thus have only stage measurements), typical daily ranges of discharge during peak snowmelt were ~2-4 mm/day in 2006 (above-average SWE), 0.2-0.6 mm/day in 2007 (below-average SWE), and 0.4-1 mm/day in 2008 (roughly average SWE). Even τ values as small as ~0.2-0.5 days are sufficient to generate significant lags between peak snowmelt and peak streamflow, implying that these lags could be associated with storage changes of only 0.4-2 mm in 2006, 0.04-0.3 mm in 2007, and 0.08-0.5 mm in 2008 (the ET cycles, and their associated ranges of storage, are about 1-2 orders of magnitude smaller). This simple calculation implies that significant dynamical phase lags can be generated from small daily variations in soil water and shallow groundwater, and that a substantial groundwater aquifer is not required.

This inference can be tested by comparing daily streamflow cycles in Sagehen Creek with those in Upper Independence Creek. The Upper Independence basin is dominated by glacially scoured granodiorites (Sylvester and Raines, 2017) and lacks the volcanic and volcaniclastic deposits that host Sagehen's extensive groundwater aquifer. Despite this sharp contrast in hydrogeology, Figs. A and B show that snowmelt and ET cycles are similar in Upper Independence Creek and Sagehen Creek. Streamflow cycles lag the solar flux curve by slightly more at the Sagehen main gauge than at the other four stations shown in Figs. A and B, reflecting the fact that the main gauge is farther downstream from its most distant headwaters (7.9 km, compared to 2.6-3.9 km for the other four stations) and integrates over a larger drainage area (27.6 km2 vs 4.7-7.7 km2 for the other stations), and thus accumulates commensurately larger kinematic wave lags. The daily cycle amplitudes also differ, due to differences in drainage areas and channel cross-sections among the

different stations. Nevertheless, the clear conclusion from Figs. A and B is that the shapes of the daily cycles, and their phase lags relative to the solar flux, are strikingly similar between the granitic, glacially scoured Upper Independence basin, and the groundwater-dominated Sagehen basin. This strongly suggests that similar mechanisms shape the streamflow cycles in both basins, despite the marked differences between their geological settings.

3. With regards to 2 above, the paper lightly addresses comparisons and contrast between Sagehen and Independence Creek. These could be strengthened through better consideration of dominant terms in different hydrogeologic settings and with further discussion of how these two sites relate to the sites in the literature. Sarah Godsey, the second author, has a nice paper on how geology relates to low flow sensitivity to snow across the Sierra, and it seems like this could be a nice tie in with this study and a discussion on hydrogeologic setting.

A multi-site intercomparison study would certainly be interesting, but would be an entirely different study from the one we present here. Challenges confronting any such intercomparison would be the differences in which variables are measured at which sites, as well as the general problem of data availability (although Prof. Lundquist's Yosemite Hydroclimate Network, http://depts.washington.edu/mtnhydr/data/yosemite.shtml, is a good example of how this problem will be gradually overcome). But again, this would be an entirely different study. Beyond the comparisons between Sagehen and Independence outlined above, we do not want to make assumptions about "dominant terms in different hydrogeologic settings" for other basins without having a clear basis for those assumptions.

If the authors have questions for me regarding these comments or would like to discuss, I can be reached at Jessica Lundquist, jdlund@uw.edu.

Thanks for the very helpful discussion that we subsequently had by video conference. We particularly appreciate your suggestion that a conceptual diagram would be help readers to visualize the groundwater-stream interactions that underlie the lag in daily cycles. We will therefore add the following figure to the manuscript:

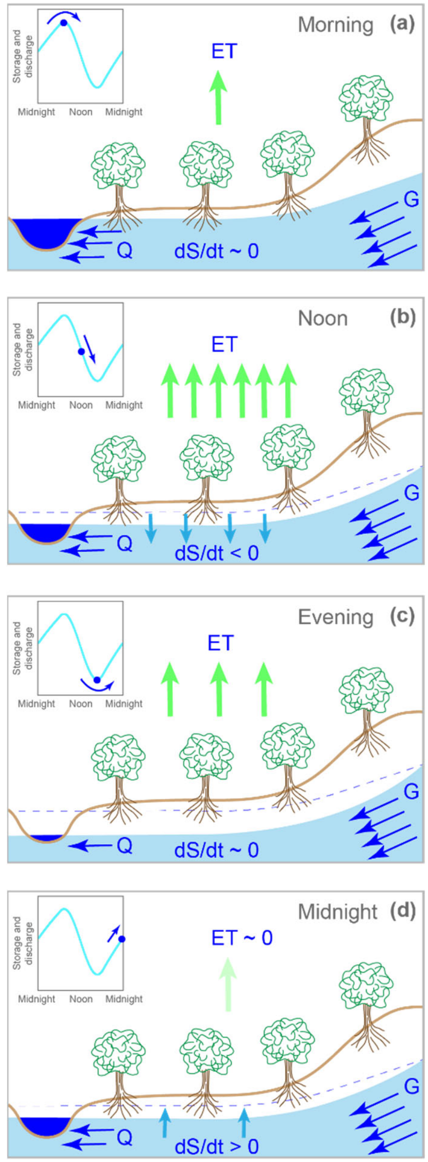

Figure X. Visualization of groundwater-stream coupling that leads to lagged evapotranspiration cycles in groundwater levels and streamflow (snowmelt cycles are similar but reversed). Streamflow is supplied by drainage from riparian groundwater, and this drainage rate is faster at higher levels of riparian groundwater storage (S). Riparian groundwater storage changes at a rate dS/dt that depends on the flux balance between streamflow (Q), evapotranspiration (ET), and groundwater recharge from surrounding uplands (G). The relative magnitudes of these fluxes in each panel are indicated by the number of arrows; upland recharge (G) is constant but the other fluxes vary from panel to panel. Inset figures show the corresponding phases of the daily cycle in streamflow and groundwater levels. In the morning (a), groundwater storage and streamflow reach their maximum and begin to decline as the evapotranspiration rate rises enough, relative to the difference between groundwater recharge and discharge, that the riparian aquifer reaches equilibrium and begins to decline. Around noon (b), high evapotranspiration fluxes lead to a strongly negative flux balance and a rapid draw-down of groundwater storage, and thus a rapid decline in streamflow (the dashed line indicates the morning high-stand of groundwater levels and stream stage, as a reference). Toward evening (c), riparian groundwater and stream stage reach their minimum and begin to rise when evapotranspiration rates and streamflows decline enough that the riparian aquifer reaches equilibrium and begins to refill. During the night (d) riparian groundwater levels (and thus stream stages) slowly rebound, because evapotranspiration is nearly zero and upland recharge exceeds stream discharge.

I apologize for my time delay in getting this posted. *Citation: Lundquist, J. D. and M. D. Dettinger, 2003. Linking diurnal cycles in river discharge to interannual variations in climate. Proceedings, AMS 17th Conference on Hydrology. Long Beach, California. available at: https://ams.confex.com/ams/annual2003/webprogram/Paper55265.html

Specific Comments Follow:

The paper has a whole has a very nice literature review, but the intro seems to diminish, rather than highlight the work that went before.

That is certainly not our intention. In several cases, though, we need to point out limitations and inconsistencies in the literature. We have tried to do that as gently as possible, consistent with the need to also be clear.

line 91: What is an “integrodifferential relationship” ? This is confusing.

Another reviewer also found this confusing, and we will change it. What we meant is a relationship that is described by a differential equation rather than an algebraic one.

Lined 105-109: I think the Loheide and Lundquist paper is a link here. These two assumptions are compatible if the stream and the groundwater levels essentially rise and fall at the same time. Most papers state that ET flux variations are only true in this very linked riparian zone. I don’t follow the argument that they must be separate hypotheses.

We will try to clarify this argument in the manuscript, because the assumptions underlying the water table fluctuation approach and the missing streamflow approach are in fact mathematically inconsistent with one another. This inconsistency has nothing to do with whether groundwater and streamwater rise and fall at essentially the same time (which they also do in our conceptual model, and also in our data).

Here is the problem. "Missing streamflow" methods must assume that daily additions and removals of water from the catchment are transmitted 1:1 to the stream; otherwise, the change in streamflow does not quantitatively reflect the snowmelt or evapotranspiration rate. But daily additions and removals of streamflow are not transmitted 1:1 to the stream if groundwater levels also vary on a daily cycle, because in this case, the daily addition of snowmelt (for example) is partitioned between <u>both</u> the daily change in streamflow and the daily change in groundwater storage.

Conversely, water table fluctuation methods assume that daily removals of groundwater by ET are reflected 1:1 in changes in groundwater storage (net of an assumed constant input from upland recharge and constant output to streamflow); otherwise, the change in groundwater level does not quantitatively reflect the evapotranspiration rate. But daily removals of groundwater by ET are not reflected 1:1 in groundwater storage if streamflow (which is generated predominantly from groundwater…) also varies on a daily cycle.

Thus the "missing streamflow" approach assumes that ET and snowmelt will only change streamflow fluxes (and thus groundwater storage will be constant), and water table fluctuation approaches assume that ET and snowmelt will only change groundwater storage (and thus that streamflow fluxes will be constant). Thus these premises really are inconsistent with one another.

Lines 115-120: Again, I must beg to differ here. The Lundquist papers focused on the early (snowmelt-dominated) season, in a granite-lined basin with a meadow/riparian system whose groundwater levels responded essentially in synch with the streamflow levels. Again, it’s not incompatible, but it’s also very nuanced. I think a better way to discuss this would be that the ideas may be system specific and not directly transferable across systems. I think most people are making simplifications that matter for their systems without explicitly discussing other possible systems. So yes, it makes sense to bring them all together, but the “incompatible” statements don’t seem right to me.

Our statement was that studies that attribute lags in daily cycles exclusively to travel times and flow velocities are incompatible with the assumptions that underlie water table fluctuation (WTF) methods. WTF methods assume that groundwater integrates its inputs, which will create a substantial phase lag even in the absence of any travel-time lags. If the assumptions of the WTF approach are correct, then the first several hours of the lag in groundwater or streamflow cycles cannot be attributed to travel times. Thus the two approaches do, in fact, make incompatible assumptions.

This has nothing to do with whether groundwater levels and streamflow levels are synchronized with one another (which they are in our conceptual model, and also often are in our data, as well as in your data from Tuolumne Meadow). Rather, the issue is (as stated in lines 111-121) whether the cyclic response by *both* groundwater and streamflow lags the cyclic forcing by snowmelt or ET, and whether this lag arises from a phase lag due to integration in the shallow groundwater system, or due to travel times.

The phase lag that we have identified at Sagehen is also seen at Independence Creek, and it is also present in your own Yosemite data, including at Budd Creek, Delaney Creek, and Lyell Fork below Maclure (at 2940 m, and only about 4 km below the headwaters at Lyell Glacier). Thus these different geological settings exhibit a consistent pattern of behavior. Generating this same pattern of behavior, with roughly the same lag time, by travel-time delays would require the same rather particular set of conditions (depth of snowpack, distance to channel, length of channel network, etc.) to hold across these very different settings.

Line 130: Loheide and Lundquist (2009) had observations as well.

We will change this sentence to eliminate the distinction between modeling and observational studies.

Also, with regards to “few studies have examined things together”, it seems to me that there are few diurnal cycle studies in general, but it seems like about as many have looked at both as have looked at one.

We agree that there are few diurnal cycle studies in general, but even among this group, studies of coupled groundwater/surface water cycles are relatively scarce – particularly those that actually measure both groundwater and surface water cycles, along with measurements of sapflow/ET as a driver. Even scarcer are studies that have looked at both groundwater/surface water cycles in response to both snowmelt and ET, in the spatial context of elevation gradients and the temporal context of seasonal shifts from snowmelt to ET and back again.

Upper Independence Basin is more similar to the Tuolumne watershed (compare and contrast your results with the literature).

As we point out above, the daily cycles in streamflow at Upper Independence, and in headwater streams in the Tuolumne basin, are similar to those at Sagehen despite the substantial difference in lithology.

A fair bit of the literature is also concerned with how much of the riparian area actually takes part in diurnal fluctuations. Can you address this issue?

We cannot, for the reasons described in Section 3.3. To do this by modeling requires assuming that we actually know the volume of the daily snowmelt or ET forcing, but as Section 3.3 makes clear, we cannot know this unless we also know the time constant (tau) of the riparian soil water/groundwater system. Alternatively, one could detect the spatial extent of groundwater fluctuations using direct measurements, but it would require a more extensive groundwater monitoring network than we have.

line 240: Given the sharp rain-shadow gradient in these areas, I would recommend using the 800-m PRISM normals for distributing the Snotel rather than elevation weights (different locations at the same elevation can get quite different amounts of snow). However, I doubt that this would change any of your main results here, so this comment is mainly for future reference rather than a requirement to redo your precipitation mapping for this particular paper.

Thanks, yes, this is an interesting point. The SNOTEL sites are sited along the rain-shadow gradient, so they capture the rain shadow effect rather well. In any case our results do not depend on mass balances, so they don't require that we have an ideal interpolation of the SNOTEL data.

line 335: also in Lundquist and Cayan 2002

We will add this reference.

line 360: This discussion is relevant to your "incompatibility" argument, see notes above.

We don't understand the point here. The Loheide and Lundquist study was conducted more than six weeks after snowmelt ended in Tuolumne Meadow, and the snowmelt signal in the stream was generated much higher up in the basin (where there are no groundwater measurements). Thus the Loheide/Lundquist paper does not bear directly on how snowmelt signals are transmitted to the stream, which is our focus here.

Your Fig. 9 is in L&C 2002, see their Fig 14. This is also in Lundquist and Dettinger 2003, a preprint from a conference (https://ams.confex.com/ams/annual2003/webprogram/Paper55265.html, also attached here). See Figures 5 and 6, which essentially show what you are getting at here.

We disagree with the claim that "Your Fig. 9 is in L&C 2002", which could be construed as accusing us of using prior work without attribution. We are sure that this was not your intention, but nonetheless we need to set the record straight. Below we show Figure 14 of L&C 2002 and our Figure 9, side by side.

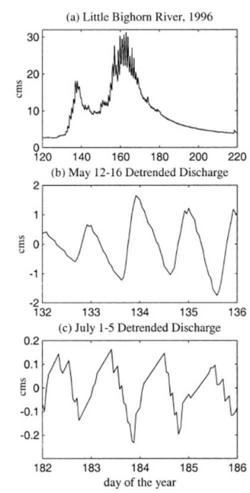

FIG. 14. (a) A 1996 hydrograph for the Little Bighorn River, illustrating how diurnal cycle changes as snowmelt forcing gives way to evapotranspiration/infiltration forcing. Periods illustrated in (b) and (c) were fit to a line, which was then subtracted out to accentuate the diurnal fluctuations.

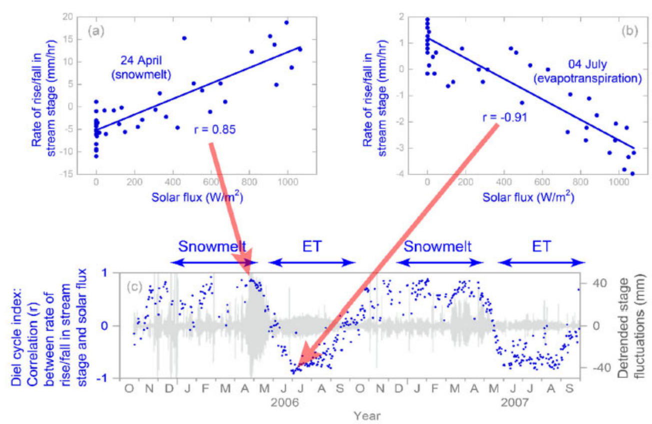

Figure 9. Correlations between solar flux and rates of rise and fall of water levels (Sagehen Creek, B transect) during two example days, one when the catchment was snow-covered and the stream exhibited a strong snowmelt cycle (24 April 2007), and another when the catchment was snow-free and the stream exhibited a strong evapotranspiration cycle (4 June 2007). In the lower plot, the correlation coefficients (blue dots) for each day indicate the relative dominance of snowmelt or evapotranspiration as generators of daily cycles in Sagehen Creek, while the gray shading shows the amplitude of the detrended daily stage fluctuations.

We are perplexed by the statement that the figure on the right is contained in the figure on the left. The figure on the left (from L&C 2002) shows only that streams can exhibit daily cycles driven by both snowmelt and evapotranspiration, and that these cycles have different shapes. Claiming that that our Figure 9 makes the same points is simply inconsistent with Sections 3.4 through 3.6 of our paper.

Below we show Figures 5 and 6 from Lundquist and Dettinger (2003). Again, we do not think that our Figure 9 is equivalent to these or contained in them. The figures below concern how the <u>asymmetry</u> of the daily cycle changes between snowmelt and ET-dominated cycles. Our Figure 9 concerns the <u>phases</u> of the cycles, and in particular, the phase relationship between time derivative of stream water levels and the solar flux (as a driver, through snowmelt and ET, of those rises and falls in stream water levels). This is quantified through the diel cycle index, which is nowhere mentioned in Lundquist and Dettinger (2003) or L&C 2002.

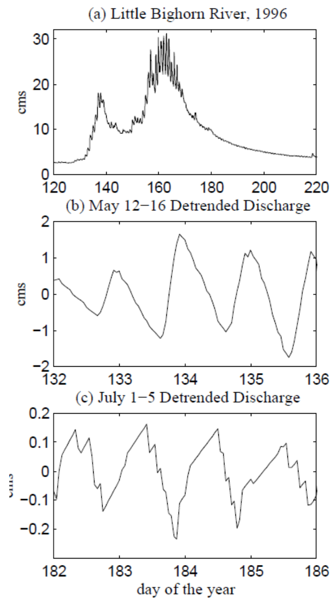

Figure 5: *(a) The 1996 hydrograph for the Little Bighorn River, illustrating how the diurnal cycle changes as snowmelt forcing gives way to evapotranspiration/ infiltration forcing. Periods illustrated in (b) and (c) were fit to a line, which was then subtracted out to accentuate the diurnal fluctuations.*

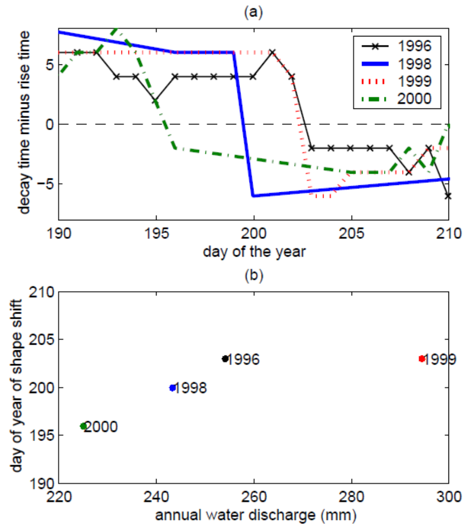

Figure 6: *(a) Shifting of the flow in the Little Bighorn River from a longer diurnal decay time (snowmelt-dominated) to a longer rise time (evapotranspiration/infiltration-dominated), as the recent snowmelt season draws to a close. (b) The date of the shift as a function of the total discharge for each year. In general, drier years shift earlier in the summer.*

Fig. 10: You're using straight sinusoids. We know that they're assymmetric. See Lundquist and Cayan 2002.

We agree that they're asymmetric, and in fact our analysis explains *why* they're asymmetric (see our Figure 7, and Section 3.3, particularly the paragraph beginning on line 480 – where we already cite two Lundquist papers). The point of this figure was to simply show that the disappearance of the diel cycle in the stream was due to the destructive interference between the snowmelt and ET cycles. The asymmetry in those cycles is not important to this point, but we will re-draw the figure to include it.

Line 429: You mean Lundquist and Dettinger (2005) here (not Lundquist and Cayan 2005).

You're right, sorry, that was just a typo. We'll fix it (we had it right in the reference list).

Line 430: Again, I think it's worth comparing and contrasting how the assumptions made in these different systems really relate to the underlying geology. In a granitic system like Tuolumne, there isn't much of a riparian aquifer (unlike in Sagehen, with deep soils) Section 2.2 in Lundquist et al. 2005 discusses the hillslope/riparian flow paths.

Yes, but Section 2.2 of Lundquist et al. (2005) discusses these flow paths in terms of the transit time of the water, which is not what controls how rapidly changes in flow rates will be transmitted to the stream. Changes in flow rates propagate at the kinematic wave velocity, not at the mean flow velocity. This is true in snowpacks, in unconfined groundwater systems, and in open-channel flow (in confined groundwater systems, changes in flow rates propagate even faster, at the pressure wave propagation velocity).

Loheide and Lundquist 2009 goes on to show that for the Tuolumne system, the riparian groundwater levels are driven by the stream water levels and not vice versa.

One cannot make that statement about riparian groundwater levels throughout "the Tuolumne system", but only about Tuolumne meadow, and only during the period studied by Loheide and Lundquist, more than a month after snowmelt ended there. The daily cycles studied by Loheide and Lundquist 2009 are driven by snowmelt many kilometers upstream from Tuolumne meadow (and understandably, by that late in the season, they drive the variations in the groundwater rather than the other way around, since there is no

remaining snowpack, and thus no locally-generated snowmelt, at the Tuolumne Meadow groundwater wells).

But the snowmelt cycles in the Tuolumne River entered the river somehow, and the headwater gauges (Lyell Fork below Maclure, Budd Creek, and Delaney Creek) indicate that snowmelt cycles enter the stream with several-hour lags relative to the snowmelt rate itself. We show that similar lags can arise whenever inflow rates to the stream are coupled to riparian groundwater storage, which integrates the snowmelt input itself. (In principle, this lag can also arise by kinematic wave propagation through snowpacks, hillslopes, and channels, but it would take some rather special circumstances for the resulting kinematic wave lag to be so similar in so many different settings.)

Again, you are correct that Sagehen should be modeled differently, but your paper as a whole would be a stronger contribution if you put your results in the context of the varying hydrogeology represented in the literature.

We are not saying that Sagehen should be modeled differently, or saying that its geology differs in ways that are important for these purposes (although we recognize that this may be your view). We are instead saying that it is essential to recognize that in all catchments, rates of streamflow are linked to the volume of water stored in the near-stream aquifer, which in turn integrates inputs from snowmelt and removals from ET. This conceptual picture is consistent with the phase relationships observed not only at Sagehen, but also at Independence Creek and the headwater Yosemite sites.

Line 584: This is illustrated in Lundquist and Dettinger 2003, see Figure 5.

We don't understand the basis for this statement. Figure 5 of Lundquist and Dettinger (2003), reproduced above, shows that snowmelt and evapotranspiration cycles have different shapes. That is different from the point made here, which is that these two cycles will destructively interfere in the stream, resulting in the daily cycle becoming weak and reversing phase as it shifts from being snowmelt-dominated to ET-dominated.

Line 620: Also, Independence Creek has more granitic geology and less groundwater reserves. It makes sense in the hydrogeologic context that this would have a snowmelt-dominated signal longer.

We don't understand the rationale behind this statement. The snowmelt-dominated signal will last as long as snow is melting in the riparian corridor, and melting in sufficient amounts that the snowmelt signal dominates over the competing evapotranspiration signal. Having more or less groundwater will not change this balance, but having more snow and melting it later certainly will. And our Figures 13 and 14 indicate that this is indeed the case here; the snow-covered fraction at Upper Independence Creek remains higher, for longer, than at Sagehen Creek.

Lines 847-850: Data do not appear to be available at this time. Please do check that everything is publicly available and clearly interpretable (with readme files, metadata, etc) before final acceptance of the publication.

We intend to do this.

