Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process

ADDENDUM

Senate Bill 3 Science Advisory Committee for Environmental Flows

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FLUVIAL SEDIMENT TRANSPORT
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Addendum

Early in the Senate Bill 3 (SB3) process, the Science Advisory Committee (SAC) issued guidance on considering geomorphological processes, specifically sediment transport, as an overlay in refining the recommended environmental flow regime for a stream or river (SAC, 2009a). Since then, several Basin and Bay Expert Science Teams (BBESTs) have contended with issues emerging from the details of applying this guidance, particularly in interpreting the role of sedimentary processes in altering the geomorphology of the stream. The purpose of this addendum is to clarify and augment the previous guidance to address these concerns.

Background

A highly simplified schematic of the causal connections between the flow regime and the health of the ecosystem is shown in Figure 1. The problem of establishing a flow regime that maintains the "sound ecological environment," as assessed by suitable metrics, is essentially one of prediction: given a seasonal pattern of flows, determine the resulting ecosystem metrics. This requires identification and quantification of the cause-and-effect relations from flow to elements of the ecosystem, as suggested by the arrows in Fig. 1. This figure shows several intermediate classes of attributes or mechanisms, each affected by streamflow, each of which can influence stream ecosystem conditions. One of these is geomorphology.

By "geomorphology" is meant the physical configuration of the watercourse, its bed and shoreline, and the surrounding terrain to an elevation that is occasionally inundated (at some unstated frequency of occurrence), and the physical processes that establish this configuration (e.g., Richards, 1982, Chorley et al., 1984). Because geomorphology can exert controls on the hydraulics and ecology of the watercourse, and can be altered by the flow of water in the watercourse (one of the principal physical processes), it has been included in the SB3 environmental flow determination as an overlay.

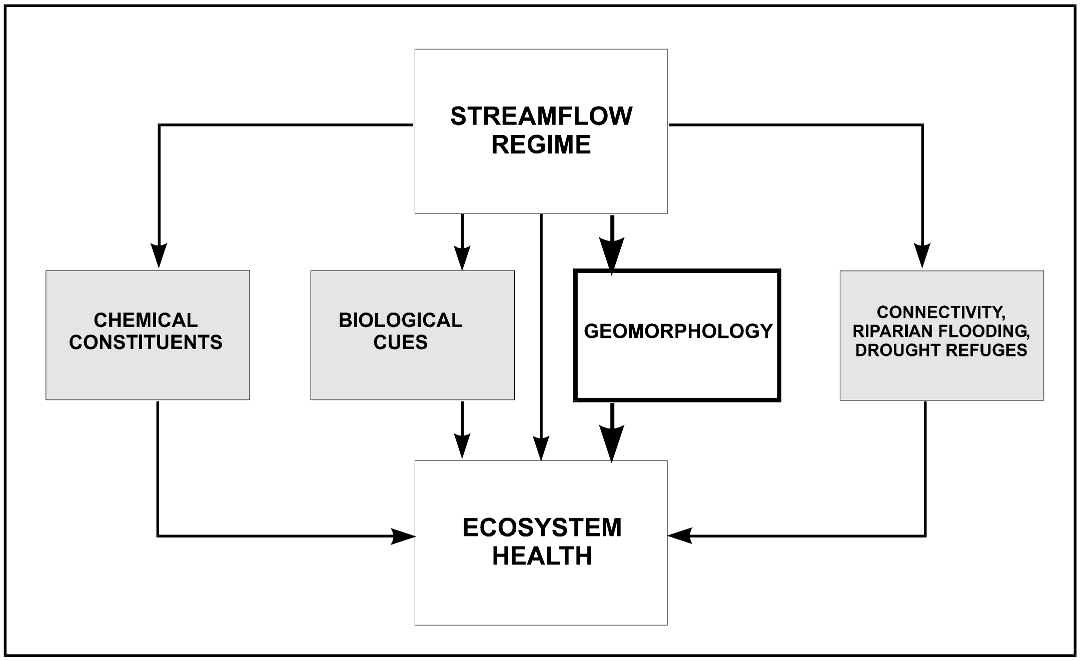

Figure 1 - Schematic of causal pathways from streamflow to the ecosystem of the watercourse

Some of the mechanisms through which geomorphology affects the ecological functioning of a watercourse include:

- establishes a distribution of depths across the channel section
- organizes and ducts stream flow to establish high-velocity and stagnant zones
- presents a variety of sediment types
- affords alternate channel configurations
- controls the inundation of the riparian corridor through barriers and cut banks

The effect of any of these varies with the stage of the stream. Any modifications of geomorphology over time will perforce alter these functions as well.