The pulse of a montane ecosystem: ~~coupled~~coupling between daily cycles in solar flux, snowmelt, transpiration, groundwater, and streamflow at Sagehen and Independence Creeks, Sierra Nevada, USA

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Abstract

. Water levels in streams and aquifers often exhibit daily cycles during rainless periods, reflecting ~~diurnal~~**daytime** extraction of shallow groundwater by evapotranspiration (ET) and, during snowmelt, ~~diurnal~~**daytime** additions of meltwater. These cycles can ~~potentially~~ aid in understanding the mechanisms that couple solar forcing of ET and snowmelt to ~~variations~~**changes** in streamflow. Here we analyze three years of 30-minute solar flux, sap flow, stream stage, and groundwater level measurements at Sagehen Creek and Independence Creek, two snow-dominated headwater catchments in California's Sierra Nevada mountains. **Despite their sharply contrasting geological settings (most of the Independence basin is glacially scoured granodiorite, whereas Sagehen is underlain by hundreds of meters of volcanic and volcaniclastic deposits that host an extensive groundwater aquifer) both streams respond similarly to snowmelt and ET forcing.** During snow-free summer periods, daily cycles in solar flux are tightly correlated with variations in sap flow, and with the rates of water level rise and fall in streams and riparian aquifers. During these periods, stream stages and riparian groundwater levels decline during the day and rebound ~~during the~~**at** night. ~~During~~ **These cycles are reversed during** snowmelt~~, daily cycles in solar flux have the opposite effect~~, with stream stages and riparian groundwater levels rising during the day in response to snowmelt inputs, and ~~declining~~**falling** at night as the riparian aquifer drains.

~~The mid-day peak in solar flux coincides with the fastest rates of water level rise~~**Streamflow** and ~~decline~~ **groundwater maxima and minima** (during snowmelt**-** and ET-dominated periods, respectively~~), not with~~**)** **lag** the ~~maxima or minima~~**mid-day peak** in ~~water levels themselves~~**solar flux by several hours**. A simple conceptual model explains ~~these temporal patterns~~**this lag**: streamflows depend on riparian aquifer water levels, which integrate snowmelt inputs and ET losses over time, and thus will be phase-shifted relative to the peaks in snowmelt and evapotranspiration rates. ~~The highest and lowest riparian water levels (for snowmelt and ET cycles, respectively) will not occur at mid-day when the solar forcing is strongest, but rather in the late afternoon when the solar forcing declines enough that the riparian aquifer transiently achieves mass balance.~~ Thus, although the lag between solar forcing and water level cycles is often interpreted as a travel-time lag, our analysis shows that it is ~~predominantly~~**mostly** a dynamical phase lag, at least in small catchments. Furthermore, although ~~daily~~**daily** cycles in streamflow have often been used to estimate ET fluxes, our simple conceptual model demonstrates that this is infeasible unless the **response** time ~~constant~~ of the riparian aquifer can be determined.

As the snowmelt season progresses, snowmelt forcing of groundwater and streamflow weakens and evapotranspiration forcing strengthens. ~~Because these two forcings have opposite phases, groundwater and stream level variations reflect the balance between them.~~ The relative dominance of snowmelt vs. ET can be quantified by the diel cycle index, **which measures** the correlation ~~coefficient~~ between the solar flux and the rate of rise or fall in streamflow or groundwater~~, which will be close to +1 and -1 when water level cycles are dominated by snowmelt and ET, respectively.~~**.** When the snowpack melts out at an individual location, the ~~diel cycle index in the~~ local groundwater shifts abruptly from snowmelt-dominated cycles to ET-dominated cycles. ~~Streamflow, however,~~ **Melt-out, and the corresponding shift in the diel cycle index, occur earlier at lower altitudes and on south-facing slopes, and streamflow** integrates these transitions over the drainage network. Thus the ~~transition in the streamflow~~ diel cycle index ~~begins~~**in streamflow shifts gradually, beginning** when the snowpack melts out near the gauging station, and ~~ends~~**ending**, months later, when the snowpack melts out at the top of the basin and the entire drainage network becomes dominated by ET cycles. During this long transition, ~~Sagehen Creek's upper reaches exhibit snowmelt cycles at the same time that its lower reaches exhibit ET cycles, implying that~~ snowmelt signals generated in the upper basin are **gradually** overprinted by ET signals generated lower down in the basin.

~~Sequences of Landsat images show that the~~**The** gradual springtime transition in the diel cycle index ~~mirrors~~**is mirrored in sequences of Landsat images showing** the springtime retreat of the snowpack to higher ~~and higher~~ elevations, and the corresponding advance of photosynthetic activity across the basin. ~~Furthermore, trends~~**Trends** in the catchment-averaged MODIS enhanced vegetation index (EVI2) **also** correlate closely with ~~both~~ the late springtime shift from snowmelt to ET cycles and **with** the autumn shift back toward snowmelt cycles. **Seasonal changes in streamflow cycles therefore reflect catchment-scale shifts in snowpack and vegetation activity that can be seen from Earth orbit.** The data and analyses presented here illustrate how streams can act as mirrors of the landscape, integrating physical and ecohydrological signals across their contributing drainage networks.

Key words: diel cycle; diurnal cycle; streamflow; groundwater; snowmelt; evapotranspiration; sap flow; solar radiation; phase lag.

1 Introduction

In mountain regions, streamflow and shallow groundwater levels often exhibit 24-hour cycles driven by either snow/ice melt or evapotranspiration. Both snowmelt and evapotranspiration cycles result from daily variations in solar flux, but are of opposite phase (Lundquist and Cayan, 2002; Mutzner et al., 2015; Woelber et al., 2018), because melt processes contribute water to the shallow subsurface during daytime, while evapotranspiration removes it during daytime. These daily cycles have been used to investigate streamflow generation and runoff routing (Wondzell et al., 2007; Barnard et al., 2010; Woelber et al., 2018), to infer dominant processes affecting catchment water balances ~~(Lundquist and Cayan, 2002; Czikowsky and Fitzjarrald, 2004)~~**(Lundquist and Cayan, 2002; Czikowsky and Fitzjarrald, 2004)**, and to estimate temporal patterns of landscape-scale evapotranspiration (ET) and precipitation rates (Bond et al., 2002; Kirchner, 2009; Cadol et al., 2012). The analysis of daily cycles may thus be a useful diagnostic tool in catchment hydrology, helping to characterize eco-hydrological processes at the catchment scale (Lundquist et al., 2005; Gribovszki et al., 2010).

However, in many cases it remains unclear how daily cycles in groundwater and streamflow should be quantitatively linked to daily cycles of snowmelt and ET fluxes. How are the amplitudes or phases of groundwater cycles related to the amplitudes and phases of the snowmelt and ET cycles that drive them? How are these groundwater cycles transmitted to streamflow, and how are streamflow cycles integrated along the channel network? While these linkages have been modeled (both conceptually and numerically) based on various mechanistic assumptions ~~(Gribovszki et al., 2010)~~**(as reviewed by Gribovszki et al., 2010)**, empirical verification remains sparse due to the scarcity of coupled observations of snow accumulation and melt, daily ET cycles, and fluctuations in both groundwater and streamflow at multiple locations along channel networks.

Daily groundwater cycles have been widely used to infer riparian evapotranspiration rates using various forms of a groundwater mass balance first proposed by White (1932):

$$E_G = S_y\,(24r + s) \tag{1}$$

where E_G is the consumption of groundwater by evapotranspiration, expressed as a daily rate, S_y is specific yield, r is the hourly rate of night-time water table rise during hours when ET is assumed to have no effect (thus reflecting a constant rate of riparian aquifer recharge), and s is the net daily decline in the water table. This approach and its many subsequent elaborations (e.g., Loheide et al., 2005; Loheide, 2008; Butler et al., 2007; Soylu et al., 2012; Fahle and Dietrich, 2014) are collectively termed the "water table fluctuation" (or WTF) method~~.~~ **(Healy and Cook, 2002).** The WTF method assumes that the daily cycle in ET results only in a daily cycle in groundwater levels, and not a daily cycle in streamflow, which would need to be taken into account in the groundwater mass balance ~~(but see Gribovszki et al., 2008 for an example where this is explicitly included)~~**(but see Gribovszki et al., 2008 for an example where this is explicitly included)**. The WTF method also implies that a given rate of evapotranspiration (or a given rate of snowmelt input) should be reflected in a given rate of rise or fall in groundwater levels. ~~Therefore the~~**The** WTF method **therefore** implies that **groundwater levels integrate snowmelt or evapotranspiration signals, and thus that** there should be ~~an integro-differential relationship (and thus~~ a roughly 6-hour phase lag~~,~~ **(**see Sect. 3.3 below) between daily groundwater cycles and the evapotranspiration or snowmelt cycles that drive them.

Daily cycles in streamflow have also been widely used to infer evapotranspiration rates, based on summing the "missing streamflow" between the actual streamflow cycle and a line connecting daily peak flows, assumed to represent the streamflow that would occur in the absence of ET (e.g., Tschinkel, 1963; Hiekel, 1964; Meyboom, 1965; Reigner, 1966; Bond et al., 2002; Boronina et al., 2005; Barnard et al., 2010; Cadol et al., 2012; Mutzner et al., 2015). The missing streamflow method pre-dates all of these cited applications by decades, given that as early as the 1930's, Troxell observed that "Others have connected the points of maximum discharge during the diurnal fluctuation and assumed that the curve thus obtained would represent the probable flow of the stream if there were no losses, also that the difference between this quantity and the actual discharge represents the transpiration-loss" ~~(Troxell, 1936).~~**(Troxell, 1936).** The latter assumption outlined by Troxell implies that evapotranspiration losses are subtracted 1:1 from streamflow and thus that they are not buffered by changes in groundwater storage.

From the two preceding paragraphs, it should be clear that WTF approaches (for inferring ET rates from groundwater cycles) and missing streamflow approaches (for inferring ET rates from daily streamflow cycles) are founded on fundamentally incompatible assumptions. Missing streamflow methods assume that ~~the~~ daily ~~cycle~~**cycles** in ET ~~results only in a~~**are transmitted 1:1 to** daily ~~cycle~~**cycles** in streamflow, ~~and~~ **implying that they must** not ~~a daily cycle~~**be buffered by changes** in groundwater levels~~, whereas~~ **(and thus that the groundwater cycles required by WTF approaches cannot exist). Conversely,** WTF approaches assume ~~the exact opposite. One~~**that daily cycles in ET are volumetrically equal to daily cycles in groundwater levels, implying that no part of these ET cycles** can ~~of course question whether either~~**be**

transmitted to the stream (and thus that the streamflow cycles required by missing streamflow methods cannot exist). There may be conditions under which one or the other set of assumptions is ~~realistic~~**approximately correct**, but ~~they certainly cannot~~ **clearly** both ~~be correct~~**cannot be valid at the same time**.

The timing of daily streamflow maxima and minima, and their lags relative to the daily peaks of snowmelt or ET rates, have also been widely interpreted as reflecting travel times and flow velocities through snowpacks, hillslopes, and river networks (e.g., Wicht, 1941; Jordan, 1983; Bond et al., 2002; Lundquist et al., 2005; Lundquist and Dettinger, 2005; Wondzell et al., 2007; Barnard et al., 2010; Graham et al., 2013; Fonley et al., 2016). These applications, like the missing streamflow method, invoke assumptions that are incompatible with those that underlie WTF approaches. ~~The~~ WTF ~~is~~**approaches are** based on a mass balance in which groundwater integrates ET cycles (because a given ET flux results in a given rate of change in groundwater levels). This implies that there will ~~often~~ be a ~~roughly 6~~**several**-hour phase lag (for the same reason that the integral of a sine function is a cosine and vice versa) between ET cycles and **both** groundwater ~~cycles -- and also, by extension, between ET cycles~~ and streamflow cycles~~,~~ **(**given that streamflows are closely linked to groundwater levels~~.~~**).** This phase lag must be taken into account before inferring travel-time delays from observed time lags between **snowmelt or ET cycles and the resulting** streamflow maxima or minima ~~and the snowmelt or ET cycles that drive them~~.

Clarifying how groundwater and streamflow cycles ~~depend on~~**are linked to** the snowmelt or ET cycles that drive them will require coupled observations of groundwater and stream stage, as well as rates and patterns of snow accumulation and melt, and daily cycles in vegetation water uptake and its meteorological drivers. Such integrated observational studies are rare. Few studies have examined interactions between snowmelt and ET cycles, though exceptions include Lundquist and Cayan ~~(2002)~~**(2002)**, Mutzner et al. ~~(2015) and Woelber et al.~~**(2015) and Woelber et al.** (2018). Likewise, few studies have linked daily cycles in groundwaters and streams, although exceptions include ~~observations by~~ Troxell ~~(1936)~~**(1936)**, Klinker and Hansen (Klinker and Hansen, 1964), ~~Wondzell et al. (2010), and Woelber et al. (2018), and models by Czikowsky and Fitzjarrald (2004), Grobovszki et al.~~**Czikowsky and Fitzjarrald (2004), Gribovszki et al.** ~~(2008)~~**(2008)**, Szilagyi et al. ~~(2008) and~~**(2008),** Loheide and Lundquist ~~(2009).~~ **(2009), Wondzell et al. (2010), and Woelber et al. (2018).** And due to the scarcity of simultaneous spatially distributed measurements spanning mesoscale basins, the spatial aggregation of snowmelt and ET cycles across elevation gradients remains greatly under-studied.

Here we contribute to closing these knowledge gaps using detailed, multi-year ecohydrological time series, including solar flux, snowmelt, snow water equivalent, riparian tree sap flow fluxes, stream stages (recorded at ~~13~~**12** sites spanning a 500-meter elevation gradient), and groundwater levels (recorded in two dozen wells), from Sagehen and Independence Creeks in California's Sierra Nevada Mountains. These time series, together with a simple conceptual model of riparian groundwater mass balance, demonstrate both the potential and the limitations of using snowmelt- and ET-induced daily cycles in streamflow and groundwater to infer catchment-scale processes. We compare these time series measurements with remote sensing observations of the spring/summer retreat of the seasonal snowpack and the corresponding advance of photosynthetic activity, to illustrate how daily cycles in groundwater levels and stream stages mirror the spatial and temporal patterns of seasonal ecohydrological transitions at the catchment scale. The Mediterranean climate of Sagehen and Independence Creeks is characterized by heavy winter snowfall and by strong solar radiation and very little precipitation during the snowmelt and growing seasons, making ~~these basins ideal for studying~~**it relatively easy to see** how snowmelt and evapotranspiration are reflected in daily cycles in groundwater and streamflow.

2 Field site and data

2.1 Field site

The Sagehen (pronounced "sage hen") basin is located on the east slope of California's Sierra Nevada mountain range, approximately 12 km north of the town of Truckee (Fig. 1a). Sagehen Creek is a headwater tributary that flows eastward from the crest of the Sierra Nevada into Stampede Reservoir on the Truckee River. ~~The Sagehen basin is part of the US Forest Service's Sagehen Experimental Forest, and includes the Sagehen Creek Field Station (39°25´54.45" N, 120°14´19.30" W, 1935 m a.s.l.), which has been operated by the University of California, Berkeley, since 1951.~~ The catchment ranges in elevation from 2663 m on Carpenter Ridge to 1877 m at the lowermost streamflow monitoring location, where it has a drainage area of 34.7 km^2. The uppermost part of the catchment is a steep, glaciated cirque, and the lower catchment is a broad U-shaped valley bordered by broad rolling uplands.

~~;~~

The Sagehen basin has a Mediterranean climate with cold, wet winters and warm, dry summers. Monthly average temperatures recorded at Sagehen Creek Field Station between 1997 and 2009 ranged from -3.5 °C in January to 15.9 °C in July. Average annual precipitation between 1 June 1953 and 31 Dec 2010 at the same location was 850 mm, and average annual snowfall and snow depth were 515 and 33 cm, respectively. Sagehen Creek is downwind of the Sierra crest, so there is a pronounced gradient in precipitation (and particularly in snowfall) from the headwaters toward the eastern (downstream) end of the basin, due to a combination of declining altitudes and a deepening rain shadow. Because precipitation occurs predominantly in the winter and snowfall accounts for more than 80% of the annual precipitation, the annual runoff is strongly controlled by snowmelt, which generates peak flows in late spring or early summer, with annual minima occurring in the late summer and fall ~~(Godsey et al., 2014)~~**(Godsey et al., 2014)**.

The Sagehen basin is densely vegetated, with roughly 90% covered by forests and 10% **covered** by meadows and shrubs. The forest is dominated by lodgepole pine (*Pinus contorta*), Ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi*), Douglas fir (*Pseudotsuga menziesii*), sugar pine (*Pinus lambertiana*), white fir (*Abies concolor*), red fir (*Abies magnifica*), and incense cedar (*Calocedrus decurrens*). Grassy meadows are predominantly found along the main stream. Shrub vegetation occurs on soils too poor, rocky, or shallow to support conifer forests, and also as a post-fire or post-harvest successional stage to mixed conifer forests on deeper, more productive soils (Bailey et al., 1994).

Soils at Sagehen are ~~classified as Alfisols and consist of~~ deep, well-drained acidic ~~soils~~**Alfisols** developed in weathered volcanic parent material. Typically, soil profiles in the Sagehen basin present a dark grayish-brown, gravelly, sandy loam from the surface to roughly 60 cm and a subsoil of yellowish-brown, cobbly, sandy, loam that extends to a depth of 115 cm ~~(Johnson and Needham, 1966).~~**(Johnson and Needham, 1966).** Lithology is dominated by Tertiary volcanic rocks, primarily Miocene-Pliocene andesitic flows (and, on the north side of the lower Sagehen basin, Pliocene basalt flows), overlying several hundred meters of Tertiary volcaniclastic deposits which in turn overlie Cretaceous granodiorites of the Sierra Nevada batholith ~~(Hudson, 1951; Sylvester and Raines, 2017).~~**(Hudson, 1951; Sylvester and Raines, 2017).** This >~~400m~~**400 m** layer of volcanic rocks hosts a substantial groundwater aquifer, with ~~mean~~**geothermal data suggesting groundwater circulation to depths exceeding 100 m (Brumm et al., 2009). Mean** groundwater ages in springs feeding Sagehen Creek **have been** estimated at approximately 28 years during baseflow conditions and 15 years during snowmelt ~~(Rademacher et al., 2005)~~**(Rademacher et al., 2005)**, varying from year to year in response to changes in annual snowmelt volumes and thus recharge rates ~~(Manning et al., 2012)~~**(Manning et al., 2012)**. This groundwater system sustains flows in springs, fens, and Sagehen Creek itself during the dry season, which typically lasts from May through September. **Even during peak snowmelt, cosmogenic ^{35}S measurements indicate that over 85% of Sagehen Creek streamflow is derived**

from stored groundwater, with less than 15% originating as recent snowmelt (Uriostegui et al., 2017). Quaternary colluvial, alluvial, and glacial deposits lie on top of the volcanic rocks, ranging from a few meters on most hillslopes to >15 m in the riparian zone at lower elevations ~~(Manning et al., 2012)~~**(Manning et al., 2012)**. Measured hydraulic conductivities in the surficial deposits near the creek range from 10^{-6} to 10^{-4} m s^{-1} ~~(Manning et al., 2012)~~**(Manning et al., 2012)**, indicating the ~~capability~~**capacity** to support considerable groundwater flow.

The Sagehen basin was affected by extensive timber harvesting, grazing and wildfires in the late nineteenth and early twentieth century, but there has been little change in land use since the early 1950's ~~(Erman et al., 1988)~~**(Erman et al., 1988)**. Two access-limited dirt roads cross the catchment, which also hosts a small US Forest Service campground. The only permanent habitation is the headquarters of Sagehen Creek Field Station, and the principal human activity is research (mainly in ecology, biology and hydrology) conducted by several universities and government agencies. Recreational uses include fishing, hunting, hiking, cross-country skiing, and snowmobiling.

In contrast to the Sagehen basin, the adjacent Upper Independence basin was deeply scoured by Pleistocene glaciers that removed the Tertiary volcanic rocks and exposed the underlying Cretaceous granodiorites over much of the catchment ~~(Sylvester and Raines, 2017).~~**(Sylvester and Raines, 2017).** As a result, ~~much of~~**the** Upper Independence ~~Creek~~**basin** lacks ~~the~~**Sagehen's** extensive groundwater system~~ that sustains low flows in Sagehen Creek, resulting in contrasting baseflow behavior between the two catchments~~. Dry-season low flows in Upper Independence Creek are nonetheless sustained by groundwater seeping from the Tertiary volcanic deposits that ring the basin, particularly on the steep north~~-facing~~ slopes of Carpenter Peak, which retain snow cover long after the rest of the basin has melted out. The Upper Independence basin~~ also~~ extends approximately 4 km farther west than the Sagehen basin does, and thus it likely receives somewhat more precipitation, being less affected by the rain shadow of the Sierra crest. The steep north-facing slopes of the Upper Independence basin also keep their snow cover later into the summer than the Sagehen basin does. Roughly 50% of the Upper Independence basin consists of ~~unvegetated~~**bare** granodiorite outcrops and talus slopes, whereas the Sagehen basin is almost completely vegetated. The Upper Independence Creek basin is largely undisturbed, with no roads, no developed trails, and old-growth forest. Example ground-level views of the Sagehen and Independence basins are shown in Fig. S1.

There were no impoundments or diversions on either Sagehen Creek or Upper Independence Creek at the time of this study. Sagehen Creek has been gauged continuously since 1953 at an altitude of 1929 m and a drainage area of 27.6 km^2 **(https://waterdata.usgs.gov/ca/nwis/inventory/?site_no=10343500&agency_cd=USGS)** as part of the U.S. Geological Survey's Hydrological Benchmark Network ~~(Mast and Clow, 2000)~~**(Mast and Clow, 2000)**, and LiDAR-derived digital elevation data are available **from https://opentopography.org/** for both the Sagehen and Upper Independence basins~~.~~ **(Kirchner, 2012; Huntington, 2013; Guo, 2014).** Further background information on the Sagehen basin can be found in Mast and Clow ~~(2000)~~**(2000)** and on the Sagehen Creek Field Station web site ~~(https://sagehen.ucnrs.org/).~~**(https://sagehen.ucnrs.org/).**

2.2 Field instrumentation

The field data presented here were collected during three water years (defined as 1 October-30 September): 2005-6, 2006-7 and 2007-8. Solar flux, air temperature, wind velocity, relative humidity, precipitation, and atmospheric pressure were recorded by a weather station located near Sagehen Creek Field Station (Fig. 1a). Precipitation, air temperature, snow depth and snow water equivalent (SWE) are also available from three Natural Resources Conservation Service SNOTEL (snow telemetry) stations located adjacent to the Sagehen Creek catchment, each equipped with a snow pillow~~.~~ **(https://www.wcc.nrcs.usda.gov/snow/).** The SNOTEL stations are, in order of increasing elevation: i) Independence

Creek (~~39°29' N, 120°17' W,~~ 1968 m a.s.l.), near the confluence of Independence Creek and Little Truckee River, approximately 7 km NNW from the Sagehen main stream gauge, ii) Independence Camp (~~39°27' N, 120°18' W,~~ 2135 m a.s.l.), near the outflow of Independence Lake, approximately 5 km WNW from the Sagehen main stream gauge, and iii) Independence Lake (~~39°26' N, 120°19' W,~~ 2546 m a.s.l.), on the divide between the Sagehen Creek basin and the adjacent Upper Independence Creek basin (Fig. 1a). These SNOTEL stations lie outside the Sagehen Creek catchment but are adjacent to it, spanning roughly the same altitude range and the same range of distances from the Sierra crest. Thus they provide a reasonable proxy for the gradient in precipitation, snow accumulation, and snowmelt timing across the Sagehen basin.

Sap flow was measured using Granier ~~(1987)~~**(1987)** thermal dissipation probes (Dynamax inc.) installed in June 2005 in four trees close to the weather station and the B transect of groundwater wells (see below). Three trees were outfitted with duplicate probes to test for consistency. The timing and magnitude of sap flow variations were similar among the ~~various~~ monitored trees, so the average of all the available measurements was used for further analysis. Because our analysis is focused on the timing of sap flow and its relationship to groundwater and streamflow fluctuations, it was not necessary to calibrate the sap flow measurements or quantitatively extrapolate them to stand-scale evapotranspiration fluxes. The sap flow sensors were not removed and re-inserted into new sites on the tree trunks each year, but instead remained in the same sites; thus the sap flow measurements show year-to-year declines that are artifacts of the wound healing response of the trees.

Water stage was measured by TruTrack and Odyssey capacitance water level loggers (www.trutrack.com and http://odysseydatarecording.com/, respectively) at six locations along Sagehen Creek (see Table 1 and Fig. 1): the lower culvert, the main gauge (the USGS gauging station), the B transect (approximately 120m west of the main gauge), the D transect (at Kiln meadow), the middle culvert (where the Sagehen road crosses the creek, upstream of Kiln meadow) and the upper culvert (where the road again crosses the creek, just below its headwater cirque). Water stage was also measured on three lateral tributaries of Sagehen Creek: one entering from the north (Kiln Creek), and two entering from the south (South Tributaries 1 and 2). Water stage was also measured at four locations on Upper Independence Creek, of which ~~the lowermost site (IND-01) is~~**three are** used here. The Sagehen main gauge stage recorder is co-located with the US Geological Survey gauging station, whereas all other stage recorders were installed specifically for this study (Fig. 1a). The capacitance water level loggers were calibrated in the lab and referenced to an arbitrary datum that differed for each stream location. Therefore, water stage was not comparable from one location to another. No rating curves were available to convert water stage into discharge, except at the main gauge. Thus all stream data are presented here as stage, in millimeters relative to an arbitrary datum that varies from site to site.

Shallow groundwater level variations were monitored in 24 wells equipped with TruTrack and Odyssey capacitance water level loggers. In the 1980's, five transects of shallow groundwater wells were hand-augered to 1m, or to refusal, in the Sagehen Basin, and were sleeved with 1.5m PVC pipes (8 cm diameter), perforated over the bottom 0.5 m ~~(Allen-Diaz, 1991).~~**(Allen-Diaz, 1991).** We instrumented 24 wells in the two longest transects, labeled B and D. The B transect crosses Sagehen Creek just downstream of the field station. The northern B transect consists of four wells extending 32m northward from the stream across the seasonally wet Sagehen East Meadow, close to the weather station and the sap flow trees. The southern B transect consists of ten wells (of which the first nine were instrumented) extending 330m southward from the stream across dry and seasonally wet meadows and, in the farther reaches of the transect, lodgepole pine (*Pinus contorta*) forest (Fig. 1c). The D transect is located at Kiln Meadow, roughly 1.5 km upstream of the B transect. The D transect consists of six wells that extend 132m northward from the stream across a seasonally wet sedge meadow, and nine wells (of which five were instrumented) that extend 280m southward from the stream across seasonally wet meadows and lodgepole pine forest (Fig. 1b).

2.3 Field data

The original meteorological, hydrometric, and sap flow measurements were collected at 10, 15, and 30-minute intervals. All of the records were aggregated to a consistent 30-minute time base for analysis, and all times are reported in Pacific Standard Time. Weather and snow water equivalent (SWE) data from the three SNOTEL stations were at daily temporal resolution. The stage recorders were downloaded infrequently, and often failed; as a result, data gaps of up to a year in length are found in several of the stage records, and up to two years in some groundwater wells~~ on the southern sides of the two transects~~.

To ~~take~~ account ~~of~~**for** the combined role of snowmelt and rainfall during the melting season, we calculated the total water input at each of the SNOTEL stations by subtracting the net change in snow water equivalent (as measured by the snow pillow) from total precipitation over each daily time step. Thus, any precipitation that was stored as increased SWE was not counted as liquid water input to the catchment until it subsequently melted. Since there is a strong elevation gradient in SWE (see Section 3.1), we computed an area-weighted average of the total water input, assigning a weight to each SNOTEL station by defining its area of influence. We defined three elevation bands centered on each SNOTEL station, with the band limits defined by the midpoint in elevation between each pair of adjacent stations, and by the top and the outlet of the basin~~.~~ **(see Fig. S2).** Measurements at each SNOTEL station were weighted according to the catchment area in each elevation band. Independence Creek SNOTEL station (1968 m) had a weight of 32%, Independence Camp (2135 m) had a weight of 58%, and Independence Lake (2546 m) had a weight of only of 10%, reflecting the relatively small fraction of the Sagehen Creek basin at these higher elevations. **Because the resulting average water input values are used only for visualization and not for mass balance analyses, we did not account for other factors (such as slope, aspect, and forest cover) that can also influence the spatial distribution of precipitation and snow accumulation.**

To more precisely compare stream stage and groundwater level fluctuations with potential weather drivers, we estimated the rate of change of stage or groundwater level for each time step i from the difference between the measurements immediately before and after, i.e.,

$$\left(\frac{dh}{dt}\right)_i = \frac{h_{i+1} - h_{i-1}}{2\,\Delta t} \tag{2}$$

where h is groundwater level or stream stage, t is time, and Δt is the sampling interval (0.5 hours). Thus the rates of change reported here are averaged over one hour, centered on each 30 minutes. To visualize daily stream and groundwater variations while excluding longer-term patterns, we also calculated water level anomalies relative to the running 24-hour average as follows:

$$h'_i = h_i - \frac{1}{48}\left(\sum_{j=i-24}^{i-1} h_j + \sum_{j=i+1}^{i+24} h_j\right) \tag{3}$$

where h'_i is the detrended water level, relative to a 24-hour average composed of 48 half-hourly measurements surrounding (but excluding) h_i itself.

3. Analysis, Results and Discussion

3.1 Climate forcing

Precipitation, air temperature, and SWE data at the three SNOTEL stations clearly show an elevation gradient in precipitation and snow accumulation across the Sagehen Creek catchment (Fig. 2, Tables 2 and 3). Precipitation patterns were similar among the three stations, with year-to-year Pearson's correlation coefficients for total cumulative precipitation for 29 water years (1981-2009) between 0.94 and 0.98 ($p<0.01$, $n=29$) across all pairs of sites. SNOTEL stations at higher elevations (and also closer to the Sierra crest) had somewhat higher precipitation totals, and also markedly greater seasonal snow accumulation despite a difference of less than 1 °C in average temperature across the nearly 600 m range of elevations (Tables 2 and 3). The higher-altitude stations also began accumulating snow earlier in the winter, and their melt seasons began later and lasted longer (Fig. 2).

Annual precipitation totals and peak SWE varied substantially from year to year, with larger cumulative precipitation totals and peak snow-water equivalent in water year 2005-6, followed by 2007-8 and 2006-7 (Fig. 2, Tables 2-3). Comparison with the long-term averages (Table 3) shows that precipitation at all stations was well above the long-term average in 2005-6, and well below the long-term average in the other two water years.

During the summer and early fall, intense solar fluxes and high temperatures (with daily highs often well above 30°C) created ideal conditions for high evapotranspiration fluxes. Consistent with Sagehen's Mediterranean climate, from May to October precipitation events were infrequent, sporadic, and generally small. Thus the hydrologic effects of snowmelt and evapotranspiration were minimally obscured by precipitation from late spring through early fall.

3.2 Climatic control on daily cycles in stream stage and groundwater level

Clearly visible daily cycles were observed in all water level records (both stream stages and groundwater levels) during rain-free periods between late spring and early autumn. Daily cycles in several stream stage records (particularly the upper culvert and the three tributary streams) became indistinct as the streams dried up; likewise the daily cycles in several groundwater wells became indistinct as the water level reached the bottom of the sensor. Our analysis of groundwater cycles will focus on the northern side of the B transect, just downstream of the field station (Fig. 1c), because records from three of the four water level sensors are complete for two full years, and because this transect is situated close to the weather station and the **trees equipped with** sap flow ~~trees~~**sensors**.

During the snowmelt period in late spring, stream stages and groundwater levels typically reached their maxima in late afternoon and their minima shortly after dawn (Fig. 3c-d). This temporal pattern has also been observed in previous studies of snowmelt-induced daily cycles in streamflow and groundwater levels (e.g., Loheide and Lundquist, 2009; Lundquist et al., 2005; Lundquist and Dettinger, 2005), and has been attributed to daytime melting of the snowpack during periods of high temperatures and strong solar radiation (Fig. 3). During the summer, the phase of the daily cycles reversed, with stream stages and groundwater levels typically reaching their maxima in the early morning and their minima late in the afternoon (Fig. 4). This temporal pattern has also been observed in previous studies of evapotranspiration-induced daily cycles in streamflow and groundwater levels during dry periods (e.g., Kozeny, 1935; Troxell, 1936; Dunford and Fletcher, 1947; Hiekel, 1964; Klinker and Hansen, 1964; Burt, 1979; Kobayashi et al., 1990; **Lundquist and Cayan, 2002;** Butler et al., 2007; Wondzell et al., 2007; Gribovszki et al., 2008; Gribovszki et al., 2010), and has been attributed to daytime riparian evapotranspiration in response to strong solar fluxes and low relative humidity (Fig. 4). The night-time rebound in groundwater levels can be attributed to groundwater recharge delivered to the alluvial aquifer from upslope ~~(Tschinkel,~~

~~1963). The average groundwater level, and thus~~**(Tschinkel, 1963). The average groundwater level, and thus average** discharge to the stream, will adjust to the balance between the average recharge from upslope and the average evapotranspiration losses. During summer days, however, evapotranspiration losses will be substantially higher than the 24-hour average, so the short-term ~~mass~~**flux** balance in the riparian aquifer will be negative and groundwater levels (and thus drainage rates to the stream) will fall during the daytime. Conversely, at night evapotranspiration losses will be minimal, the short-term ~~mass~~**flux** balance will be positive, and groundwater levels (and thus streamflows) will rise ~~(e.g., Troxell, 1936; Tschinkel, 1963).~~**(e.g., Troxell, 1936; Tschinkel, 1963). Figure 5 shows a simplified schematic of the mass balance that determines the evolution of riparian groundwater storage, and thus the rise and fall in stream discharge over time.**

The examples shown in Figs. 3 and 4 illustrate the fundamental role of solar radiation in driving daily fluctuations in the stream and in groundwater. The rate of rise and fall in groundwater levels is tightly coupled to the solar flux (top panels in Figs. 3 and 4) in both the snowmelt-dominated and evapotranspiration-dominated periods. However, the sign of that coupling reverses between the two periods, consistent with solar radiation driving water inputs to the riparian zone during spring snowmelt, and driving water extraction from the riparian zone by evapotranspiration during mid-summer. During mid-summer, the daily cycle in the solar flux is very tightly correlated with the sap flow flux (top panel of Fig. ~~5~~**6**), and both the solar flux and the sap flow flux are very tightly correlated with the rate of decrease in groundwater levels (note the inverted scale of the groundwater fluctuations in the bottom two panels of Fig. ~~5~~**6**). Day-to-day, and even hour-to-hour, variations in solar flux are reflected in both sap flow rates and riparian zone groundwater declines (Fig. ~~5~~**6**). During snow-free periods, approximately the same timing of daily cycles is observed among most of the wells, both in meadows and in adjacent forests (Fig. ~~S2~~**S3**), suggesting that they reflect a local synchronous response ~~in~~**to** ET ~~forces~~**forcing**.

Variations in stream stage are synchronous, or nearly so, with variations in groundwater levels (Figs. 3-4), further suggesting strong coupling between the stream and the riparian aquifer ~~(Troxell, 1936; Cadol et al., 2012)~~**(Troxell, 1936; Cadol et al., 2012)**. One can of course question whether the groundwater cycles drive the stream stage cycles, or the other way around, as has been reported in some riparian meadows ~~(e.g., Loheide and Lundquist, 2009)~~**(e.g., Loheide and Lundquist, 2009)** and glacial forefields ~~(e.g., Magnusson et al., 2014)~~**(e.g., Magnusson et al., 2014)**. However, that possibility can be excluded in the case of the B transect shown in Figs. 4-~~5~~**6**, because the mean water levels in the wells are 0.2-1 m above the stream stage, and both the water levels and the amplitudes of the daily cycles increase with distance from the channel (Fig. ~~6~~**7**). When groundwater cycles are driven by stream stage variations, by contrast, their amplitude decreases with distance from the stream.

In July 2009, following the field measurements reported here, the US Geological Survey drilled several deeper wells adjacent to the stream channel at the B transect, the D transect, and the middle culvert ~~(Manning et al., 2012)~~**(Manning et al., 2012)**. At the B transect, a well drilled to a depth of 10.4 m (and screened below 4.3 m depth) had a static water level of 1.5 m above the stream, and 0.6 m above the ground surface. At the D transect, a well drilled to a depth of 14.5 m (and screened below 2.3 m depth) had a static water level of 0.7 m above the stream. And just upstream from the middle culvert, a well drilled to a depth of 13.1 m (and screened below 2.4 m depth) had a static water level of 0.3 m above the stream ~~(see Tables A1 and A2 of Manning et al., 2012)~~**(see Tables A1 and A2 of Manning et al., 2012)**. These water levels, recorded in September 2009 under dry conditions, demonstrate that groundwater feeds the stream rather than the other way around, even under the driest conditions. These measurements also demonstrate an upward hydraulic gradient in the valley axis at all three locations, consistent with ~~our hypothesis of groundwater~~**fracture** flow from upslope recharging the riparian aquifer during mid-summer, thus sustaining both streamflow and plant water use.

3.3 Dynamical phase lags between solar flux and hydrometric response

A clear feature seen in Figs. 3, 4, and ~~6~~7, and in many previous studies, is the time lag between the daily cycles of solar flux and groundwater and streamwater levels: the solar flux peaks near noon, but the water levels reach their maximum (or, during ET-dominated periods, their minimum) in late afternoon or early evening. This time lag has been widely interpreted as indicating the time it takes for a pulse of water from snowmelt (or, conversely, a pulse of water removal by ET) to reach the channel, or to travel downstream to the measurement point (e.g., Wicht, 1941; Jordan, 1983; Bond et al., 2002; Lundquist et al., 2005; Lundquist and Dettinger, 2005; Wondzell et al., 2007; Barnard et al., 2010; Graham et al., 2013; Fonley et al., 2016). Here we show that**, at least in small catchments,** this is not primarily a travel-time lag, but rather a dynamical phase lag. Dynamical phase lags arise ~~through the structure of integro-differential systems.~~**whenever one system component integrates another.** In this case, because riparian groundwater integrates meltwater and evapotranspiration fluxes, daily cycles in groundwater should lag those in meltwater or evapotranspiration by roughly six hours, even in the absence of travel-time lags, for the same reason that a sine wave input, when integrated, yields a cosine wave with a 90-degree phase lag relative to the input. **Streamflows depend on riparian groundwater levels; thus, streamflow maxima and minima lag behind peak snowmelt or ET because it takes time for the effects of each day's snowmelt or ET to accumulate in the riparian aquifer (see Fig. 5).**

We demonstrate this principle using a simple conceptual model of a stream and its adjacent riparian aquifer. Following the simple dynamical systems approach of Kirchner ~~(2009)~~**(2009)** we assume that stream discharge (Q) depends directly on the storage (S) in the riparian aquifer, which is recharged by liquid precipitation (P), snowmelt (M) and groundwater flow from upslope (G), and is drained by stream discharge (Q) and evapotranspiration (~~E). Thus the~~ET**). This** simple dynamical system~~ becomes~~**, shown in simplified form in Fig. 5, can be represented mathematically as**:

~~$$Q = f(S) \quad \text{and} \quad \frac{\mathrm{d}S}{\mathrm{d}t} = P + M + G - E - Q \quad , \tag{4}$$~~

$$Q = f(S) \quad \text{and} \quad \frac{\mathrm{d}S}{\mathrm{d}t} = P + M + G - ET - Q \quad , \tag{4}$$

where storage is expressed in volume per unit riparian area, and fluxes are expressed in volume per unit riparian area per unit time. Any other consistent system of units can also be used (for example, storage in volume per unit stream length and fluxes in volume per unit stream length per time); the numerical values will differ, but the equations and the underlying concepts remain the same. Several mechanisms may link increases in riparian storage to increases in stream discharge, including steepening of hydraulic gradients, rising water tables reaching shallower, more permeable till layers (the "transmissivity feedback" hypothesis of Bishop, 1991), increasing connectivity between local zones of mobile saturation ~~(Tromp-van Meerveld and McDonnell, 2006)~~**(Tromp-van Meerveld and McDonnell, 2006), extension of flowing stream networks (Godsey and Kirchner, 2014; Van Meerveld et al., 2019)**, and activation of preferential flowpaths.

Directly from the form of Eq. (4), we can see that maxima or minima in riparian storage (and thus groundwater level) will generally lag maxima in the fluxes of meltwater or evapotranspiration, for the simple reason that these fluxes directly control the rate of change of storage ($\mathrm{d}S/\mathrm{d}t$), and storage itself integrates this rate of change over time. Thus, for example, the peak of a daily snowmelt pulse will not correspond to the peak in storage (and thus discharge), but rather to the fastest rate of increase of storage **(**and **thus of** discharge~~.~~**).** The peak of storage and discharge will instead occur later, as the snowmelt pulse is ending and the ~~mass~~**flux** balance in Eq. (4) is shifting from positive to negative. **One can see this behavior in Figs. 3 and 4: groundwater levels change fastest near the peak of the solar flux (Figs. 3a, 4a, and 5b), but the groundwater**

levels themselves reach their maxima (or, for ET cycles, minima) several hours later (Figs. 3c, 4c, and 5c), when the rate of groundwater rise/fall changes sign.

Integration of a periodically cycling input implies a phase lag of roughly one-quarter cycle in the output, or roughly six hours in the case of a daily cycle in meltwater or ET forcing. The exact value of the time lag will depend on the shape of the cyclic forcing function and the form of the relationship between storage and discharge. For purposes of illustration, we can make the simplifying assumption that discharge is a linear function of storage $Q = f(S) = S/\tau$, where S is riparian storage relative to the level of the stream and τ represents the characteristic response timescale of the linear reservoir. In real-world cases, storage-discharge relationships are likely to be strongly nonlinear~~, with the characteristic time constant τ being much~~ **(e.g., Penna et al., 2011), with the characteristic response time τ being** shorter at high flows (as may occur, for example, during peak snowmelt) than during summer low flows ~~(e.g., Sect. 12 of Kirchner, 2009)~~**(e.g., Sect. 12 of Kirchner, 2009)**. Nonetheless, any nonlinear storage-discharge relationship will be approximately linear over a sufficiently narrow range of storage variations, such as one would expect for individual daily cycles of storage and discharge. Making this assumption, Eq. (4) becomes the first-order linear differential equation

~~$$\frac{\mathrm{d}S}{\mathrm{d}t} = P + M + G - E - \frac{S}{\tau} \quad , \qquad (5)$$~~

~~where P, M, G, and E may all be time-varying, and Q and $\mathrm{d}Q/\mathrm{d}t$ are related to S and $\mathrm{d}S/\mathrm{d}t$ by the proportionality constant $1/\tau$. We can further assume that, at least over small ranges of water level, specific yield (drainable porosity) S_y is approximately constant and thus the rate of change in groundwater level is $\frac{\mathrm{d}h_G}{\mathrm{d}t} = \frac{\mathrm{d}S}{\mathrm{d}t}\frac{1}{S_y}$. We can also assume that, at least over small ranges of stream stage, the slope m of the stage-discharge rating curve is nearly constant and thus the rate of change in stream stage is $\frac{\mathrm{d}h_Q}{\mathrm{d}t} = \frac{\mathrm{d}Q}{\mathrm{d}t}\frac{1}{m} = \frac{\mathrm{d}S}{\mathrm{d}t}\frac{1}{m\tau}$. The assumptions underlying this simple model are similar to those made by Gribovszki et al. (2008) in their analysis of riparian evapotranspiration. Our assumptions differ from those of Troxell (1936), Loheide (2008), Cadol et al. (2012), and Soylu et al. (2012) because our analysis explicitly recognizes that the rate of discharge from the riparian aquifer to the stream is not constant, but instead depends on riparian aquifer storage. Our analysis also differs fundamentally from those of Bond et al. (2002), Lundquist and Cayan (2005), Lundquist et al. (2005), Wondzell et al. (2007), and Graham et al. (2013), who assume that water fluxes from snowmelt or evapotranspiration are added or subtracted 1:1 from streamflow itself, rather than from a riparian aquifer that feeds the stream (which buffers and phase-lags the hydrologic signals that the stream receives).~~

$$\tau \frac{\mathrm{d}Q}{\mathrm{d}t} = P + M + G - ET - Q \quad , \qquad (5)$$

where P, M, G, and ET may all be time-varying, and Q and $\mathrm{d}Q/\mathrm{d}t$ are related to S and $\mathrm{d}S/\mathrm{d}t$ by the proportionality constant $1/\tau$. We can further assume that, at least over small ranges of riparian groundwater levels, specific yield (drainable porosity) S_y is approximately constant and thus the rate of change in groundwater level is $\frac{\mathrm{d}h_G}{\mathrm{d}t} = \frac{\mathrm{d}S}{\mathrm{d}t}\frac{1}{S_y}$. We can also assume that, at least over small ranges of stream stage, the slope m of the stage-discharge rating curve is nearly constant and thus the rate of change in stream stage is $\frac{\mathrm{d}h_Q}{\mathrm{d}t} = \frac{\mathrm{d}Q}{\mathrm{d}t}\frac{1}{m} = \frac{\mathrm{d}S}{\mathrm{d}t}\frac{1}{m\tau}$. Thus S_y and m can be used to convert storage and discharge variations into changes in groundwater levels and stream stages.

The assumptions underlying this simple model are similar to those made by Gribovszki et al. (2008) in their analysis of riparian evapotranspiration. Our assumptions differ from those of Troxell (1936), Loheide (2008), Cadol et al. (2012), and Soylu et al. (2012) because our analysis explicitly recognizes that the rate of discharge from the riparian

aquifer to the stream is not constant, but instead depends on riparian aquifer storage. Our analysis also differs fundamentally from those of Bond et al. (2002), Lundquist and Dettinger (2005), Lundquist et al. (2005), Wondzell et al. (2007), and Graham et al. (2013), who assume that water fluxes from snowmelt or evapotranspiration are added or subtracted 1:1 from streamflow itself, rather than from a riparian aquifer that feeds the stream (which buffers and phase-lags the hydrologic signals that the stream receives).

If the external forcing is sinusoidal, solving a linear equation like (5) is a well-known textbook problem in linear systems theory. For example, if the combined forcing $P + M + G -$ ~~$E -$~~ $ET = \bar{Q} + A\cos(\omega t)$, where $\bar{Q}$ **is average discharge,** A **is the amplitude of the forcing cycle, and** ω is ~~the~~**its** angular frequency (and thus for a daily cycle, $\omega = 2\pi$ day^{-1}), Eq. (5) can be solved analytically to yield

~~$$S = \tau \frac{A}{\sqrt{1+\omega^2\tau^2}} \cos(\omega t - \phi) \quad , \qquad (6a)$$~~

~~$$Q = \frac{S}{\tau} = \frac{A}{\sqrt{1+\omega^2\tau^2}} \cos(\omega t - \phi) \quad , \qquad (6b)$$~~

~~$$\frac{\mathrm{d}S}{\mathrm{d}t} = \omega\,\tau \frac{A}{\sqrt{1+\omega^2\tau^2}} \cos\left(\omega t + \frac{\pi}{2} - \phi\right) \quad , \text{ and} \qquad (6c)$$~~

~~$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \omega \frac{A}{\sqrt{1+\omega^2\tau^2}} \cos\left(\omega t + \frac{\pi}{2} - \phi\right) \quad , \text{ where} \qquad (6d)$$~~

$$Q = \bar{Q} + \frac{A}{\sqrt{1+\omega^2\tau^2}} \cos(\omega t - \phi) \quad , \qquad (6a)$$

$$S = \tau\, Q = \bar{S} + \tau \frac{A}{\sqrt{1+\omega^2\tau^2}} \cos(\omega t - \phi) \quad , \qquad (6b)$$

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \omega \frac{A}{\sqrt{1+\omega^2\tau^2}} \cos\left(\omega t + \frac{\pi}{2} - \phi\right) \quad , \text{ where} \qquad (6c)$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \omega\,\tau \frac{A}{\sqrt{1+\omega^2\tau^2}} \cos\left(\omega t + \frac{\pi}{2} - \phi\right) \quad , \text{ and} \qquad (6d)$$

$$\phi = \arctan(\omega\tau) \quad . \qquad (6e)$$

Thus, in this simplified example, **streamflow will be a sinusoidal cycle that is damped by a dimensionless factor of** $\sqrt{1+\omega^2\tau^2}$**,** storage will be a sinusoidal cycle that is damped by a factor of $\sqrt{\frac{1}{\tau^2}+\omega^2}$ (which has dimensions of 1/time), ~~streamflow will be a sinusoidal cycle that is damped by a dimensionless factor of $\sqrt{1+\omega^2\tau^2}$,~~ and both storage and ~~streamfow~~**streamflow** will be phase-shifted by an angle $\arctan(\omega\tau)$ relative to the external forcing. These sinusoidal cycles in storage and discharge, when re-scaled by factors of $\frac{1}{S_y}$ and $\frac{1}{m}$, respectively, will yield the corresponding sinusoidal cycles in groundwater level and stream stage. If the riparian aquifer's **response** time ~~constant~~ τ is short (such that $\omega\tau \ll 1$), the cycle in S will be small (Eq. ~~6a~~**6b**) and most of the cycle in the forcing will be transmitted directly to Q, so the amplitude of the cycles in Q will nearly equal the amplitude of the forcing (Eq. ~~6b~~**6a**). In this case, the phase shift ϕ will be small (Eq. 6e) and the cycles in storage (and thus discharge) will be nearly synchronized with the forcing (Eqs. 6a and 6b). Thus, the assumptions underlying "missing streamflow" methods, as outlined in Sect. 1, are met when the aquifer's **response** time ~~constant~~ τ is short ($\omega\tau \ll 1$~~).~~**; for a daily cycle this corresponds to $\tau \ll 4$ hours).** Conversely, in the more typical case that the riparian aquifer's **response** time ~~constant~~ τ is long enough that $\omega\tau \gg 1$, the forcing cycles will mostly be absorbed by variations in storage (which now will mostly integrate the forcing cycles rather than transmitting them to discharge). This more typical case corresponds to the assumptions underlying water table fluctuation (WTF) methods for inferring ET from groundwater cycles (as outlined in Sect. 1). When $\omega\tau \gg 1$, cycles in the rate of rise and fall in riparian storage $\mathrm{d}S/\mathrm{d}t$ will have nearly the same amplitude as the forcing (Eq. ~~6c~~**6d**), but cycles in stream discharge Q will be strongly damped (Eq. ~~6b~~**6a**). In this case, the phase shift ϕ will approach $\frac{\pi}{2}$ (Eq. 6e) and thus cycles in storage and discharge will lag the forcing by about 90 degrees, or six hours for a daily cycle (Eqs. 6a and 6b). ~~Under these conditions, however,~~**However, unlike the storage and discharge themselves, their** rates of rise and fall~~ in storage and discharge~~ (that is, $\mathrm{d}S/\mathrm{d}t$ and $\mathrm{d}Q/\mathrm{d}t$ in Eqs. 6d and 6e) will be nearly synchronized with the forcing (e.g., Fig. ~~5~~**6**), because their phase lags $\phi - \frac{\pi}{2}$ will be small.