Geomorphology in the SB3 work

Geomorphology is an implicit factor in the Texas Instream Flow Program and SB2 strategy, in that the hydraulics of flow over the streambed defines various habitat zones of the channel (NRC, 2005, TCEQ et al., 2008). For in-channel habitat modeling of base flows, streambed elevations (i.e., morphology) are a basic input to the hydraulic calculations. The results of hydraulic modeling are in turn used to delineate the preference zones of fish based on depth, velocity and substrate. Stream channel and near-channel elevations also play an important role in defining the sediment transport capabilities of flow regime elements (base, pulse, and overbank flows); connectivity to near channel waterbodies, such as oxbow lakes (pulse and overbank flows); and inundation of riparian areas (overbank flows). Therefore, these geomorphological elements are somewhat imbedded in the regime definitions that have been adopted for HEFR and the associated streamflow analyses for SB3.

Geomorphology has been explicitly addressed in two of the earliest guidance documents the SAC issued, *viz*. geographical scope (SAC, 2009b) and fluvial sediment overlay (SAC, 2009a). In the former, the geomorphological features of the stream environment inform the classification procedure. In the latter, the focus is entirely upon sediment transport. The scour, transport and deposition of sediment is a central process in geomorphology, underlying most of the mechanisms by which alluvial channels are formed and maintained. In estuaries, sediment influxes are particularly important in maintenance of deltas against erosion (SAC, 2009c), and sediment carried out of the estuaries can be important in maintaining the coastal shoreline. Apart from its geomorphological role, sediment is also an important waterborne property, acting as a carrier for nutrients and certain contaminants, affecting penetration of light in the water column, hence primary production, and disrupting the metabolism of organisms that flux water, such as bivalves and fish. In the turbid environment of the Texas estuary, these can be especially important. For this reason, sediment, including loads and related processes, is recommended as an overlay for the estuarine inflow determination (see SAC, 2009c).

There is a truly vast literature on the transport of sediment by flowing water, much of which is concentrated upon sediment dynamics at the stream bed, i.e., mobilization of sediment particles, entrainment into the flowing water, and gravitational settling (for which the work of Brig. R.A. Bagnold, e.g. 1988, is fundamental). The 2009 guidance (SAC, 2009a) briefly reviewed the estimation of suspended load and bedload components and described the modeling tool SAM (Thomas et al., 2002). The capability of SAM of immediate relevance to environmental-flow considerations is the numerical calculation of sediment yield based upon the cumulative frequency distribution of flow (i.e., the so-called flow duration curve) and of sediment load.

The Sabine-Neches BBEST considered geomorphology and employed SAM sediment load calculations. The BBEST employed the results of TWDB-sponsored research in the basin that had been carried out to address key questions such as sediment delivery of the river and the state of equilibrium of its morphology (Phillips, 2007, Phillips and Slattery, 2006, 2007). The BBEST concluded,

> In spite of the presence of major reservoirs within the Neches and Sabine River systems, recent geomorphological studies by the TWDB under the SB 2 program indicate that these systems are likely functioning normally for Gulf Coast riverine systems with regard to sediment transport. Except for relatively short reaches immediately below the reservoirs, the measurement of sediment concentration and transport are at levels that would be expected and desired for these systems, indicating a present level of health and a sound ecological environment as it relates to fluvial geomorphology. No adjustments to the HEFR regime for fluvial geomorphology were considered to be appropriate … [SN BBEST, 2009, pg. 92]

The Trinity-San Jacinto BBEST report generally addressed the importance of sediment transport but ultimately postponed any direct consideration, notably application of the SAC guidance, to future adaptive management.