In less idealized cases, the forcing functions P, M, G, and ~~E~~ET may be non-sinusoidal (but nonetheless periodic) functions of time. In such cases, Eq. (5) can be solved to any desired precision using Fourier methods. The solution is straightforward because the Fourier transform of the derivative operator is simply $\mathrm{i}\omega$ – that is, $\mathrm{F}\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right) = \mathrm{i}\omega\,\mathrm{F}(x)$, where F() denotes the (complex) Fourier transform , x is some function of time, and ω is angular frequency – so the Fourier transforms of ordinary differential equations are algebraic equations. For example, the Fourier transform of Eq. ~~(5), together with the relationship $Q = S/\tau$, yields~~**(5) is**

~~$$\mathrm{i}\,\omega\,\mathrm{F}(S) = \mathrm{F}(P + M + G - E) - \frac{\mathrm{F}(S)}{\tau} \quad , \qquad (7)$$~~

$$\mathrm{i}\,\omega\,\tau\,\mathrm{F}(Q) = \mathrm{F}(P + M + G - ET) - \mathrm{F}(Q) \quad , \qquad (7)$$

with the solutions

~~$$\mathrm{F}(S) = \tau\frac{1 - \mathrm{i}\,\omega\,\tau}{1 + \omega^2\,\tau^2}\,\mathrm{F}(P + M + G - E) \quad , \qquad (8a)$$~~

~~$$\mathrm{F}(Q) = \frac{\mathrm{F}(S)}{\tau} = \frac{1 - \mathrm{i}\,\omega\,\tau}{1 + \omega^2\,\tau^2}\,\mathrm{F}(P + M + G - E) \quad \text{, and} \qquad (8b)$$~~

~~$$\mathrm{F}\left(\frac{\mathrm{d}Q}{\mathrm{d}t}\right) = \mathrm{i}\,\omega\,\mathrm{F}(Q) = \mathrm{i}\,\omega\frac{1 - \mathrm{i}\,\omega\,\tau}{1 + \omega^2\,\tau^2}\,\mathrm{F}(P + M + G - E) \quad . \qquad (8c)$$~~

$$\mathrm{F}(Q) = \frac{1 - \mathrm{i}\,\omega\,\tau}{1 + \omega^2\,\tau^2}\,\mathrm{F}(P + M + G - ET) \quad , \qquad (8a)$$

$$\mathrm{F}(S) = \tau\,\mathrm{F}(Q) = \tau\frac{1 - \mathrm{i}\,\omega\,\tau}{1 + \omega^2\,\tau^2}\,\mathrm{F}(P + M + G - ET) \quad , \qquad (8b)$$

$$\mathrm{F}\left(\frac{\mathrm{d}Q}{\mathrm{d}t}\right) = \mathrm{i}\,\omega\,\mathrm{F}(Q) = \mathrm{i}\,\omega\frac{1 - \mathrm{i}\,\omega\,\tau}{1 + \omega^2\,\tau^2}\,\mathrm{F}(P + M + G - ET) \quad , \quad \text{and} \qquad (8c)$$

$$\mathrm{F}\left(\frac{\mathrm{d}S}{\mathrm{d}t}\right) = \mathrm{i}\,\omega\,\mathrm{F}(S) = \mathrm{i}\,\omega\,\tau\frac{1 - \mathrm{i}\,\omega\,\tau}{1 + \omega^2\,\tau^2}\,\mathrm{F}(P + M + G - ET) \quad . \qquad (8d)$$

Equation (8) can be applied straightforwardly by 1) taking the Fourier transforms of the forcing functions, 2) multiplying the resulting complex Fourier coefficients as shown in Eq. (8) to obtain the Fourier ~~transform~~**transforms** of the ~~storage S,~~ discharge Q, ~~or rate~~**storage S, and their rates** of change ~~of discharge~~ $\frac{\mathrm{d}Q}{\mathrm{d}t}$ **and** $\frac{\mathrm{d}S}{\mathrm{d}t}$, and then 3) taking the inverse Fourier ~~transform~~**transforms** to obtain S, Q, ~~or~~ $\frac{\mathrm{d}Q}{\mathrm{d}t}$**, and** $\frac{\mathrm{d}S}{\mathrm{d}t}$ as ~~a function~~**functions** of time. ~~As an illustration,~~**This Fourier method is preferable to numerically integrating Eq. (5) because initialization is not required (the input, and the solution, go on forever** in **both directions) and there is no risk of numerical instability. In** Fig. ~~7~~**8** we show the behavior of Eq. (5) assuming no precipitation (P), a constant groundwater inflow rate (G), and a reasonable range of riparian aquifer ~~time~~

~~constants~~**response times** τ (0.2 to 5 days). We represent both snowmelt rates M (dark blue curves) and evapotranspiration rates E (light blue curves) using a rectified half-wave cosine function (Fig. ~~7a~~**8a**), which roughly approximates the mid-summer solar flux curve (Figs. 4-~~6~~**7**).

The daily cycles shown in Fig. ~~7b~~**8b**-d are asymmetrical, rising or falling more steeply during the daytime than their subsequent recovery at night. They also exhibit large apparent time lags, with discharge peaks (or minima in the case of ET cycles) between 3 and 5 PM, depending on the value of τ, and discharge minima (or maxima in the case of ET cycles) between 6 and 7 AM. Figure ~~8a~~**9a** shows that these time lags remain several hours long for all aquifer ~~time constants~~**response times** τ longer than about 0.1 day. These time lags, as well as the asymmetry of the discharge curves, have often been attributed to travel-time delays for transport through the snowpack, aquifer, or river network (Wicht, 1941; Jordan, 1983; Bond et al., 2002; Lundquist et al., 2005; Lundquist and Dettinger, 2005; Wondzell et al., 2007; Barnard et al., 2010; Graham et al., 2013; Fonley et al., 2016). Figure ~~7~~**8** shows instead that they can arise purely from the internal dynamics of the riparian aquifer itself, as it integrates either cyclic water inputs from snowmelt or cyclic riparian losses from ET. That is, lags between snowmelt or ET and discharge cycles can arise purely as dynamical phase lags, determined by the characteristic response time τ of the aquifer in relation to the shape and period of the cyclic forcing. These dynamical phase lags must first be taken into account before any additional lag can be attributed to the celerity of kinematic waves in snowpacks, hillslopes, or stream channels. (Jordan (1983) is the only one of the authors cited above who explicitly recognizes that the propagation speed of the daily cycles is determined by kinematic wave celerity. The others appear to assume that these cycles propagate at the speed of water movement per se, which is inconsistent with decades of work on both snowpacks ~~(e.g., Colbeck, 1972)~~**(e.g., Colbeck, 1972)** and streams ~~(Beven, 1979).)~~**(e.g., Beven, 1979).** Like the apparent time lag, the asymmetry in the discharge cycles can arise simply because the daytime forcing is briefer, and stronger, than the night-time rebound of the riparian aquifer ~~(see also Czikowsky and Fitzjarrald, 2004, for a similar analysis of this asymmetry based on somewhat different assumptions).~~**(see also Czikowsky and Fitzjarrald, 2004, for a similar analysis of this asymmetry based on somewhat different assumptions).** Although the time-integrating behavior of the riparian aquifer is recognized by many riparian groundwater models (e.g., Loheide et al., 2005; Loheide, 2008; Soylu et al., 2012), it is almost universally overlooked in studies of daily streamflow cycles.

Figures ~~7~~**8** and ~~8a~~**9a** also show that over wide ranges of the aquifer **response** time~~ constant~~ τ, and particularly for $\tau \geq 0.5$ day, the rate of change of discharge $\mathrm{d}Q/\mathrm{d}t$ ~~(dashed line~~**(Figs. 8f-g and dotted lines** in ~~Fig. 8a~~**Figs. 9a-b**), unlike discharge itself (~~dotted line~~**Figs. 8c-d and solid lines** in ~~Fig. 8a~~**Figs. 9a-b**), closely mirrors the cyclic forcing by snowmelt or ET~~ (solid line)~~**.**. This occurs because unless τ is small compared to the period of the cyclic forcing, the variations in the term S/τ in Eq. (5) will be small compared to the variations in the forcing by meltwater (M) or evapotranspiration ($~~E~~ET$), with the result that cycles in $\mathrm{d}S/\mathrm{d}t$ (and by extension $\mathrm{d}Q/\mathrm{d}t$) will closely correspond to cycles in the forcing itself. This observation implies that to track travel-time lags through the hydrologic system, one should look for lagged correlations between cycles in solar ~~flux~~ forcing and *rates of change* in groundwater levels, stream discharges, or stream stages (rather than those levels, discharges, or stages themselves, which will be shifted by the dynamical phase lags shown in Fig. ~~7~~**9a**). Cross-correlating each day's cycle in $\mathrm{d}h_Q/\mathrm{d}t$ between the main gauge and the lower culvert, we find that the average time lag between them is 0.96±0.04 hours, for an average celerity of 3.4 km hr^{-1} over the 3.3 km reach between these two points. Changes in flow depth should propagate downstream with the celerity of a kinematic wave, $c = \mathrm{d}Q/\mathrm{d}A$, where A is the cross-sectional area of the channel ~~(Beven, 1979).~~**(Beven, 1979).** Predicting kinematic wave celerity requires estimates of channel cross-sectional area across a range of discharges, which are available at Sagehen only for stage measurements at the main gauge and the B transect. These two sites are broadly representative of the pools and riffles, respectively, which make up most of the morphology of lower Sagehen Creek, and their wave celerities imply average lag times of 2.3 and 1.0 hours, respectively, for changes in discharge to travel between the main gauge and lower culvert. A precise comparison is not possible, because the channel also receives synchronized snowmelt or evapotranspiration signals along the reach between these two measurement points (which have shorter lag times than one would expect for a kinematic wave to travel the full distance). Nonetheless, these calculations suggest that the daily cycles in $\mathrm{d}h_Q/\mathrm{d}t$ propagate downstream as kinematic waves, as expected, with the superposition of local signals added by the riparian aquifer en route.

A further interesting consequence of the simple model in Eqs. (4) and (5) is that the peak in the rate of change in the riparian aquifer comes slightly *before* the peak in the rate of snowmelt or evapotranspiration (see Fig. ~~7d~~**8d**-f). This model behavior mimics the time shifts shown in Fig. ~~5~~**6**, in which the sap flow curve lags the solar flux curve by about an hour, but the peak rate of change in groundwater *leads* the sap flow curve by about an hour (and thus is nearly synchronized with the solar flux). This seems counterintuitive: it looks like the change in groundwater precedes the sap flow curve, and thus an effect precedes its cause. However, it results directly from the fact that the aquifer integrates both the sap flow flux and the discharge flux, coupled with the fact that near the noontime peak, storage and thus discharge are declining over time, meaning discharge is slightly lower (and thus that groundwater storage is declining slightly slower) at noon than just before noon. As one can see from the dotted line in Fig. ~~8a~~**9a**, this counterintuitive (but physically and mathematically correct) negative lag can be several hours long if the riparian aquifer **response** time ~~constant~~ τ is much shorter than 1 day. For more typical aquifer ~~time constants~~**response times**, however, this negative lag may be short enough that it is difficult to detect.

Several studies have sought to use daily cycles in streamflow to quantify riparian evapotranspiration rates, or to estimate the fraction of the catchment that can transmit ET signals to streamflow (e.g., Tschinkel, 1963; Meyboom, 1965; Reigner, 1966; Bond et al., 2002; Boronina et al., 2005; Barnard et al., 2010; Cadol et al., 2012; Mutzner et al., 2015). The simulations shown in Fig. ~~7~~**8** show that any such inferences are problematic, because the amplitudes of daily cycles in streamflow depend not only on the snowmelt or ET forcing, but also on the riparian aquifer **response** time ~~constant~~τ. For example, Figs. ~~7c~~**8c** and ~~7d~~**8d**, or Figs. ~~7f~~**8f** and ~~7g~~**8g**, show daily streamflow cycles that are nearly identical, but whose amplitudes differ by a factor of five, resulting from exactly the same forcing but a factor-of-five difference in the aquifer **response** time ~~constant~~ τ. As the blue lines in Fig. ~~8b~~**9b** show, the amplitudes of the daily cycles in discharge (and in the rate of change in discharge) are strongly dependent on the **response** time ~~constant~~ τ whenever $\tau > 0.1$ days or so. As τ becomes larger, discharge becomes less sensitive to changes in storage, and daily cycles in riparian storage due to snowmelt or ET are reflected in smaller daily cycles in streamflow. This is doubly problematic because the time "constant" τ will not actually be constant, but instead will vary as the catchment dries out over long recession periods, if the storage-discharge relationship is nonlinear ~~(Kirchner, 2009). However, for all time constants~~**(Kirchner, 2009). However, for all response times** τ greater than about 0.2 days, the amplitude of daily cycles in the rate of change in riparian storage ($\mathrm{d}S/\mathrm{d}t$) is very close to the amplitude in the snowmelt or ET forcing (dotted green line in Fig. ~~8b~~**9b**). These results suggest that it may be possible to quantitatively infer riparian ET rates from daily cycles in the rates of rise and fall in riparian groundwater, but not from daily cycles in groundwater levels themselves (solid green line in Fig. ~~8b~~**9b**), or from daily cycles in streamflow (blue lines in Fig. ~~8b~~**9b**).

Although this conceptual model has been developed in the context of Sagehen Creek, which has an extensive groundwater aquifer, the mechanisms described here do not require substantial aquifer storage. In the model, changes in discharge equal changes in storage divided by the characteristic response time τ. This directly implies that the daily range of storage also equals τ times the daily range of discharge. At the Sagehen main gauge, where we can measure daily cycles in units of discharge (at the other stations we lack rating curves and thus have only stage measurements), typical daily ranges of discharge during peak snowmelt were ~2-4 mm/day in 2006 (above-average

SWE), 0.2-0.6 mm/day in 2007 (below-average SWE), and 0.4-1 mm/day in 2008 (roughly average SWE). Even τ values as small as ~0.2-0.5 days are sufficient to generate significant lags between peak snowmelt and peak streamflow, implying that these lags could be associated with storage changes of only 0.4-2 mm in 2006, 0.04-0.3 mm in 2007, and 0.08-0.5 mm in 2008 (the ET cycles, and their associated ranges of storage, are about 1-2 orders of magnitude smaller). This simple calculation implies that significant dynamical phase lags can be generated from small daily variations in soil water and shallow groundwater, and that a substantial groundwater aquifer is not required.

This inference can be tested by comparing daily streamflow cycles in Sagehen Creek with those in Upper Independence Creek. The Upper Independence basin is dominated by glacially scoured granodiorites (Sylvester and Raines, 2017) and lacks the volcanic and volcaniclastic deposits that host Sagehen's extensive groundwater aquifer. Despite this sharp contrast in hydrogeology, Figs. 10 and 11 show that snowmelt and ET cycles are strikingly similar in Upper Independence Creek and Sagehen Creek. Streamflow cycles lag the solar flux curve by slightly more at the Sagehen main gauge (Figs. 10f and 11f) than at the other four stations shown in Figs. 10 and 11, reflecting the fact that the main gauge is farther downstream from its most distant headwaters (7.9 km, compared to 2.6-3.9 km for the other four stations) and integrates over a larger drainage area (27.6 km^2 vs 4.7-7.7 km^2 for the other stations), and thus accumulates commensurately larger kinematic wave lags. The daily cycle amplitudes also differ, due to differences in drainage areas and channel cross-sections among the different stations. Nevertheless, the clear conclusion from Figs. 10 and 11 is that the shapes of the daily cycles, and their phase lags relative to the solar flux, do not differ substantially between the granitic, glacially scoured Upper Independence basin and the groundwater-dominated Sagehen basin. This strongly suggests that similar mechanisms shape the streamflow cycles in both basins, despite the marked differences between their geological settings.

3.4 Correlations between solar flux and changes in water levels: the diel cycle index

The analyses presented in Sects. 3.2 and 3.3 clearly show that~~ the~~ rates of change in groundwater levels and stream stages are coupled to solar flux forcing through two different mechanisms – snowmelt and evapotranspiration – that have opposite effects. If forcing by solar flux drives snowmelt, groundwater levels and stream stages rise during the day, and decline at night. Conversely, if forcing by solar flux drives evapotranspiration, groundwater levels and stream stages **rise at night, and** decline during the day~~, and rise at night~~. The very close coupling between solar flux and water level response (particularly in groundwater; see Fig. ~~5~~**6**) suggests that the correlation between solar forcing and rates of change in water levels could be used to indirectly measure how much those water levels are influenced by snowmelt (thus resulting in positive correlations) or evapotranspiration (thus resulting in negative correlations).

Figure ~~9~~**12** illustrates the concept. For each day, we calculated the Pearson product-moment correlation coefficient between the solar flux in each 30-minute period and the simultaneous rate of change in stream stage. The two upper plots in Fig. ~~9~~**12** show two sample days, one near peak snowmelt (showing a clear positive correlation with solar flux), and the other in mid-summer (showing a clear negative correlation with solar flux). We excluded any days when the total solar flux was less than 80% of the clear-sky value for that day of the year, because one would not expect a clear correlation with solar forcing on days with heavy cloud cover. Days when more than 5 mm of precipitation fell were also excluded, as were days when more than 5 mm of precipitation fell **on** the previous day, as a precaution against spurious correlations that might arise from the catchment's storm runoff response. As Fig. ~~9~~**12** shows, these daily correlations provide a dimensionless index that expresses the relative influence of snowmelt (correlation $\approx$+1) and evapotranspiration (correlation $\approx$-1) as drivers of groundwater and streamflow fluctuations. We therefore call these correlations the "diel cycle index", as a more efficient shorthand for "daily correlations between solar flux and the rate of rise and fall in stream stage or groundwater level". (The term "diel" refers to 24-hour cycles, whereas the frequently used alternative term "diurnal" strictly refers only to daytime, just as "nocturnal" refers to ~~nighttime~~**night-time**.)

3.5 Destructive interference between snowmelt and evapotranspiration cycles

Several circumstances can ~~give rise to~~**result in** diel cycle index values near zero. When catchments are dry or frozen, stream stages can decline to the point that stage fluctuation measurements are dominated by noise (from instrument limitations, surface waves, eddies, and so forth) and thus correlations with solar flux may be weak. Overcast and rainy periods can also lead to confounded results, which is why they are excluded by the filters described above. Last but not least, during the transition between snowmelt-dominated and evapotranspiration-dominated periods, the stream will feel the offsetting effects of both snowmelt and evapotranspiration, as illustrated schematically in Fig. ~~10~~**13**. The stream will integrate both snowmelt cycles (e.g., from higher altitudes and north-facing slopes that are still snow-covered) and evapotranspiration cycles (e.g., from lower altitudes and south-facing slopes that have already melted out), and because these two cycles have opposite phases, they will destructively interfere (see Fig. ~~10~~**13**).

As the melt season ends, the snowpack will contract and become fragmented, and thus the stream and the groundwater system will be fed by a declining snowmelt flux (blue line in Fig. ~~10~~**13**), making the snowmelt cycles weaker. As spring gives way to summer, evapotranspiration fluxes will increase as temperatures and solar fluxes both rise, strengthening the evapotranspiration cycles over time (red line in Fig. ~~10~~**13**). From the observer's perspective, it will appear as if the snowmelt cycle disappears and then the evapotranspiration cycle grows to take its place (bottom panel in Fig. ~~10~~**13**). But what is actually occurring instead is that both cycles are present simultaneously, one becoming weaker and the other becoming stronger, and cancelling one another when they are of equal strength. Thus in settings where both processes are active, we should keep in mind that we will always observe their net effects, and not just whichever process is dominant ~~(see also Mutzner et al., 2015)~~**(see also Mutzner et al., 2015)**.

3.6 Differing transitions between snowmelt and evapotranspiration cycles in groundwater and streamflow

Figure ~~11~~**14** shows how the diel cycle index evolves over time at the B transect at Sagehen Creek. During the winter and early spring, the diel cycle index generally ranges between about 0.5 and 1, indicating that intermittent snowmelt is the main driver of daily ~~streamwater~~**streamflow** cycles. Conversely, during the summer when the sap flow measurements indicate active transpiration, the diel cycle index is generally close to -1 in groundwater and roughly -0.7 to -1 in the stream. In April and May of 2007 one can see that the diel cycle index transitions from positive to negative values later, and more slowly, in the southern B transect of groundwater wells (on the north-facing side of the valley) than in the northern B transect (on the south-facing side of the valley), reflecting longer-lasting snow patches on the north-facing slopes.

The most striking contrast, however, is between the transition in the diel cycle index values in the groundwater wells, which respond to the local balance between snowmelt and evapotranspiration forcing, and in the stream, which responds to the integrated effects of that forcing over its contributing area (Fig. ~~11~~**14**). The groundwater wells promptly transition from diel cycle index values of ≈+1 (snowmelt) to ≈-1 (evapotranspiration) roughly simultaneous with the disappearance of the snowpack at the altitude of the B transect (indicated by the first of the two vertical dashed lines each year). The daily cycle amplitudes, ~~show~~**shown** in gray in Fig. ~~11~~**14**, are very small for several days during this transition, consistent with the destructive interference described in Fig. ~~10~~**13**. Simultaneous with this abrupt transition in groundwater cycles, the stream's diel cycle index begins a gradual two-month transition toward evapotranspiration-dominated values, which only becomes complete when the snowpack disappears at the top of the basin (indicated by the second of the two vertical dashed lines each year). This gradual shift in dominance from snowmelt to evapotranspiration presumably reflects the gradual retreat of snow cover toward the top of the basin, and the corresponding gradual advance of active photosynthesis and transpiration as the snowpack vanishes.

This conceptual model is supported by the timing of diel cycle index transitions in the gauged subcatchments as well. As Fig. ~~12~~**15** shows, the transition from snowmelt-dominated cycles toward evapotranspiration-dominated cycles takes place later at the higher-elevation gauges at Sagehen Creek. At the lower culvert, the diel cycle index shifts from positive to negative in late May, for example, but the same transition does not take place at the upper culvert until mid-July (Fig. ~~12~~**15**). The latest transition of all is at Independence Creek. Although the gauge at Independence Creek is 300 m lower than the Upper Culvert, a sizeable fraction of the Independence Creek basin is at substantially higher altitudes, and includes steep north-facing slopes that hold snow relatively late into the summer, explaining the greater persistence of positive diel cycle index values. One sees similar contrasts between north-facing and south-facing tributaries to Sagehen Creek (see Fig. ~~S3~~**S4**). Kiln Creek, which faces south, transitions from positive to negative diel cycle index values two to three weeks earlier than South Tributaries 1 and 2, which span similar elevations but face north. Distinct snowmelt cycles also begin earlier, and peak snowmelt discharge occurs about 3 weeks earlier, in south-facing Kiln Creek compared to the two north-facing tributaries (Fig. ~~S3~~**S4**).

In Figs. ~~11, 12~~**14, 15**, and ~~S3~~**S4**, one can see that the evapotranspiration cycles in streamflow are often less distinct than those in groundwater, where diel cycle index values approach -1. There are several possible explanations. First, in groundwater, snowmelt and evapotranspiration cycles are often of roughly equal amplitude, but as the daily stage anomalies in Figs. ~~11, 12~~**14, 15**, and ~~S3~~**S4** show, evapotranspiration cycles in ~~streamwater~~**streamflow** are often much smaller than snowmelt cycles are. This may reflect the decreasing sensitivity of discharge to changes in storage as the catchment dries out (see Sect. 3.3). But whatever their origins, the smaller-amplitude stream stage cycles in mid-summer are more vulnerable to confounding by measurement noise than the larger-amplitude snowmelt cycles. Also, as streamflow declines, so will the kinematic wave speed at which discharge cycles are propagated through the channel network, increasing the destructive interference between signals generated close to the measurement point and far from it, and thus making the measured cycles less distinct~~.~~ **(Wondzell et al., 2007).** Finally, if low flows delay the evapotranspiration cycles sufficiently, they may accumulate significant phase lags relative to the solar flux that drives them, reducing their correlation with solar flux even if the lagged correlation remains strong. One could, of course, expand the diel cycle index to include lagged correlations (e.g., Bond et al., 2002; Barnard et al., 2010) as a means of detecting travel-time lags, but we have not done so here in the interests of simplicity, and also to avoid "cherry-picking" correlations at the lags that make them strongest.

It is important to note that in larger catchments, diel cycles may accumulate significant time lags in the channel network, leading to snowmelt cycles with diel cycle index values near zero (if the channel lag time is roughly 6 hours) or even diel cycle index values that are negative (if the channel lag time is roughly 12 hours). Thus, diel cycle index time series like Figs. 12, 14, and 15 should be interpreted with caution in larger catchments. Because channel lag times can lengthen during the summer as snowpacks retreat to higher elevations (Lundquist and Cayan, 2002) and streamflows decline (leading to slower kinematic wave propagation speeds), snowmelt cycles alone could potentially result in diel cycle index values that gradually transition from positive to negative. Such scenarios can be distinguished from true snowmelt-evapotranspiration transitions by inspecting the stream stage time series themselves. In transitions from snowmelt to evapotranspiration cycles, such as those shown in Figs. 12, 14, and 15, the amplitude of the streamflow cycle will nearly vanish as the diel cycle index approaches zero. By contrast, if the transition in the diel cycle index is caused by growing transmission lags of a snowmelt cycle, the streamflow cycle

amplitude will not reach a minimum as the diel cycle index approaches zero. It may also be possible to distinguish snowmelt and evapotranspiration cycles based on their asymmetry rather than their phase (Lundquist and Cayan, 2002), with snowmelt cycles being characterized by rapid rises and gradual falls, and evapotranspiration cycles being characterized by rapid falls and gradual rises; we have not tested that approach here.

3.7 Remote sensing evidence of snowpack retreat and expansion of photosynthetic activity

During the late spring and early summer of 2006, images are available from Landsat 5 for five cloud-free intervals that illustrate the progressive retreat of the winter snowpack and the expansion of photosynthetic activity in the Sagehen and Independence basins (Fig. ~~13~~**16**). The left-hand panels of Fig. ~~13~~**16** show the Normalized Difference Snow Index (NDSI), which compares the green and mid-infrared bands to identify snow (shown as white in these false-color images) by its much higher reflectance in the visible spectrum than at mid-infrared wavelengths ~~(Dozier, 1989; Riggs et al., 1994).~~**(Dozier, 1989; Riggs et al., 1994).** The right-hand panels show the Normalized Difference Vegetation Index (NDVI), which compares the red and near-infrared bands, identifying photosynthetically active vegetation (shown as green in these images) by its higher reflectance in the near-infrared than in the visible spectrum ~~(Tucker, 1979).~~**(Tucker, 1979).**

The spatial evolution of the snow and vegetation indices in Fig. ~~13~~**16** mirrors the temporal evolution of the diel cycle index values at the various gauging stations (Figs. ~~11, 12~~**14, 15**, and ~~S3~~**S4**). In early April, when all three SNOTEL stations are near their peak snowpack accumulation (Fig. 2), almost the entire landscape is snow-covered and there is little evidence of photosynthetic activity (Fig. ~~13a~~**16a**,b). Shortly thereafter, the lowest-elevation stage recorders (the lower culvert and main gauge) begin to exhibit strong snowmelt cycles (Fig. ~~12~~**15**), as the lowest elevations and south-facing slopes begin to melt. The north side of the B transect melts out in early May (Fig. ~~13c~~**16c**,d), and the diel cycle index abruptly shifts to reflect evapotranspiration forcing, although the stream still reflects the ongoing snowmelt in the surrounding catchment (Fig. ~~11~~**14**). By mid-May (Fig. ~~13e~~**16e**,f), south-facing Kiln Creek has melted out and exhibits evapotranspiration cycles (Fig. ~~S3~~**S4**), but South Tributaries 1 and 2, which face north, still have significant snow cover and exhibit snowmelt cycles. By early June (Fig. ~~13g~~**16g**,h), only the middle culvert, upper culvert, and Independence Creek catchments have significant snow cover and retain a strong snowmelt signature in their daily cycles. At the B transect stream, the main gauge, and the lower culvert**,** this snowmelt cycle has been largely obscured, or even reversed, by evapotranspiration cycles from the increasing vegetation activity at all but the highest elevations (Figs. ~~11~~**14** and ~~12~~**15**). By early July, snow remains only in the steep terrain at the perimeter of the Independence Creek basin and the cirque above the upper culvert (Fig. ~~13i~~**16i**), and only Independence Creek's diel cycle index retains a clear snowmelt signature. The daily cycles in the upper culvert are disappearing as it dries up, and the daily cycles in the other Sagehen stage recorders are showing increasing dominance by evapotranspiration (Figs. ~~11, 12~~**14, 15**, and ~~S3~~**S4**). Thus from May through July, the daily cycles in streamflow reflect the gradual retreat of the snow-covered area to the higher elevations (Fig. ~~13~~**16**, left panels), and its replacement by a gradually expanding area of strong photosynthetic activity (Fig. ~~13~~**16**, right panels).

The remote sensing images in Fig. ~~13~~**16** are visually compelling, but leave open the question of whether we can more quantitatively link the spatial dynamics of snow and vegetation to the daily cycling in streamflow. Landsat imagery provides high spatial resolution, but is available only every 8 or 16 days, and if an individual image is obscured by cloud cover, the gap between usable images becomes even wider. The MODIS (Moderate Resolution Imaging Spectroradiometer) satellites, by contrast, provide nearly daily coverage, but at only 500-m resolution. Therefore we extracted average values of MODIS snow and vegetation indices for each of the catchments and subcatchments, to track their seasonal evolution in greater detail. We calculated NDSI, the Normalized Difference Snow Index, as (GREEN-SWIR)/(GREEN+SWIR), where GREEN is band 4 and SWIR (shortwave infrared) is band 6, directly from daily surface reflectance data from the MODIS Terra and Aqua satellites, file series MOD09GA and MYD09GA (level 2G-lite, collection 6: Vermote et al., 2015). Terra and Aqua are identical satellites on nearly identical orbits, but Terra passes over northern hemisphere mid-latitudes in the morning, and Aqua passes over northern hemisphere mid-latitudes in the afternoon, so solar illumination of the surface differs between the two. Pixels with cloud cover in the surrounding 1 km square (or in any adjacent 1 km square) were excluded. For each day, we created a 7-day composite (from 3 days before the day in question to 3 days after) of non-excluded values at each pixel, and took the median of these 7 values. We then averaged these pixel median values over the drainage basins for each gauging station. Compared to the NDSI snow cover product provided in the file series MOD10A1 ~~(Riggs et al., 2016)~~**(Riggs et al., 2016)**, this calculation yields much lower scatter. It also does not artificially clamp low-NDSI values to zero snow cover (as the MOD10A1 NDSI snow cover product does), and thus preserves greater sensitivity to partial snow cover in complex terrain.

We followed a similar approach in calculating EVI2, the two-band Enhanced Vegetation Index, 2.5·(NIR - RED)/(NIR + 2.4*RED + 1) ~~(Jiang et al., 2008)~~**(Jiang et al., 2008)**, directly from daily surface reflectance data from the MODIS terra and aqua satellites. Here NIR (near-infrared) is MODIS band 2 and RED is MODIS band 1. EVI2 is designed to closely mimic the original 3-band Enhanced Vegetation Index ~~(Huete et al., 2002)~~**(Huete et al., 2002)**, but with greater stability and less sensitivity to clouds and snow. Because EVI2 is relatively insensitive to thin cloud cover, and because we are interested primarily in its behavior during the summer when clouds are rare, we did not exclude cloudy pixels as we did with our NDSI calculations. Summertime EVI2 values were almost identical whether cloudy pixels were excluded or not, but temporal coverage was better when clouds were not excluded. All remote sensing images were processed using Google Earth Engine. We then averaged the Terra and Aqua daily values for NDSI and EVI2, and interpolated them with a Loess robust local smoothing curve to average out short-term noise and fill in missing values (see Fig. ~~S4~~**S5** for examples).

Figure ~~14~~**17** shows the seasonal patterns in these MODIS snow and vegetation indices, superimposed on the diel cycle index for four gauging stations at Sagehen and Independence Creeks. Note that the scale for the vegetation index, EVI2, is reversed because we expect greater vegetation activity (and thus higher EVI2 values) to be associated with negative values of the diel cycle index. The snow index (light blue curve) exhibits a marked decline during the snowmelt season, shortly before the early-summer shift from snowmelt-dominated streamflow cycles (diel cycle index ≈+1) to evapotranspiration-dominated cycles (diel cycle index ≈-1). In late summer, however, the evapotranspiration signal in streamflow weakens and the diel cycle index returns to neutral or positive values, and this transition occurs several months before the seasonal snowpack begins to accumulate again. Thus, although the disappearance of the seasonal snowpack could plausibly explain the shift from snowmelt to evapotranspiration cycles in streamflow, the accumulation of the seasonal snowpack comes too late to explain the shift back toward snowmelt cycles. Instead, the seasonal strengthening and then weakening of the evapotranspiration cycles coincides more closely with the summertime increase and then decrease in photosynthetic activity, as reflected in the vegetation index EVI2 (green curves in Figs. ~~14c-14f~~**17c-17f**) and the seasonal rise and fall in sap flow rates (Fig. ~~14b~~**17b**). The correspondence between the vegetation index and the diel cycle index is very close, particularly at Independence Creek and the Sagehen main gauge. Note that the same scale was used for the vegetation index at all three nested Sagehen gauges, but a different scale was used for Independence Creek because the large fraction of bare rock in the Upper Independence basin (see Fig. S1) limits the vegetation index's summertime maximum.

The similarities between the summertime rise and fall in the vegetation index EVI2 (green curves in Figs. ~~14c-14f~~**17c-17f**) and the strengthening and weakening of the evapotranspiration cycles in **the** stream stage measurements (dark blue dots in Figs ~~14c-14f~~**17c-17f**) suggest a cause-effect relationship. The mechanistic connection between these disparate measurements remains unclear, however. Sap flow rates in the four monitored trees peak sharply in July, almost simultaneously with the peak in the EVI2 vegetation index at Sagehen (at Independence, EVI2 peaks a few weeks later). The sap flow measurements peak more sharply than the solar flux curve does (Fig. ~~14b~~**17b**), suggesting that other limiting factors are also at work. Recent sap flow measurements on hillslopes at 2365 m in the Sagehen basin imply that early-season sap flow rates are limited by low temperatures, and late-summer sap flow rates are limited by low soil moisture ~~(Cooper et al., Snowmelt-driven differences in tree water use and limitations in the Sierra Nevada, USA, manuscript in review).~~**(Cooper et al., in press).** Soil moisture is unlikely to be limiting for our sap flow trees, however, since the water table remained close to the ground surface during the entire period of our study. Nonetheless**,** the sap flow rates in these trees decline to half of their peak values by mid-September (in the wet year, 2006) or mid-August (in the ~~dry~~**drier** years of 2007 and 2008). Although the sap flow rates in these trees decline markedly, the nearby groundwater wells continue to show ET-dominated cycles until at least October (Fig. ~~11~~**14**). Indications of autumn snowmelt first appear in the streamflow's diel cycle index values in October and November, before the seasonal snowpack becomes established at the Sagehen and Independence catchments (Fig. ~~14c-14f~~**17c-17f**). Nonetheless, hourly data from the Independence Lake and Independence Camp SNOTEL sites show intermittent early-afternoon increases in soil moisture at 5cm depth beginning in early October (data not shown), suggesting that transient snow accumulation and melt could potentially also explain the autumn onset of snowmelt cycles, before the seasonal snowpack becomes established.

The upland soils of the Sagehen basin become very dry several weeks after snowmelt ends, so it is likely that moisture limitations are reflected in the seasonal decline in the MODIS vegetation index. It seems unlikely, however, that transpiration rates in the uplands, far from the channel network, would be reflected in the daily streamflow cycles shown in Figs. ~~11, 12~~**14, 15**, and ~~14~~**17**. The groundwater wells, which are all situated near the valley axis relatively low in the basin, generally show clear evapotranspiration cycles (diel cycle index $\approx$-1) until October, when the streams have already lost their clear evapotranspiration signal and have reached neutral diel cycle index values. The reason for this divergence between the streamflow cycles and groundwater cycles remains unclear. One possibility is that by late summer, stream flows have become so low, and thus the variations in stream stage have become so small, that any correlations with external drivers like solar flux become indistinct. A further consideration is that if the relationship between storage and discharge is nonlinear (and thus the aquifer **response** time ~~constant~~ τ in Eq. **(5)** becomes larger under drier conditions), discharge will become progressively less sensitive to ET-driven storage changes as the catchment dries up (Fig. ~~8b~~**9b**), and any evapotranspiration signal in streamflow will become weaker. Finally, as streamflow declines, so will the kinematic wave celerity that controls how quickly discharge signals are transmitted downstream, increasing the phase lag (and thus decreasing the correlation with solar flux) at downstream gauging stations, and also creating greater potential for destructive interference as local signals are added to the stream from the riparian aquifer along the way.

4. Summary and outlook

The analysis presented here is based on a catchment-scale hydrological monitoring network comprising a weather station, ~~three~~**3** snow telemetry (SNOTEL) stations, ~~seven~~**6** sap flow sensors, **12** stream stage recorders distributed along the main stem and selected tributaries, and **24** groundwater level recorders in two transects of shallow groundwater wells (Figs. 1 and 2). This array of instrumentation allowed us to quantitatively explore the linkages between solar forcing, snowmelt, sap flow, and daily cycles in riparian groundwater levels and stream stage.

From late spring through autumn, diurnal forcing by snowmelt and evapotranspiration (ET) generate measurable daily cycles in riparian groundwater and stream stage (**Sect. 3.2;** Figs. 3 and 4). Snowmelt and ET are both driven by the diurnal pulse of solar flux, but generate riparian groundwater cycles of opposite sign. Snowmelt adds a pulse of water to the riparian aquifer during daytime; thus snowmelt-driven daily cycles are characterized by groundwater levels and streamflow that rise throughout the day and decline during the night. By contrast, ET extracts water from the riparian aquifer during daytime; thus ET-driven daily cycles are characterized by groundwater levels and ~~streamflow~~**streamflows** that ~~declines~~**decline** throughout the day and ~~rises~~**rise** at night, as the riparian aquifer is recharged by groundwater seepage from the surrounding uplands~~.~~ **(Fig. 5).** Daily cycles in riparian groundwater levels are typically much larger than ~~those~~**daily cycles** in stream stage, and they increase in amplitude with distance from the stream, implying that groundwater cycles are driving streamflow cycles rather than the other way around (Fig. ~~6~~**7**).

Because the riparian aquifer integrates both additions from snowmelt and subtractions from ET over time (Eq. 4), peak groundwater levels and peak streamflow (or minima, in the case of ET) occur in the late afternoon or evening, as the riparian aquifer shifts between positive and negative ~~mass~~**flux** balance, rather than mid-day when the rate of snowmelt or ET is the highest~~.~~ **(Fig.5).** Maxima (or, for ET-driven cycles, minima) in streamflow thus lag the peak solar flux by several hours (~~Fig~~**Figs**. 3 and 4). In a catchment as small as Sagehen, this is primarily a dynamical phase lag, rather than a transit-time delay (Fig. ~~7~~**8** and ~~8~~**9**). Solar forcing and sap flow rates are closely synchronized with the rates of increase/decrease in groundwater levels and streamflows (Fig. ~~5~~**6**), not with the groundwater levels and streamflows themselves.

A simple mass-balance model of the riparian aquifer (~~Eq.~~ **Sect. 3.3; Eqs. 4-**5) reproduces the essential features of the relationship between daily cycles in solar flux, groundwater levels, and stream stages. (Because storage and discharge are proportional for any given aquifer **response** time ~~constant~~ τ, the shapes of the daily cycles in Fig. ~~7~~**8** describe variations in both groundwater levels and streamflows.) During snowmelt, when groundwater levels are high and aquifer ~~time constants~~**response times** may be quite short, daily cycles in groundwater and stream stage are asymmetrical, as observed in Fig. 3 and modeled in Figs. ~~7b~~**8b** and ~~7e~~**8e**. Later in the summer when groundwater levels are lower and aquifer ~~time constants~~**response times** are likely to be longer, both the observed and modeled cycles are more symmetrical (Figs. ~~5~~**6** and ~~7f~~**8f**-g). In both the model and the observations, water level maxima (during snowmelt) and minima (during ET cycles) occur near the end of the day, rather than at mid-day when solar forcing is greatest (Figs. 3, 4, ~~7b~~**5c, 8b**-d, and ~~8a~~**9a**). Likewise the corresponding water level minima (during snowmelt) and maxima (during ET cycles) occur early in the day, rather than near midnight, in both the model and the observations (Figs. 3, 4, ~~7b~~**5a, 8b**-d, and ~~8a~~**9a**). And in both the model and the observations, the maximum rate of groundwater rise (during snowmelt) or decline (during ET cycles) occurs near mid-day, and slightly precedes the peak in the solar flux or sap flow rates (Figs. ~~5, Fig 7e~~**6, 5b, 8e**-g, and ~~8a~~**9a**). Finally, the night-time trend in the rate of rise or fall in groundwater in the model (Figs. ~~7e~~**5d and 8e**-g) mirrors the night-time trend in the groundwater observations (Fig. ~~5~~**6**). All of these features are both predicted by the model and observed in the measurements, suggesting that this simple model plausibly represents the major dynamics shaping daily cycles in groundwater and streamflow.

This simple mass-balance model implies that the amplitude of streamflow cycles depends not only on the amplitude of sap flow or snowmelt forcing, but also on the **response** time ~~constant~~τ of the riparian aquifer (Figs. ~~7b~~**8b**-g and ~~8b~~**9b**). Because this **response** time ~~constant~~ is typically unknown ~~(and may also vary with catchment wetness -- see Kirchner, 2009)~~**(and may also vary with catchment wetness: see Kirchner, 2009)**, the amplitude of daily streamflow cycles cannot be straightforwardly interpreted as a quantitative estimator of riparian ET rates. Conversely, unless this **response** time ~~constant~~ is shorter than about 0.2 days, the amplitude of daily cycles in shallow groundwater will quantitatively reflect daily cycles in ET rates (Fig. ~~8b~~**9b**), suggesting that groundwater fluctuations can be used to monitor evapotranspiration over time, if the specific yield of the aquifer can be estimated ~~(e.g., Loheide, 2008)~~**(e.g., Loheide, 2008)**. **This conceptual model also applies to catchments that lack extensive riparian aquifer storage, as indicated by the striking similarities between**

daily streamflow cycles in the glacially scoured granitic Upper Independence basin and the groundwater-dominated Sagehen basin (Figs. 10 and 11).

As the snowpack shrinks and becomes patchy in late spring and early summer, diurnal snowmelt pulses become weaker while diurnal ET pulses become stronger, with daily cycles in streamflow and groundwater reflecting the net effects of these two drivers. The relative dominance of snowmelt vs. ET can be quantified by the diel cycle index, **which measures** the correlation ~~coefficient~~ between the solar flux and the rate of rise or fall in stream stage or groundwater level (**Sect. 3.4;** Fig. ~~9~~**12**). The diel cycle index will be close to +1 and -1 when streamflow cycles are dominated by snowmelt and evapotranspiration, respectively. During the transition from snowmelt-dominated to ET-dominated cycles in streamflow, daily cycles in the stream will temporarily vanish (diel cycle index =0) when the signals from these two drivers cancel each other out (**Sect. 3.5;** Fig. ~~10~~**13**).

During snowmelt, as the snowpack melts out at an individual location the local groundwater shifts abruptly from snowmelt-dominated cycles to ET-dominated cycles (**Sect. 3.6;** Fig. ~~11~~**14**), indicating that the local groundwater cycles mostly reflect the local balance between snowmelt and ET forcing. By contrast, the springtime transition in streamflow daily cycles takes months, beginning when the snowpack melts out near the stage recording station, and ending with melt-out at the highest elevations in the catchment or sub-catchment (Fig. ~~11, 12, S3~~**14, 15, S4**). These transitions occur later where the snowpack persists longer, at higher elevations (Fig. ~~12~~**15**) and in north-facing sub-basins (Fig. ~~S3~~**S4**). During these transitions, one can observe snowmelt cycles in the stream's upper reaches simultaneously with ET cycles in its lower reaches, due to overprinting of the snowmelt signals by ET signals generated below the snow zone (Fig. ~~12~~**15**).

These gradual transitions from snowmelt-dominated cycles to ET-dominated cycles reflect the gradual retreat of the snowpack to higher and higher altitudes, and the corresponding upward advance of photosynthetic activity in the basin. Sequences of Landsat images confirm both the pattern and general timing of these progressive shifts in snow cover and photosynthetic activity (**Sect. 3.7;** Fig. ~~13~~**16**). The springtime shift in the diel cycle index follows, by several weeks, the springtime decline in the basin-averaged MODIS normalized difference snow index (blue lines in Fig. ~~14~~**17**) as the snow-covered area in the basin contracts. However, the autumn shift in the diel cycle index away from ET-dominated values (≈-1) toward neutral or positive values precedes, by several months, the late-autumn establishment of the seasonal snowpack (Fig. ~~14a~~**17a**) and the corresponding rise in the MODIS snow index. By contrast, the basin-averaged MODIS enhanced vegetation index (green lines in Fig. ~~14~~**17**) rises and falls in close synchrony with the diel cycle index in both springtime and autumn, particularly at the Sagehen main gauge (Fig. ~~14d~~**17d**) and Independence Creek (Fig. ~~14f~~**17f**). This result demonstrates that the diel cycle index closely reflects seasonal patterns of vegetation activity during snow-free periods.