The Colorado-Lavaca BBEST applied SAM to various hydrological scenarios to determine sediment yield. It concluded (CL-BBEST, 2011, pg. 7-2):

> The geomorphic overlay relied on the principal *[sic]* of maintaining the annual sediment yield and effective discharge within 10% of the historical values based on the preponderance of evidence within the published scientific literature. We recognize however, that these types of estimates have an inherent degree of uncertainty due to scatter in the data and even choice of the sediment transport equation utilized. …

> The sediment transport analyses used by the BBEST at three sites, clearly indicate the importance of sediment transport to channel stability and maintenance, and ultimately the ability to maintain a sound ecological environment. We recommend that monitoring of river reaches in terms of basic channel geometry, aquatic habitat distributions, and riparian community structure and distribution be incorporated into the adaptive management monitoring plans.

The Guadalupe-San Antonio BBEST carried out an essentially identical analysis. An identical set of paragraphs appears on page 7.5 of its report (GSA BBEST, 2011). However, the GSA BBEST goes further: in its example project evaluations, the sediment yield was found to change more than 10%, leading the BBEST to suggest hypothetical project modifications to keep the yield within 10%. The SAC identified and highlighted the BBEST's ambiguity in whether this limit on change in sediment load was intended to be part of the recommendation, and strongly suggested that the BBEST clarify this issue for its Stakeholders.

Supplemental guidance

There are two sequential causal relations involving geomorphology that connect the streamflow regime to the stream ecosystem, as indicated in Fig. 1: the response of geomorphology to streamflow, and the response of the ecosystem to geomorphology. These are addressed separately below. (We note that the more general relation of the response of the ecosystem to streamflow, shown in Fig. 1 as the direct arrow from the former to the latter, in which the intervening mechanisms are not directly addressed, is a separate evaluation, beyond the scope of this discussion.)

Streamflow effects on geomorphology

The effect of water velocity on the resuspension and settling of sediment particles is the fundamental physical process. As note above, the literature on this process is vast. The predictive problem most often focuses on whether the bed sediments will tend to scour or accumulate. There are hundreds of models presently in use addressing this problem, ranging from analytical equations to multidimensional coupled hydrodynamic and sediment transport computer models. (Khorram and Erghil, 2010, compile 52 different bedload transport relations, alone.) One of these is SAM, described in SAC (2009a). A comparison of the sediment load (or yield) carried by the streamflow into a reach with the capability (or competency) of the flow to transport sediments at the bed provides an indicator of whether the bed will be scoured or aggraded.

Much of the discussion in SAC (2009a) is directed at the meaning and computation of effective discharge. This is a conceptual device that is employed as an index. Its use among fluvial geomorphologists is not unanimous, but its adherents argue the concept has merit for perennial and slightly ephemeral streams in humid and semiarid environments (Biedenharn, et al. 2000). Effective discharge is most usefully applied to guide the selection of channel dimensions (such as depth, width, cross sectional area) during the design of engineered channels (Biedenharn, et al 2000). Since Texas rivers and streams encompass conditions from humid to arid and from perennial to ephemeral, and the BBESTs are making recommendations related to flow regimes, not channel dimensions (depth, width, cross sectional area), effective discharge may not be the most suitable metric for a geomorphic overlay. While it is straightforward to use the SAM histogram outputs to identify the effective discharge, as described in Section 7 of SAC (2009a), various flow and sediment transport correlations can mathematically entail the same effective discharge while sediment yields may differ. An example of this was encountered in the work of the Sabine BBEST, which applied SAM to WAM Run 3 and Run 8 hydrology. The two scenarios yielded essentially the same effective discharge (of 21,000 cfs at Ruliff), but the sediment yield of Run 3 was 50% of Run 8.

The desktop model SAM provides a capability for estimating sediment yield. If field data on both flow and sediment (from which the load is computed as the product of sediment concentration and flow) are available, their use is preferable. If sediment data are not available, SAM offers an array of equations[1] for the computation of both suspended load and bedload, from which an estimated sediment-load duration curve is developed and used for the yield computation. Depending on the choice of equation, results may vary considerably, so care should be taken to choose an appropriate sediment transport equation (considering factors such

[1] A module in the SAM package provides guidance on the selection of a transport equation appropriate to the site being examined.

as available data for validation[2], stream slope, and sediment material size). It is important to note that the contribution to the sediment load of sedimentary processes on the watershed, the riparian zone, or the stream channel upstream from the reach under consideration, or episodic events such as bank caving or larger-scale processes such as bar creation and migration is not included in SAM, except as implicit in the field data of sediment concentrations, if available. (There is a separate module of SAM that treats meanders but not in the context of sediment load.) In particular, the altered deposition environment below a hypothetical reservoir is not addressed by SAM, a significant shortcoming if a post-project prediction is needed for evaluating the geomorphological impacts of environmental flow recommendations.

The application of SAM has to date been limited to bedload as it is the parameter most closely related to changes in channel configuration. But it should be understood that suspended sediment loads are also affected by flow alterations. Suspended sediment loads, as well as bedloads, are ultimately deposited at some point downstream. As noted elsewhere, both of these loads are important for habitat maintenance in bays and coastal areas.

A model like SAM can be used to predict the relative change in sediment yield under various hydrological regimes, historical versus HEFR, for example. This relative change is closely related to the ratio of sediment supply to transport capacity, the SCR, which is commonly used in geomorphology to judge the response of a stream channel to a changed hydrology or a changed sediment yield (e.g., Soar and Thorne, 2001, Simon and Rimaldi, 2006). This is not a prediction of the resultant change in morphology of the stream channel, i.e. the specific zones where erosion or aggradation may result and their amounts. Indeed, that is a much more difficult problem, for which there are fewer models, and whose application requires far more time and resources than available to a BBEST (see, e.g., Hardy, 2006, Gregory et al., 2008).

The incremental change in sediment yield associated with a modification to the hydrology or sediment supply of a stream reach can be positive or negative. If the stream morphology is presently invariant in time, then this incremental change in sediment yield translates to either a

[2] In cases where sediment data is insufficient to develop a sediment-load duration curve, data that is available can be used to confirm the choice of sediment transport equation. For analysis at the five sites examined for the GSA and CL BBESTs, sediment data was available from the USGS and other sources for this purpose.

net accumulation ("aggradation") or a net evacuation ("degradation") of sediment from the reach. The condition of steady geomorphology is often used to characterize a reach in "equilibrium", i.e. one whose morphology has adjusted to the amount of sediment and water flowing through the reach, also referred to as "stable". Any change in sediment yield, through either flow or sediment modification, is conceived to result in the channel actively changing its geometry in response. It is important to emphasize that the incremental change in sediment yield (or value of SCR different from 1.0) does not imply a *rate* of change of geomorphology. To obtain such a rate would require much more sophisticated modeling, as noted above (see also below), for which the resources and data will generally be lacking to a BBEST.

While considering sediment load and stability, a spatial dimension should be recognized. While changes in the distribution of flows can affect the sediment carrying capacity, the dams that are the principal source of the changes in flow patterns, are very effective sediment traps. Typically dams remove essentially all of the bedload and a high percentage of the suspended load. Over time a new equilibrium is established downstream. The changes will tend to be greatest in the area immediately downstream of the dam because of the abrupt change in the upstream sediment load. With increasing distance downstream the change is more gradual.

Because of the widespread concern of disrupting a stable channel by hydrologic or sedimentary modifications, much attention has been given by geomorphologists to the need to diagnose a channel in equilibrium. This has proved to be complex, in part because of the multiple time scales of variation exhibited by the landscape and channel, multiple perturbations to the sediment budget, and longitudinal variation in zones of aggradation and degradation, to say nothing of the frequent absence of quantitative historical data on stream geometry. TWDB recently requested one of its researchers (Phillips, 2007) to opine on the geomorphic equilibrium of several rivers in Texas. His report evidences that this is a nontrivial task. He also provides useful philosophical ruminations on the concept and its utility, the conclusions of which were quoted by the SN BBEST (2009) in its report:

> Relaxation time equilibrium may be present in the rivers of southeast Texas, and the presence (or absence) of RTE is useful in assessing river conditions and in the application of analytical techniques and models. Characteristic form and steady-state equilibrium are

> far less common, and clearly cannot be assumed. In general, no inherent tendency toward any stronger form of equilibrium—characteristic forms, steady-states, grade, etc.—can be assumed, at least not in the form of any single characteristic or stable equilibrium state.
>
> Equilibria are arguably useful as a reference condition, but should not be assumed to [be] necessarily any more common, important, or "natural" than disequilibrium or nonequilibrium states. Managers cannot assume that there is any *single* normal, natural, or otherwise normative condition for the alluvial rivers of the study area, and should recognize the possibility—indeed, the likelihood—of multiple modes of adjustment and potential responses to disturbance.