More broadly, the analysis presented here illustrates how streams and groundwaters can serve as "mirrors of the landscape", and in particular how streams can integrate ecohydrological signals over their drainage networks. Those signals are particularly clear at Sagehen and Independence creeks, because of their Mediterranean climate and snow-dominated hydrologic regime. Nonetheless, the analysis presented here could be replicated, with modifications, in many different landscapes, including catchments that are not snow-dominated, or where snowmelt and the growing season do not overlap, as they do at our study sites. The primary measurements (time series of water levels in shallow wells and streams) are relatively straightforward and inexpensive to collect, and the focus on daily cycle timing rather than amplitude means that stream stage data can be used directly; discharge rating curves are not required. In ~~large~~**larger** basins, one ~~can~~**could** use the kinematic wave equation to account for the celerity with which discharge fluctuations propagate downstream (see Sect. 3.3) in order to interpret the timing of daily stream stage cycles. However, it will be harder to account for the dispersion that results from daily cycle signals being added all along the channel, with different time lags to the gauging station; thus interpretation of the shape of daily streamflow cycles in large basins may be challenging. ~~Comparisons~~**Despite such complications, comparisons** of daily water level cycles across contrasting landscapes and scales ~~may~~**should** help in further clarifying how hydrologic signals are transported and mixed across landscapes and down channel networks.

Code and data availability

~~The 30-minute time series of weather, water level, and sap flow measurements underlying this analysis will be archived in an online repository and the doi will be included in the final published version of the paper. The Google Earth Engine scripts used to process the remote sensing data in Figs. 14 and S4 will be made available in an online repository or in the supplement.~~

An archive of the data underlying this study is available at https://doi.org/10.16904/envidat.155. This archive includes 30-minute time series of the weather variables, sap flow fluxes, groundwater levels, and stream stages, as well as daily time series of temperature, precipitation, and snow water equivalent at the SNOTEL stations, diel cycle index values for groundwater levels and stream stages, and MODIS normalized difference snow index (NDSI) and enhanced vegetation index (EVI2) values averaged over selected subcatchments. The archive also includes the Google Earth Engine scripts that were used to extract the MODIS data.

Author contributions

JWK conceived and led the study. ~~Hydrological~~ **The hydrological** field measurements were made by JWK, SEG, **MS,** and RO, and the sap flow measurements were led by JM. JWK analyzed **all of** the ~~hydrological data~~**time series** and remote sensing images**, and developed the conceptual model**. JWK and DP drafted the figures and wrote the paper. All authors discussed the results and contributed to finalizing the paper.

Competing interests

The authors declare that they have no conflict of interest.

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Tables

Table 1. Elevations and drainage areas of the stream stage recorders at Sagehen and Independence Creeks.

Stage recorder	Elevation (m a.s.l.)	Drainage area (km^2)
Lower culvert	1877	34.1
Main gauge	1929	27.6
Stream at B transect	1931	27.4
Stream at D transect	1976	17.4
Middle culvert	2061	4.7
Upper culvert	2447	0.3
Kiln Creek	2001	2.2
South Trib. 1	~~2015~~**2105**	4.1
South Trib. 2	2117	1.3
Independence Creek IND-1	2134	7.7
Independence Creek IND-2	**2158**	**5.7**
Independence Creek IND-4	**2207**	**4.8**

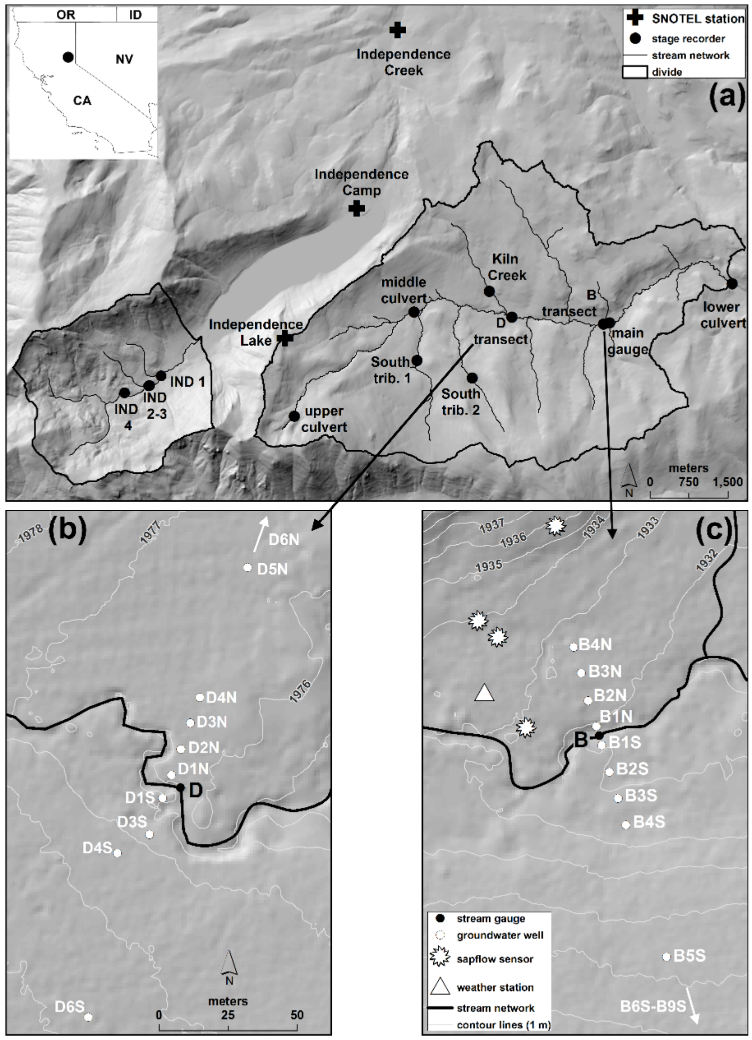
Drainage area estimates are subject to up to 1 km^2 uncertainty for all ~~sites~~**Sagehen gauges** downstream of the D transect, because the northern boundary of the lower basin is topographically indistinct. Elevations of gauges may also vary by several meters, depending on the topographic data source that is used.

Table 2. Cumulative precipitation, maximum SWE, and average temperature recorded at the three SNOTEL stations for the water years 2005-2006, 2006-2007, and 2007-2008.

SNOTEL station	Elevation (m a.s.l.)	Cumulative precipitation (mm/yr)			Maximum SWE (mm)			Average temperature (°C)		
		2005-2006	2006-2007	2007-2008	2005-2006	2006-2007	2007-2008	2005-2006	2006-2007	2007-2008
Independence Creek	1968	1224	511	559	356	287	450	6.3	6.1	5.8
Independence Camp	2135	1168	518	505	526	305	490	5.9	6.1	5.7
Independence Lake	2546	1732	856	907	1694	772	945	5.3	5.7	5.2

Table 3. Long-term average annual (water year) precipitation, SWE, and temperature recorded at the three SNOTEL stations. The observation period is reported in brackets.

SNOTEL station	Elevation (m a.s.l.)	Average annual precipitation (mm/yr)	Average annual maximum SWE (mm)	Average annual temperature (°C)
Independence Creek	1968	831 (1981-2010)	361 (1980-2014)	5.3 (1991-2013)
Independence Camp	2135	865 (1981-2010)	468 (1978-2014)	4.9 (1983-2013)
Independence Lake	2546	1206 (1981-2010)	1120 (1978-2014)	4.6 (1995-2013)


OR
ID
NV
CA
SNOTEL station
stage recorder
stream network
divide
(a)
Independence Creek
Independence Camp
Independence Lake
Kiln Creek
middle culvert
D transect
B transect
main gauge
lower culvert
South trib. 1
South trib. 2
upper culvert
IND 1
IND 2-3
IND 4
meters
0 750 1,500
(b)
D6N
D5N
D4N
D3N
D2N
D1N
D
D1S
D3S
D4S
D6S
meters
0 25 50
(c)
B4N
B3N
B2N
B1N
B
B1S
B2S
B3S
B4S
B5S
B6S-B9S
stream gauge
groundwater well
sapflow sensor
weather station
stream network
contour lines (1 m)

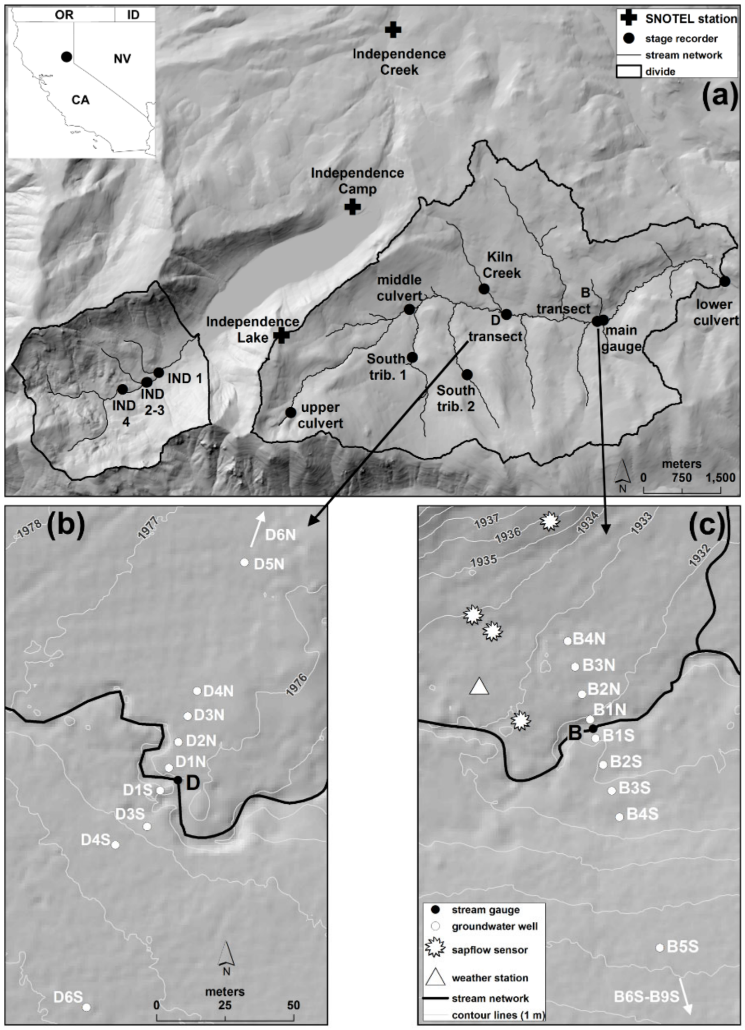
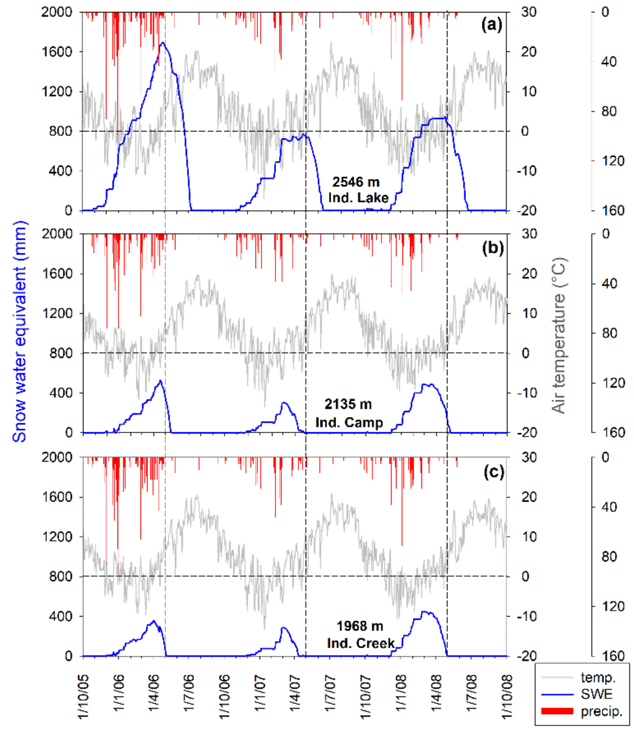


Figure 1. (a) Map of Sagehen Creek and Independence Creek catchments showing locations of stage recorders and SNOTEL stations, with inset map showing location in California. (b) Map of the D transect of shallow groundwater wells. (c) Map of the B transect of shallow groundwater wells, also showing locations of the weather station and the trees where sap flow was measured.



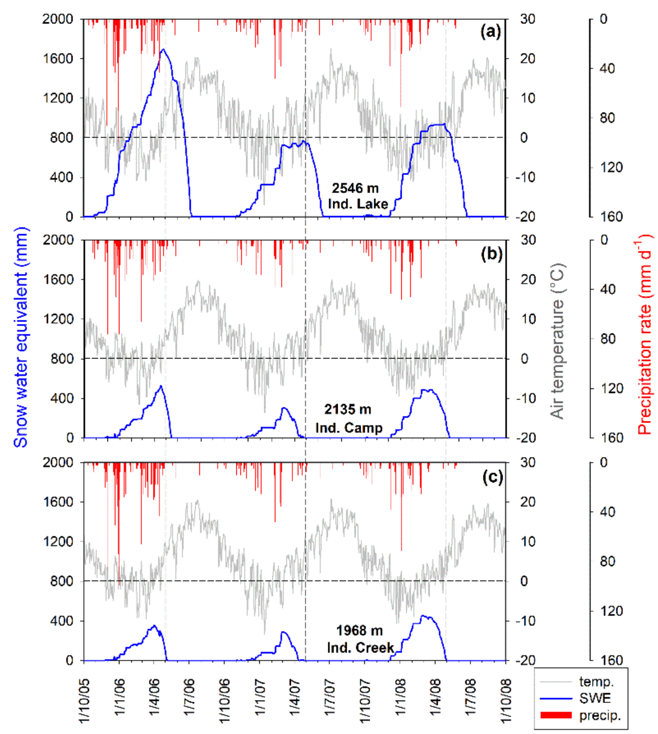
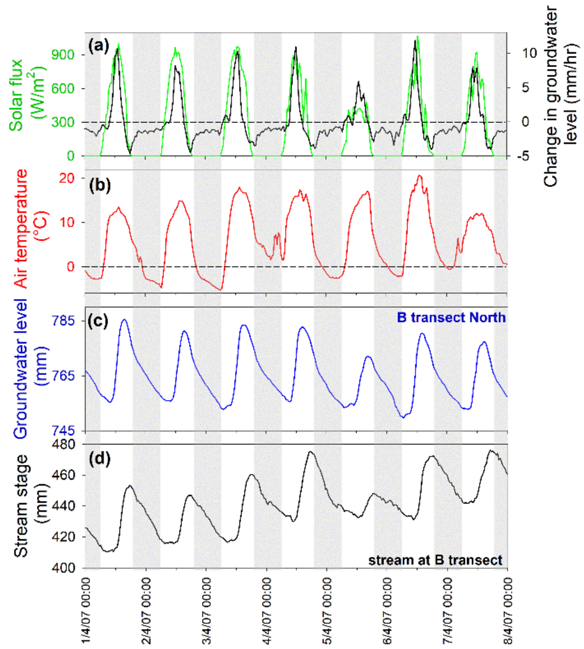


Figure 2. Daily time series of snow water equivalent (SWE), average air temperature, and precipitation at the three SNOTEL stations for the three water years 2005-6, 2006-7 and 2007-8. Vertical dashed lines indicate May 1st for all years. Horizontal dashed lines indicate 0°C. ~~The seasonal~~Seasonal snowpack ~~volume~~volumes and melt timing vary substantially among the three SNOTEL stations, which span almost the entire elevation range of the Sagehen basin.



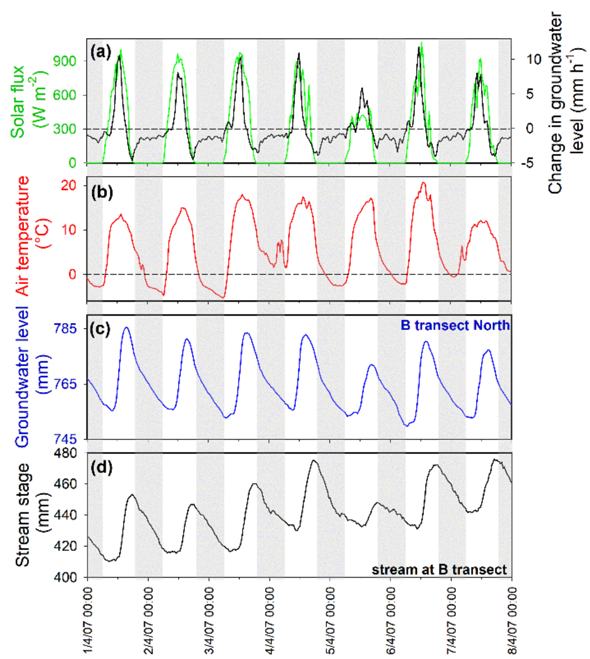
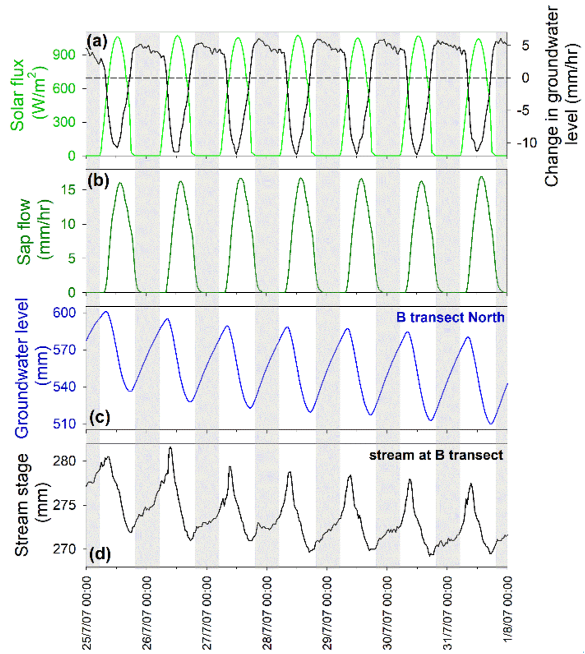


Figure 3. Daily cycles in solar flux (a), air temperature (b), groundwater level (c), and stream stage (d) at the B transect during a snowmelt-dominated period in early April of 2007. Groundwater levels and stream stage are measured relative to arbitrary datum elevations. Vertical gray bars indicate hours between sunset and sunrise (in early April approximately between 19:00 and 06:00). Groundwater level is average of wells B1N, B2N, and B3N; well B4N records were lost due to data logger failure during this period. The black curve in panel (a) shows the rate of change in the groundwater level, which is tightly coupled to the solar flux. The mid-day peak in the solar flux (a) coincides with the greatest rate of increase in groundwater levels; the groundwater levels themselves (c) peak several hours later, in late afternoon, as the solar flux declines and the rate of change in groundwater level shifts from positive to negative. Groundwater levels (c) then decline throughout the night as the riparian aquifer continues to drain into the stream, reaching a minimum in mid-morning, when the solar flux again becomes intense enough that snowmelt exceeds the rate of riparian aquifer drainage, raising the rate of change in groundwater levels (a) above zero. Day-to-day variations in solar flux are reflected in the amplitude and timing of the daily cycles in both groundwater levels and stream stage.



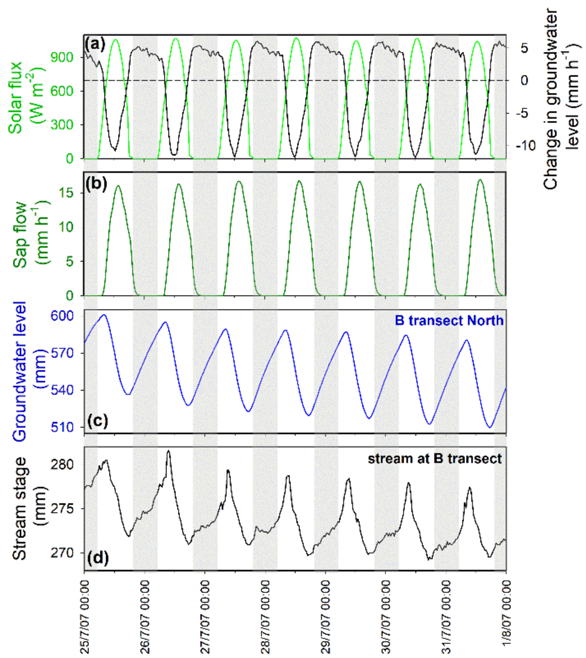


Figure 4. Daily cycles in solar flux (a), sap flow (b), groundwater level (c), and stream stage (d) at the B transect during an evapotranspiration-dominated period in late July 2007. Groundwater levels and stream stage are measured relative to arbitrary datum elevations. Vertical gray bars indicate hours between sunset and sunrise (in late July approximately between 19:30 and 05:00). Groundwater level is the average of wells B1N, B2N, B3N, and B4N. The black curve in panel (a) shows the rate of change in the groundwater level, which is almost perfectly anti-correlated with the solar flux and sap flow. Groundwater level (c) and stream stage (d) do not reach a minimum at mid-day, when solar flux and sap flow are highest, and thus groundwater levels are declining fastest (a). Instead, the groundwater level and stream stage reach their minimum in early evening, when solar flux and sap flow have decreased and the rate of change in groundwater levels crosses through zero (a). Groundwater level and stream stage then rise during the night (presumably in response to refilling of the riparian aquifer by groundwater drainage from upslope), reaching a peak in mid-morning when solar flux and sap flow rise enough to offset this groundwater influx, turning the ~~mass~~flux balance in the riparian zone (and thus the rate of change in groundwater levels) negative (a).

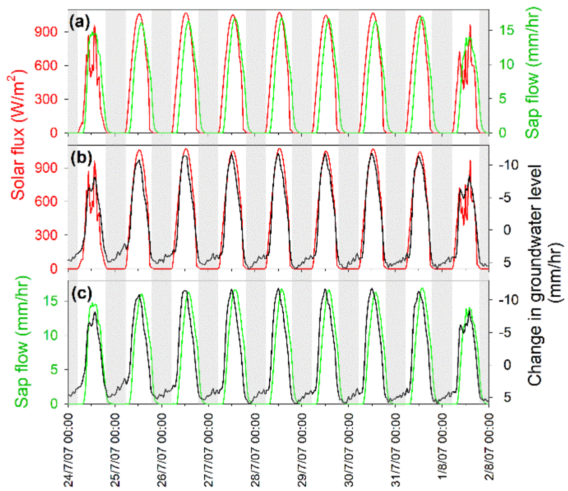

(a)
(b)
(c)
Solar flux (W/m²)
Sap flow (mm/hr)
Change in groundwater level (mm/hr)
900
600
300
0
15
10
5
0
-10
-5
0
5
24/7/07 00:00
25/7/07 00:00
26/7/07 00:00
27/7/07 00:00
28/7/07 00:00
29/7/07 00:00
30/7/07 00:00
31/7/07 00:00
1/8/07 00:00
2/8/07 00:00

Figure 5.

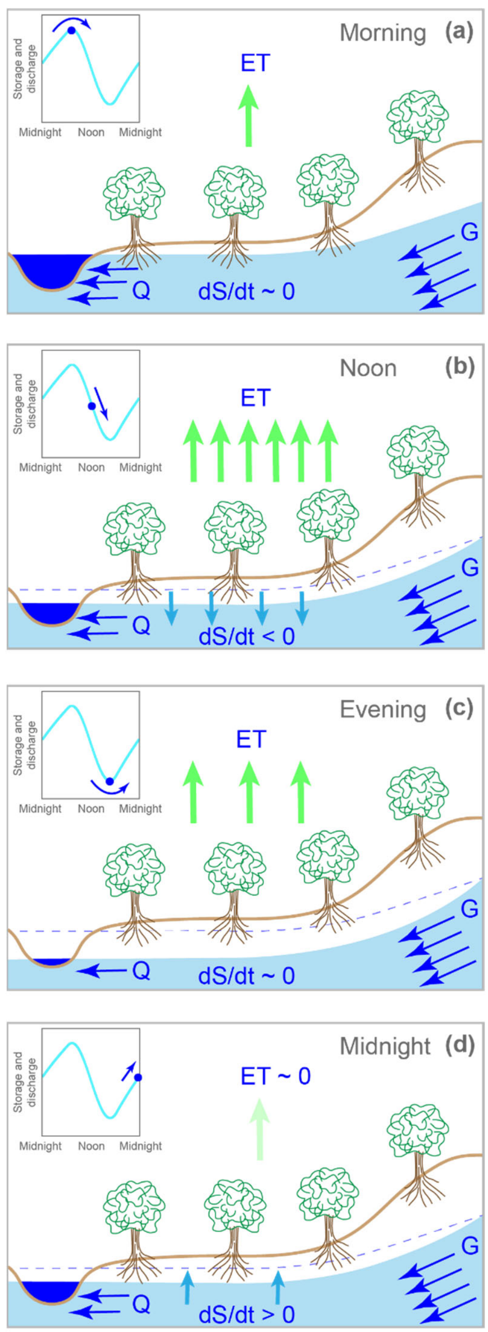

Morning
(a)
Noon
(b)
Evening
(c)
Midnight
(d)
Storage and discharge
Midnight
Noon
Midnight
ET
ET ~ 0
G
Q
dS/dt ~ 0
dS/dt < 0
dS/dt > 0

Figure 5. Visualization of groundwater-stream coupling that leads to lagged evapotranspiration cycles in groundwater levels and streamflow (snowmelt cycles are similar but reversed). Streamflow is supplied by drainage from riparian groundwater, and this drainage rate is faster at higher levels of riparian groundwater storage (S). Riparian groundwater storage changes at a rate dS/dt that depends on the flux balance between streamflow (Q), evapotranspiration (ET), and groundwater recharge from surrounding uplands (G). The relative magnitudes of these fluxes in each panel are indicated by the number of arrows; upland recharge (G) is constant but the other fluxes vary from panel to panel. Inset figures show the corresponding phases of the daily cycle in streamflow and groundwater levels. In the morning (a), groundwater storage and streamflow reach their maximum and begin to decline as the evapotranspiration rate rises enough, relative to the difference between groundwater recharge and discharge, that the riparian aquifer reaches equilibrium and begins to decline. Around noon (b), high evapotranspiration fluxes lead to a strongly negative flux balance and a rapid draw-down of groundwater storage, and thus a rapid decline in streamflow (the dashed line indicates the morning high-stand of groundwater levels and stream stage, as a reference). Toward evening (c), riparian groundwater and stream stage reach their minimum and begin to rise when evapotranspiration rates and streamflows decline enough that the riparian aquifer reaches equilibrium and begins to refill. During the night (d) riparian groundwater levels (and thus stream stages) slowly rebound, because evapotranspiration is nearly zero and upland recharge exceeds stream discharge.

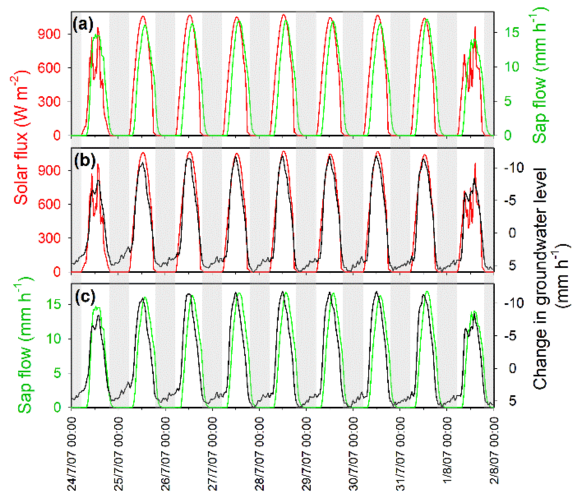
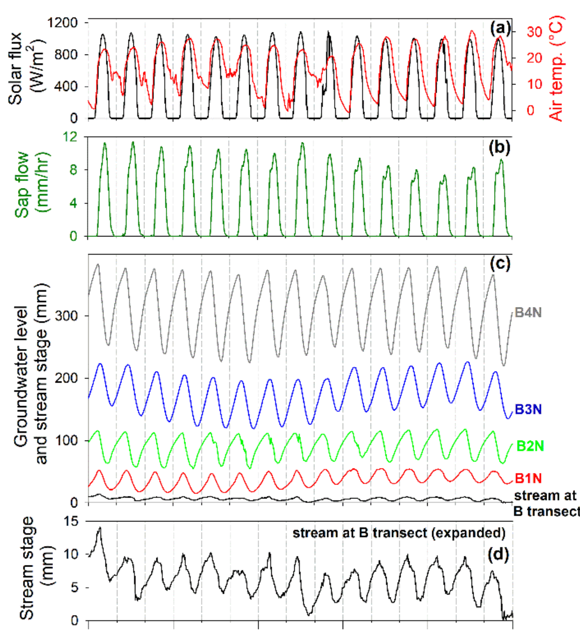


Figure 6. Daily cycles in solar flux (red), sap flow (green), and change in groundwater level (black) at transect B North (average of wells B1N, B2N, B3N and B4N) for ten days in mid-summer 2007. Note that the scale of the change in groundwater level is inverted, such that peaks correspond to maximum rates of decrease in groundwater levels. Rates of decline in groundwater levels are very closely synchronized with solar flux (b) and sap flow (c). Peak rates of decline in groundwater levels slightly precede the peaks in sap flow (c), consistent with model predictions (see Figs. ~~7~~8 and ~~8~~9). Variations in rates of groundwater rise and fall reflect day-to-day, and even sub-daily, variations in solar flux and sap flow.



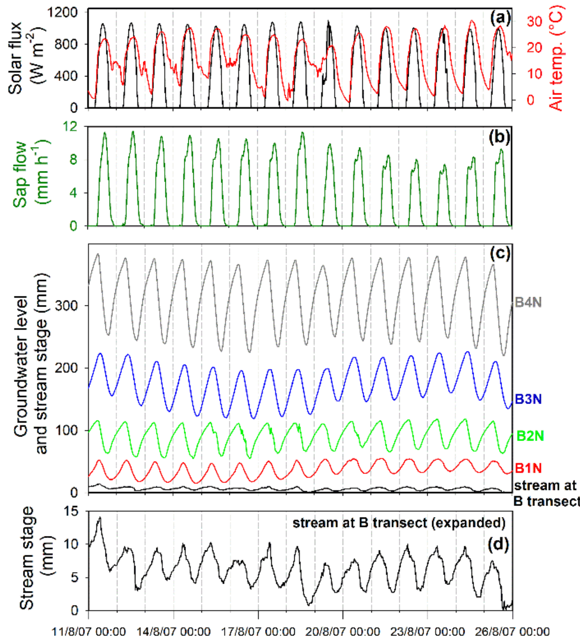


Figure ~~6~~7. Time series of solar flux (a), air temperature (a), sap flow (b), groundwater ~~level~~levels in the four wells that comprise the northern B transect (c), and water level in Sagehen Creek adjacent to the B transect (d), for 15 days in August 2007. Vertical lines indicate midnight. The raw water level data have been shifted vertically to accommodate all the time series in panel (c); real-world groundwater elevations in B1N, B2N, B3N, and B4N averaged roughly 200, 1050, 1080, and 950 mm above the ~~surface of~~water level in Sagehen Creek, respectively, during the period shown here. Daily cycle amplitudes decrease in the order [B4N > B3N > B2N > B1N > stream] as one approaches the channel, indicating that daily cycles in groundwater are driving cycles in streamflow, rather than vice versa.

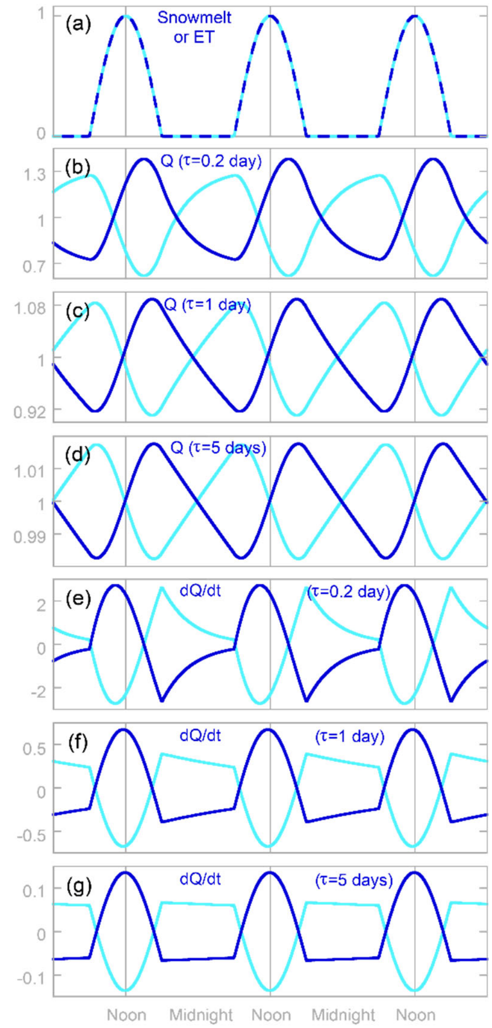


Figure ~~7~~8. Hypothetical daily pulses of snowmelt or evapotranspiration (a) and resulting daily cycles in discharge Q (b-d) and rate of change in discharge $\mathrm{d}Q/\mathrm{d}t$ (e-g), calculated by integrating Eq. (5) for different values of the riparian storage response time ~~constant~~ τ. Daily cycles driven by snowmelt and evapotranspiration are shown in dark and light blue, respectively. Note the differences in the vertical axis scales; daily cycles are markedly smaller for larger values of τ. Temporal patterns in riparian storage are identical to those in discharge, because discharge is proportional to storage. Discharge maxima (or minima for ET) come 3-5 hours after noon (b-d), and discharge minima (or maxima for ET) come 6-7 hours after midnight (b-d), because riparian storage integrates water additions from snowmelt (or removals by ET) over time. These are not travel-time lags, because Eq. (5) does not simulate transport and its associated delays. Instead, these lags arise simply because changes in riparian storage accumulate over time. Peaks in $\mathrm{d}Q/\mathrm{d}t$ (or minima for ET) come slightly before the daily peak in snowmelt or ET (e-g), reflecting the change in the aquifer's drainage rate to streamflow as aquifer storage increases (or, under the influence of ET, decreases) as the day progresses. Nonetheless, these maxima or minima in $\mathrm{d}Q/\mathrm{d}t$ occur within 30 minutes of peak solar flux for $\tau \geq 1$ day (f-g), indicating that they are not greatly time-shifted by the typical dynamics of riparian storage.

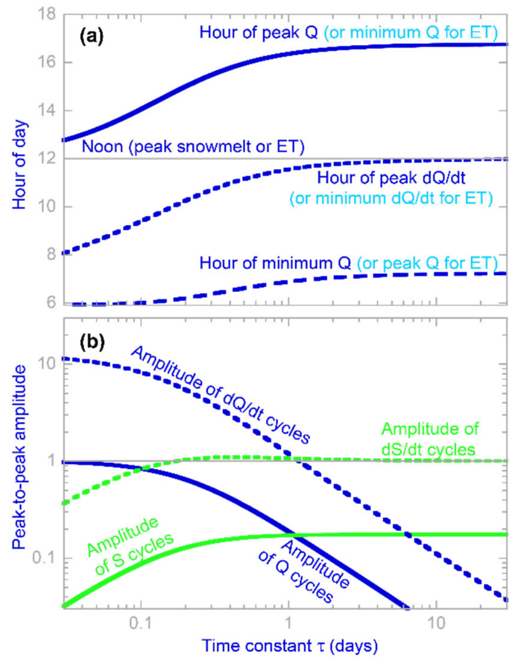
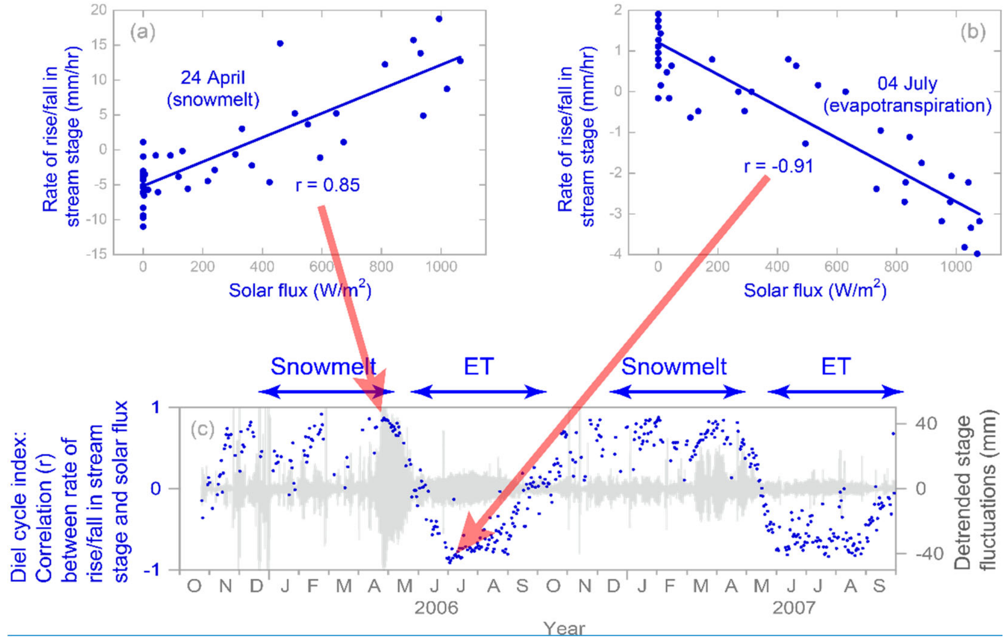
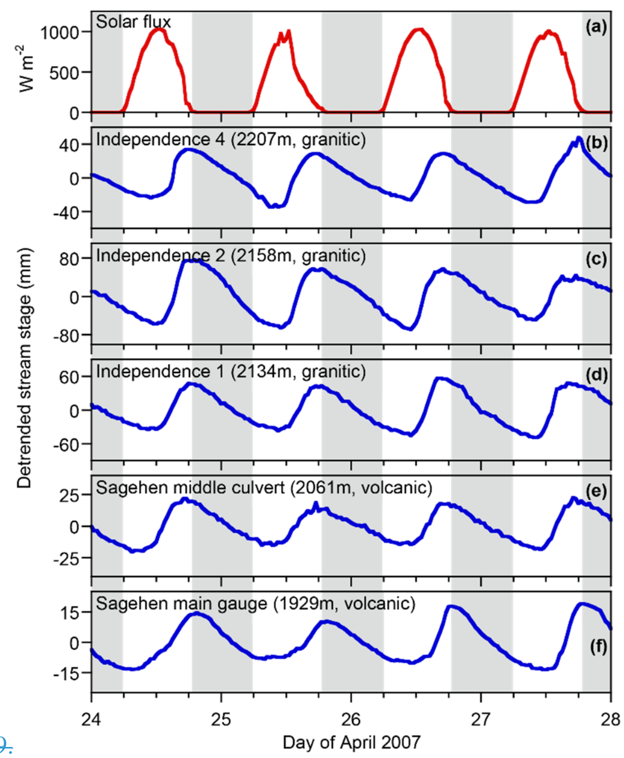


Figure 89. Timing (a) and amplitude (b) of daily cycles in streamflow (Q) and riparian aquifer storage (S) in response to daily cycles in evapotranspiration (ET) or snowmelt, as predicted by Eq. (5) across a 1000-fold range of the riparian aquifer response time ~~constant~~ τ. In Eq. (5), changes in discharge and storage are proportional to one another; therefore their cycles obey the same timing and would plot identically in panel (a). Peak discharge (or minimum discharge for ET cycles) occurs in mid- to late afternoon, rather than noon, and minimum discharge (or peak discharge for ET cycles) occurs in early morning, rather than midnight (see panel a), despite the fact that Eq. (5) includes no transport processes or transport delays. These apparent travel time lags are instead dynamical phase lags, created by the riparian storage integrating its inputs and outputs over time. Thus these lags are determined by the characteristic response time τ of the aquifer, the period of the cyclic forcing (1 day), and the shape of the forcing cycle, rather than by transport distances or kinematic wave velocities. For aquifer ~~time constants~~response times of $\tau \approx 1$ day or longer, the peak in the rate of change of discharge closely coincides with the peak in the snowmelt or ET forcing. Panel (b) shows peak-to-peak amplitudes of daily cycles compared to the amplitude of the ET or snowmelt forcing (=1 on this scale). The amplitudes of cycles in discharge (and in the rate of change in discharge) are strongly dependent on the aquifer response time ~~constant~~ τ unless τ is much less than 1 day. Conversely, for aquifer ~~time constants~~response times larger than about 0.2 days, the amplitude of the cycle in the rate of change in storage ($\mathrm{d}S/\mathrm{d}t$) closely resembles the amplitude in the snowmelt or ET forcing.





~~Figure 9.~~

Figure 10. Snowmelt-driven daily cycles in stream water levels measured in April 2007 at three locations along Upper Independence Creek, underlain by glaciated granodiorites, and two locations along Sagehen Creek, underlain by thick volcanic and volcaniclastic deposits. Stream stages were detrended using Eq. (3). The shapes and phases of the daily cycles are similar, and all exhibit similar lags relative to the solar forcing, despite the marked geological differences between the two catchments.

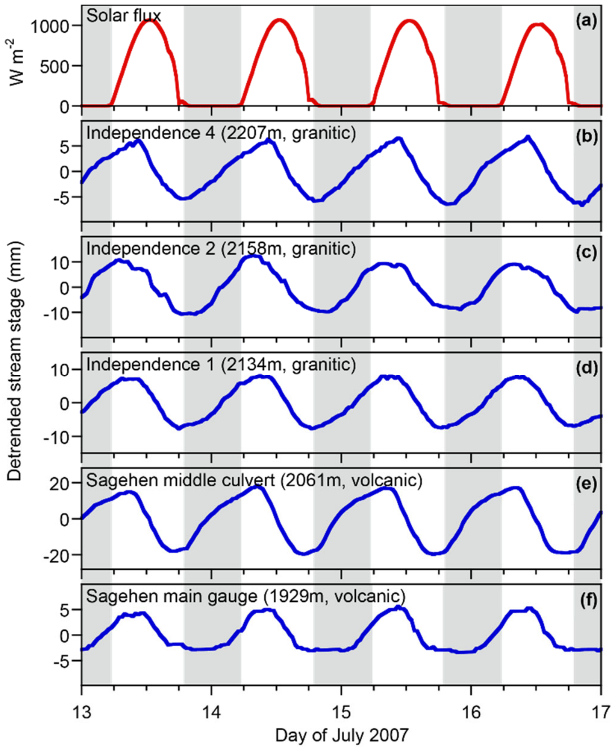


Figure 11. Evapotranspiration-driven daily cycles in stream water levels measured in July 2007 at three locations along Upper Independence Creek, underlain by glaciated granodiorites, and two locations along Sagehen Creek, underlain by thick volcanic and volcaniclastic deposits. Stream stages were detrended using Eq. (3). The shapes and phases of the daily cycles are similar, and all exhibit similar lags relative to the solar forcing, despite the marked geological differences between the two catchments.

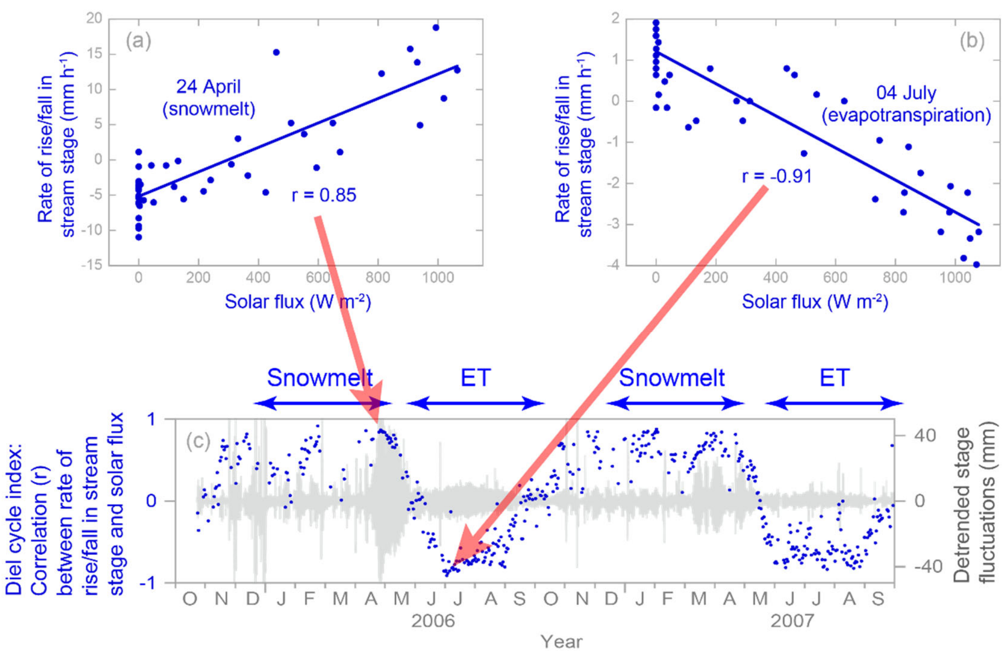
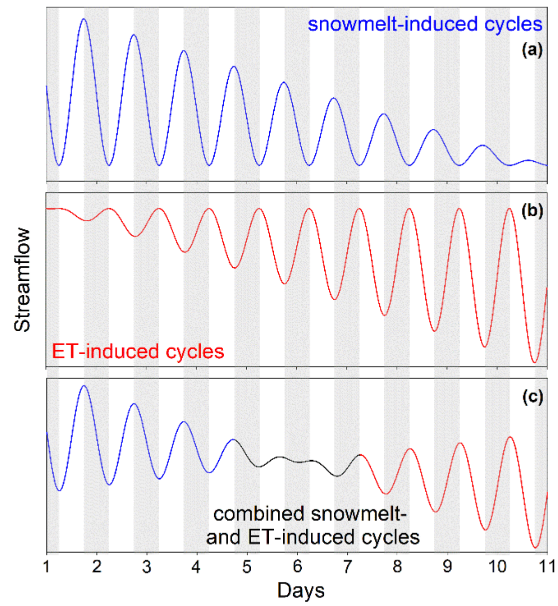


Figure 12. Correlations between solar flux and rates of rise and fall of water levels (Sagehen Creek, B transect) during two example days, one when the catchment was snow-covered and the stream exhibited a strong snowmelt cycle (24 April 2007), and another when the catchment was snow-free and the stream exhibited a strong evapotranspiration cycle (4 June 2007). In the lower plot, the correlation coefficients (blue dots) for each day indicate the relative dominance of snowmelt or evapotranspiration as generators of daily cycles in Sagehen Creek, while the gray shading shows the amplitude of the detrended daily stage fluctuations.



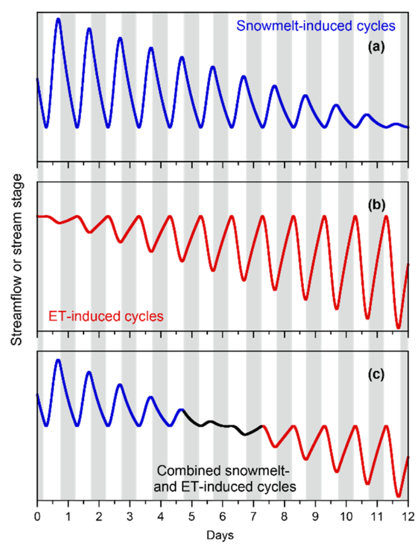
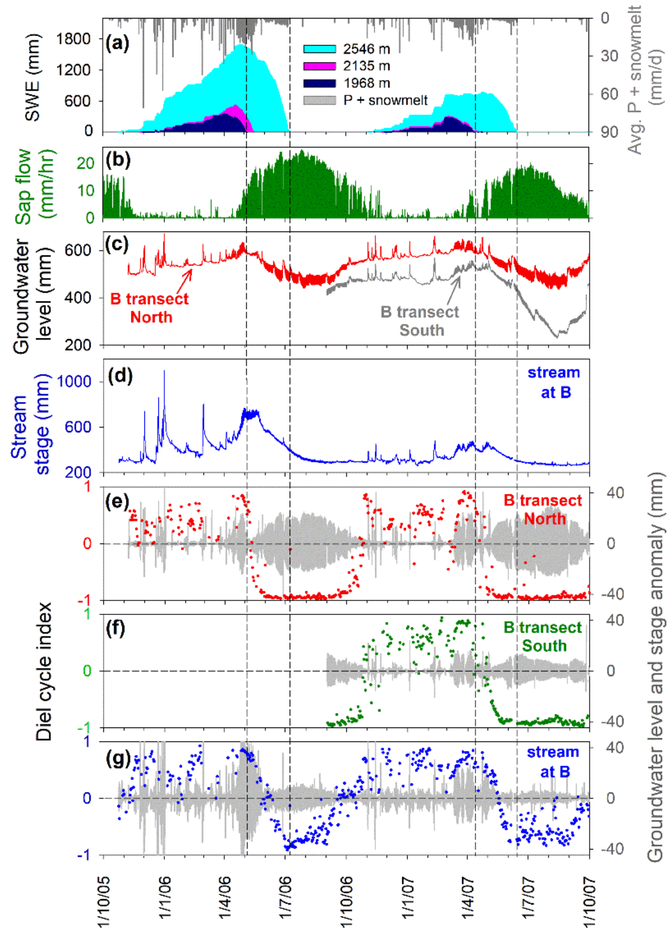


Figure ~~10~~13. Mixing of hypothetical snowmelt (a) and evapotranspiration (b) cycles in streamflow or groundwater (c) during a transition period between late spring and early summer. Major ticks correspond to midnight. Vertical gray bars indicate night-time hours between 18:00 and 06:00.