Rosgen (1996) and others have suggested that it is possible to predict the eventual shape of a channel that is experiencing aggradation or degradation (after a period of adjustment). This requires that the channel exhibit the stronger forms of equilibrium cited by Phillips above, viz. characteristic form or steady-state equilibrium. Apart from the likelihood that this is not applicable to Texas streams (see quote, above), the method itself has not been unanimously embraced by geomorphologists (e.g., Simon et al., 2007). The weaker form of equilibrium, Relaxation Time Equilibrium (RTE, see quote, above), implies only that the channel has stopped changing its geometry (width, depth, and cross-sectional area) in response to its current flow and sediment inputs. Relaxation time is a measure of the time for a system (in this case, the channel morphology) to re-acquire its pre-disturbance state after a perturbation. Estimates of this time for natural stream channels range from a few months to thousands of years (Howard, 1982, Simon, 1989). This reaction time when multiple perturbations are superposed results in complicated geomorphic variation, not obviously convergent (the multiple modes of adjustment noted by Phillips, 2007). The flashy streams of arid and semi-arid regions, a hydroclimatology that typifies many of the streams in Texas, are being increasingly viewed as normally in a state of disequilibrium (Tooth and Nanson, 2000, Gregory, 2006). **All of this contributes to a level of uncertainty in assessing the present state and probable response of the stream channel from observations of its geometry limited in time and space.**

The emergence of the 10% criterion for unacceptable change in sediment yield in the Colorado and Guadalupe BBESTs has raised questions about its appropriateness as a constraint on the environmental flow recommendations. Authority for this criterion derives mainly from the problem of channel design, for which a SCR within a close approximation of unity (0 – 10%) is considered sufficient to ensure "dynamic equilibrium" in the channel, see, e.g., Soar and Thorne (2001), Bureau of Reclamation (2006), Watson et al. (1999). The associated design methods do not provide projections of the rates of geomorphological change associated with departures of SCR from unity. As noted earlier, this is a difficult problem that would require sophisticated modeling, e.g. HEC-RAS, the USCE RMA system (née TABS), MIKE, or the Bureau of Reclamation GSTARS (Yang and Ahn, 2011), together with extensive field data. Such an undertaking is obviated by limiting the change in sediment load to a relatively small magnitude.

We do believe that this type of intensive, sophisticated analysis will be needed for larger new projects to properly assess the effects and identify appropriate mitigation. **It is our opinion that for such larger projects, geomorphic changes cannot be handled solely within a recommended flow regime, but rather require site-specific, project-specific analyses, in order to achieve management and/or mitigation strategies.**

Geomorphological effects on the stream ecosystem

This is really the central question underlying the use of geomorphology as an overlay. Field data and analysis documenting the response of the stream ecosystem to changes in geomorphology seem to fall into two broad camps: (1) alterations in stream ecology after or downstream from a perturbation that also affects geomorphology (most notably construction or removal of dams) and (2) relations between the heterogeneity of bed characteristics and measures of the stream ecosystem. While many of the former camp consider only a single species (salmon, trout, etc.), there are some that evaluate a broader sampling of the organisms and their metabolism. For example, Sweeney et al. (2004) report significant ecosystem changes following deforestation and the associated narrowing and textural homogenization of the stream. With respect to the latter camp, some studies, e.g., Yarnell et al. (2006), address the relation between sediment load and habitat heterogeneity (HH) assuming that HH will in fact result in ecosystem diversity. The recent work of Palmer et al. (2010) reviewed numerous field studies of the correlation between habitat heterogenity and ecosystem diversity, and found that "there is no evidence that HH was the primary factor controlling stream invertebrate diversity". (For instance, of 78 independent restoration projects in which habitat heterogeneity was achieved, only two exhibited significant improvements in diversity.) These results suggest that while geomorphic changes are involved in stream perturbations that have negative biological impacts, the exact role of geomorphology remains elusive.