(a)
SWE (mm)
1800
1200
600
0
2546 m
2135 m
1968 m
P + snowmelt
0
30
60
90
Avg. P + snowmelt (mm/d)
(b)
Sap flow (mm/hr)
20
10
0
(c)
Groundwater level (mm)
600
400
200
B transect North
B transect South
(d)
Stream stage (mm)
1000
600
200
stream at B
(e)
B transect North
(f)
B transect South
(g)
stream at B
Diel cycle index
1
0
-1
40
0
-40
Groundwater level and stage anomaly (mm)
1/10/05
1/1/06
1/4/06
1/7/06
1/10/06
1/1/07
1/4/07
1/7/07
1/10/07

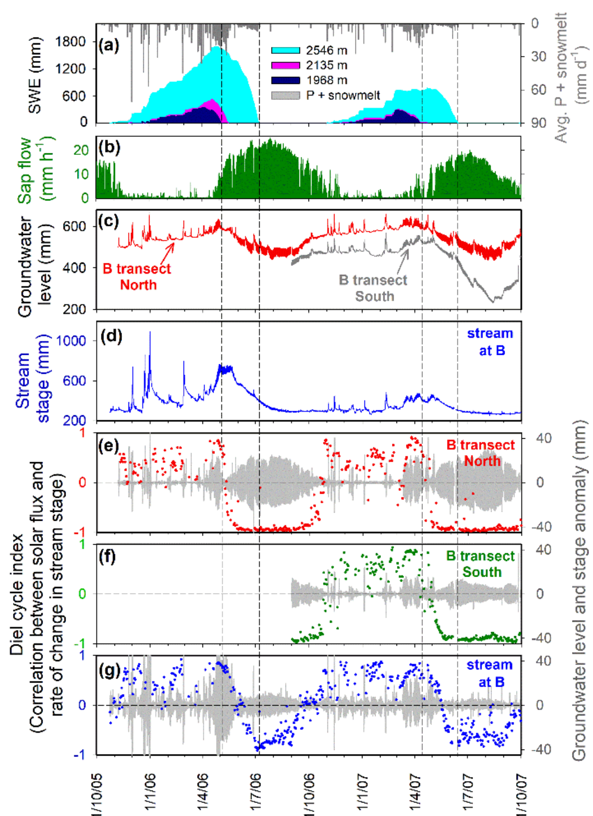
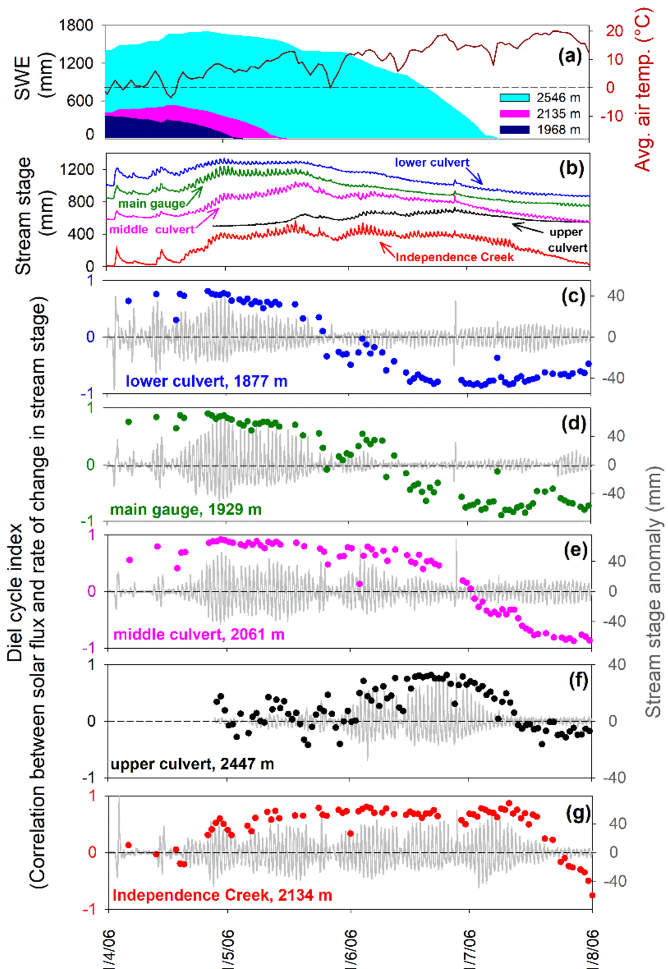

(a)
SWE (mm)
1800
1200
600
0
2546 m
2135 m
1968 m
P + snowmelt
0
30
60
90
Avg. P + snowmelt (mm d-1)
(b)
Sap flow (mm h-1)
20
10
0
(c)
Groundwater level (mm)
600
400
200
B transect North
B transect South
(d)
Stream stage (mm)
1000
600
200
stream at B
(e)
B transect North
(f)
B transect South
(g)
stream at B
Diel cycle index (Correlation between solar flux and rate of change in stream stage)
1
0
-1
40
0
-40
Groundwater level and stage anomaly (mm)
1/10/05
1/1/06
1/4/06
1/7/06
1/10/06
1/1/07
1/4/07
1/7/07
1/10/07

Figure ~~11~~14. Seasonal transitions between snowmelt- and evapotranspiration-dominated daily cycles in groundwater levels and stream stage at Sagehen Creek transect B. Daily time series of average net water input (liquid precipitation plus snowmelt) and SWE at the three SNOTEL stations (a) are shown with time series of sap flow (b), average groundwater levels (c) at the B transect North (average of wells B1N, B2N, B3N) and B transect South (average of wells B1S, B2S, B6S, B7S, B8S, B9S), and stream stage at the B transect (d) for two water years (2005-6 and 2006-7). Bottom panels show detrended fluctuations in groundwater (e-f) and stream stage (g) in gray, overlain by dots showing each day's diel cycle index (the correlation between solar flux and rise in groundwater level and stream stage; see Fig. ~~9~~12). Snowmelt cycles generate positive correlations, and ET cycles generate negative correlations. The first vertical dashed line each year marks the date that the snowpack melts out at the lowest SNOTEL station (at 1968 m, close to the altitude of the B transect). The second vertical dashed line each year marks the date that the snowpack melts out at the highest SNOTEL station (at 2546 m, near the top of the Sagehen basin). The horizontal dashed lines in panels (e)-(g) indicate correlation coefficients of zero. Almost ~~simultaneous~~simultaneously with melt-out at the lowest SNOTEL site, groundwater at B transect North (e) shifts abruptly from snowmelt-dominated cycles (diel cycle index ≈+1) to evapotranspiration-dominated cycles (diel cycle index ≈-1). Groundwater at B transect South (f) shifts somewhat more gradually, because that side of the valley faces north and retains patches of snow somewhat longer. ~~Simultaneous~~Simultaneously with the melt-out at the lowest SNOTEL site and the shift in groundwater daily cycling at the B transect, daily cycles in Sagehen Creek (g) begin a gradual two-month transition from snowmelt- to evapotranspiration-dominated daily cycles, as the snow-covered area shrinks toward the top of the basin. The transition to evapotranspiration-dominated daily cycles becomes complete almost simultaneously with melt-out of the snowpack at the highest SNOTEL site (indicated by the second dashed line each year).



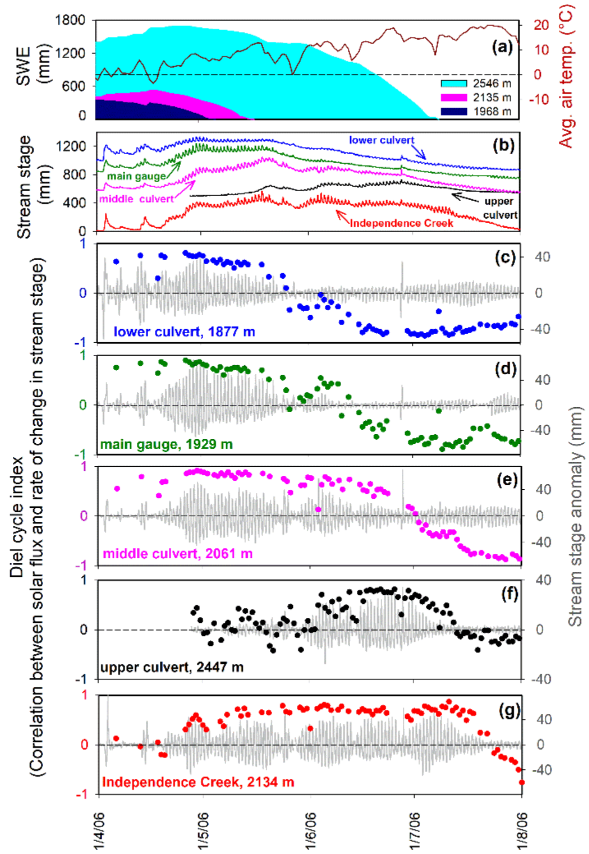


Figure ~~12~~15. Transition from snowmelt to evapotranspiration-dominated daily cycles in summer 2006 at several locations along Sagehen Creek and at Independence Creek~~.~~ gauge IND-01. Trends in snow water equivalent at the three SNOTEL stations (a) document the timing of melt-out across a range of altitudes. Stream stage time series (b) show streamflow response to seasonal melt patterns (each stage record has an arbitrary datum). Panels (c)-(g) show detrended daily stream stage fluctuations at individual measurement stations (gray lines), and daily correlations between solar flux and the rate of change in stream stage (colored dots). Correlations near 1 and -1 indicate snowmelt- and evapotranspiration-dominated daily cycles, respectively. The transition from snowmelt- to evapotranspiration-dominated cycles occurs later and faster at higher elevations, consistent with the progression of melt-out from lower to higher altitudes. At Independence Creek, the snowmelt cycle lasts relatively longer and ends relatively later, reflecting the larger fraction of higher elevations at the Independence Creek basin, and particularly the steep north-facing slopes that hold snow relatively late into the summer.

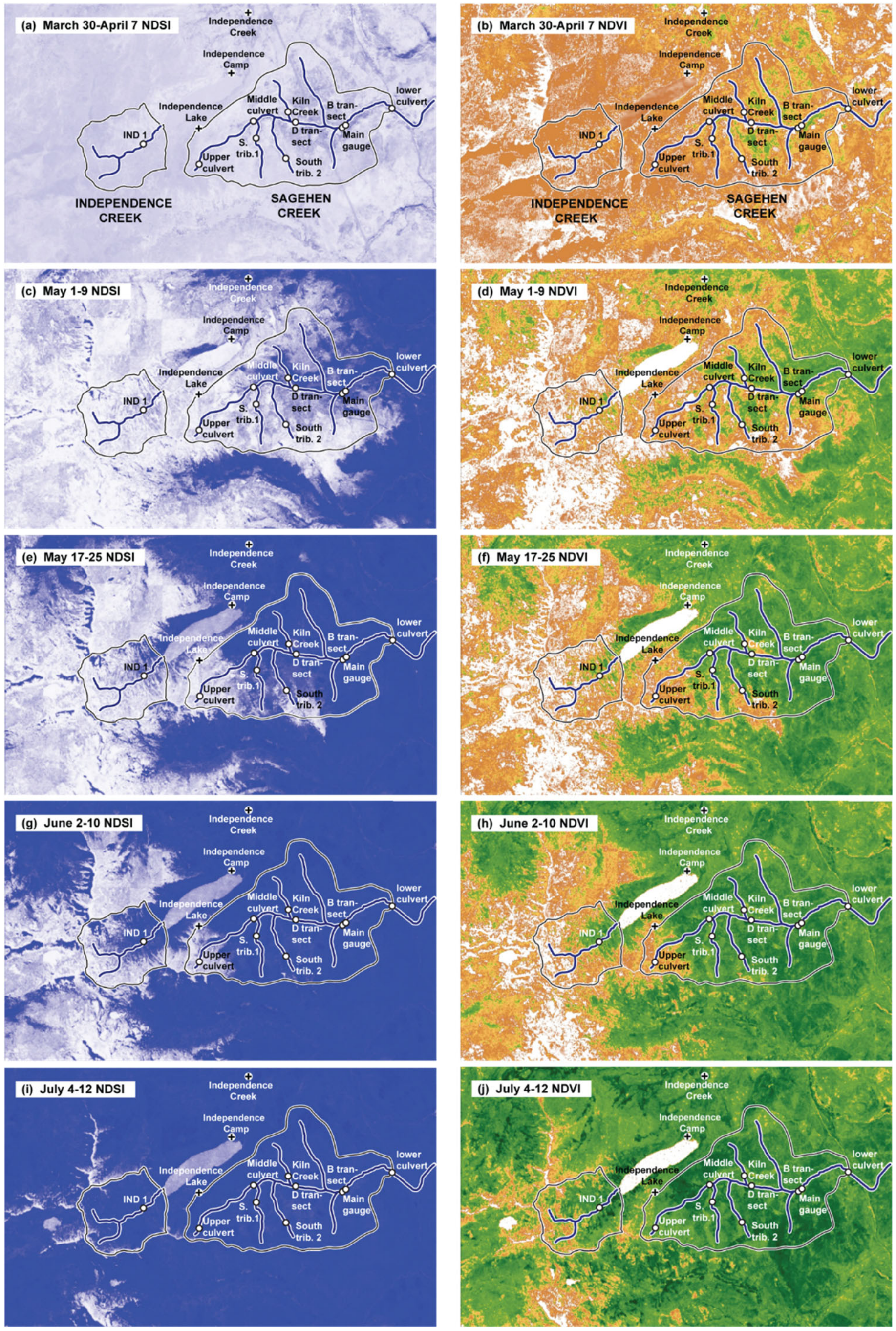
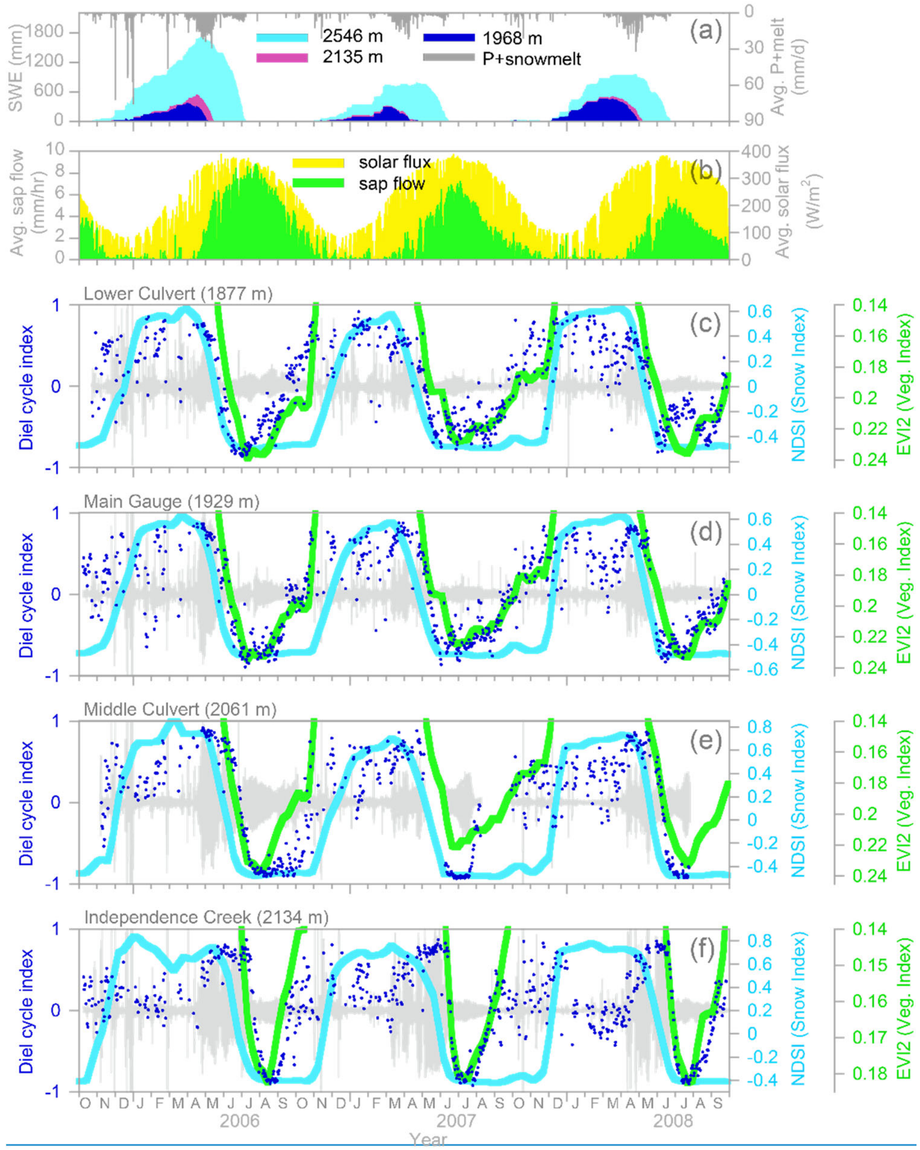


Figure ~~13~~16. Evolution of snow cover and photosynthetic vegetation at Sagehen and Independence Creeks during spring and summer 2006, as visualized by Landsat 5 Thematic Mapper NDSI (Normalized Difference Snow Index) and NDVI (Normalized Difference Vegetation Index) 8-day composites. In the left-hand plots, white and dark blue indicate high and low snow index values, respectively. In the right-hand plots, high values of the vegetation index are indicated by dark green and low values are indicated by orange and white. Almost the entire landscape is snow-covered in early April (panels a and b), when peak snowpack accumulation is recorded at the three SNOTEL stations (Fig. 2), and shortly before the lowest stage recorders (lower culvert and main gauge) begin to exhibit strong snowmelt cycles (Fig. ~~12~~15). As the melt season progresses, the lower elevations and south-facing slopes melt out quickest. In early May (panels c and d), the north side of the B transect melts out, leading to an abrupt shift to evapotranspiration-driven cycles in groundwater (Fig. ~~11~~14), although the adjacent stream stage recorder still shows strong snowmelt cycles due to contributions from snowmelt upstream. From early May to early July, the snow-covered area gradually retreats to the higher elevations and is replaced by a gradually expanding area of strong photosynthetic activity (panels c through j). This is consistent with the gradual transition from snowmelt cycles to evapotranspiration cycles in stream stage at the B transect, the main gauge, the middle culvert, and the lower culvert (Figs. ~~11~~14 and ~~12~~15). South-facing Kiln Creek melts out by mid-May (panels e and f), but South Tributaries 1 and 2, which face north, do not melt out until early June (panels g and h), consistent with the daily stream stage cycles shown in Fig. ~~S3~~S4. By early June (panels g and h), only the upper Sagehen catchment is still snow-covered, and the snowmelt cycle is offset by evapotranspiration-driven cycles at the lowest stage recorders (Fig. ~~12~~15). By early July (panels i and j), only the uppermost ridgelines retain snow cover, the snowmelt cycle is disappearing at all of the stage recorders, and the B transect, main gauge, and lower culvert stage recorders show evapotranspiration-dominated cycles, with the middle culvert following by mid-July (Figs. ~~11~~14 and ~~12~~15).


(a)
2546 m
2135 m
1968 m
P+snowmelt
SWE (mm)
Avg. P+melt (mm/d)
(b)
solar flux
sap flow
Avg. sap flow (mm/hr)
Avg. solar flux (W/m²)
Lower Culvert (1877 m)
(c)
Main Gauge (1929 m)
(d)
Middle Culvert (2061 m)
(e)
Independence Creek (2134 m)
(f)
Diel cycle index
NDSI (Snow Index)
EVI2 (Veg. Index)
2006
2007
2008
Year

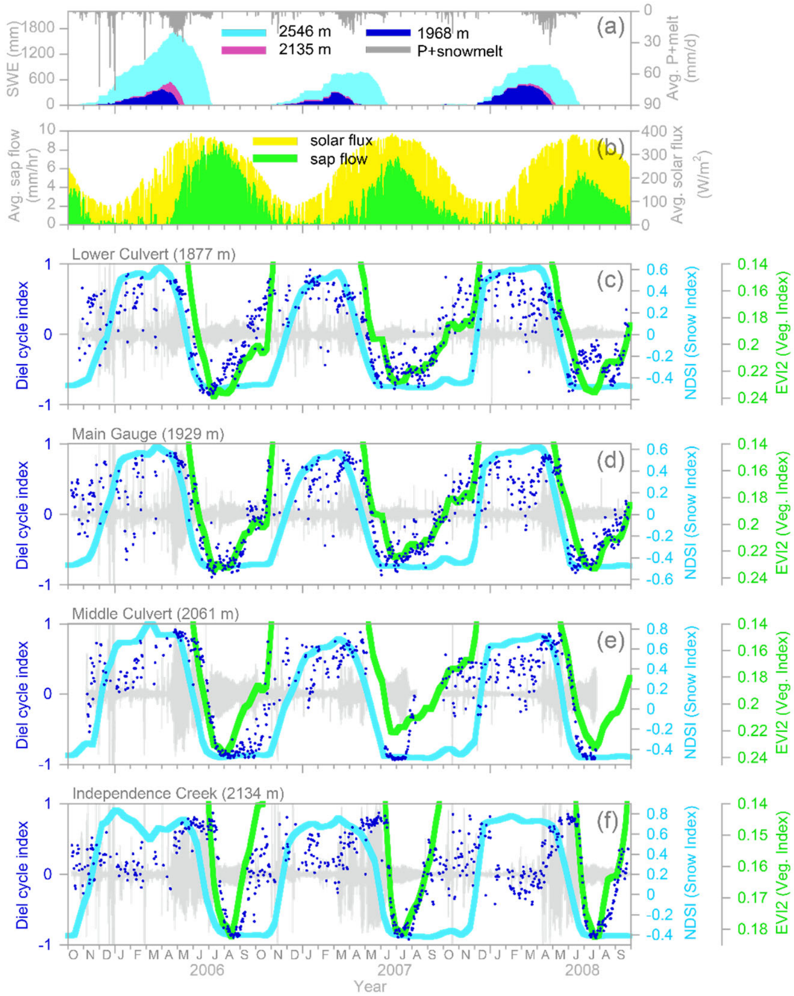


Figure 1417. Seasonal patterns in the diel cycle index (correlation between solar flux and rate of change in water level) at Independence Creek and three nested catchments at Sagehen Creek (c-f), compared to seasonal patterns in daily MODIS NDSI (Normalized Difference Snow Index, blue curves), MODIS EVI2 (two-band Enhanced Vegetation Index, green curves), snowpack accumulation and melt at three SNOTEL stations (a), and daily average sap flow in B transect trees (b). The early-summer shift from snowmelt-dominated streamflow cycles (diel cycle index ≈+≈ +1) to evapotranspiration-dominated cycles (diel cycle index ≈-≈ -1) coincides with the retreat of the seasonal snowpack (a), an increase in evapotranspiration rates (b), a decrease in the MODIS snow index (blue curves), and an increase in the MODIS vegetation index (green curves, note reversed scale). The late-summer and autumn shift from evapotranspiration-dominated cycles toward snowmelt-dominated cycles precedes snowpack accumulation (a) and the seasonal increase in the MODIS snow index by several months, but coincides with a decline in sap flow rates (b) and a decrease in the MODIS vegetation index. The MODIS snow index and vegetation index curves are Loess robust smoothing fits to daily MODIS data averaged over the contributing area to each gauging station (see text and Fig. S4S5). The vegetation index scale is inverted to better show its relationship with the diel cycle index, and values below 0.14 are not shown. Gray shading shows daily stream stage anomalies (deviations from daily running means). Inter-annual decreases in sap flow measurements are artifacts of wound healing around the sap flow sensors (see text).