It would appear that if the geomorphic change associated with a modified flow-duration curve can be expressed as modified stream cross-sections, so that changes in habitat area and duration can be quantified, then tools are available (e.g., PHABSIM) to predict biological response as a function of habitat availability. There are ways that this could be accomplished in principle, but this would require application of sophisticated sediment transport models, which, as noted above, require substantial input data, and are unrealistic for use by a BBEST.

For modest modifications to the sediment budget, one possible approach for a BBEST might be to try to develop a predicted alteration of cross-section due to modified sediment loads (which can be computed from SAM), and feed this into the hydraulic analyses of PHABSIM to assess the modification in habitat distributions that would result. We understand that efforts similar to this are in planning and/or underway in the San Antonio River system. The key to this approach is a viable method to translate a change in sediment load to a modification in stream cross-section geometry. **We do not know of a suitable functional relation or model that would produce a stream cross-section from sediment load information, other than complex multidimensional models with high demands for data and validation studies, as noted above.**

Another cogent issue is the nature of ecosystem adaptation to the modifications in channel morphology and profile. We have several potential case studies in Texas of downstream incision below dams (e.g., below Lake Whitney, and Lake Livingston). It would appear useful to quantify the differences in both the physical habitat and biological community of nearby systems, with and without major reservoirs, when before-and-after data do not exist. While differences in both would be expected, we observe that stream and river stations downstream of major reservoirs, some in relatively close proximity to the upstream impoundment, have been judged by the BBESTs to exhibit a sound ecological environment.

With respect to the 10% limit on change in sediment yield discussed in the previous section, we find that there is little to no information describing how much change to the physical configuration of a channel is allowable before adversely impacting the ecosystem dependent on that channel.

Conclusions

We regard geomorphology as an important characteristic of the stream environment and acknowledge that it needs consideration in the environmental flow process. There are two fundamental causal pathways underlying the role of geomorphology in environmental flow determination (Fig. 1): a functional relation between flow regime and principal elements of the stream morphology such as stream cross-section, and a relation between these elements of stream morphology and the health of the stream ecosystem. As a corollary, we considered whether there is a clear, defensible threshold in any of the geomorphological controls, notably sediment load, beyond which resulting changes in the geomorphology produce unacceptable impacts on the stream ecosystem health.

The establishment of stream geometry response to changes in the distribution of flows and/or sediment loads proves to be complex. Alterations in morphology can be localized while the larger channel system is stable, or vice versa. Moreover, the time scale of streambed evolution in response to change can range from geological to catastrophic. Concurrent responses to multiple perturbations, some of which may drive the channel to mulitiple equilibria, can create high variability in the channel evolution. All of this creates considerable uncertainty in inferring geomorphic equilibrium (or stability) of the stream at a specific location such as a gauge site, as well as whether an alteration in sediment load associated with changes in the regime of streamflow is sufficient to de-stabilize stream geomorphology. Quantitative methods for projecting the stream response involve sophisticated modeling and extensive field data, and are generally unsuitable for the limited time and resources of a BBEST.

The adaption of the stream biology to adjustments in stream cross-section is equally uncertain, requiring substantial stream monitoring data to establish. **The literature appears inconclusive**

on the features of the stream geomorphology of central importance to the ecosystem health, though such features can be identified, and in some cases, quantified for specific organisms. It is a fact that there are numerous examples of geomorphological alterations in Texas streams and rivers from dams. Some of these are found in the rivers and tributaries addressed by SB3 BBESTs, all of which have been judged by the BBESTs to exhibit a "sound ecological environment".

The proposed use of a 10% limit to alteration in sediment load is derived primarily from channel design practices in civil engineering and is directed at ensuring that a designed channel will remain stable. This is a criterion employed in lieu of quantification of the channel response to such an alteration. **There is inadequate information in the literature to justify using such a criterion which if exceeded will precipitate changes in the morphology that will unacceptably impact the biology.** While a position of minimizing change to avoid possible negative impacts may be attractive given the uncertainty of the science, this is not the charge of SB3. Rather, the BBESTs are charged to use the best available science together with professional judgment to determine what flows are scientifically justified for a healthy ecosystem,

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