Professional Peer Review of

Evaluation of the Proposed Edwards Aquifer Recovery Implementation Program Drought of Record Minimum Flow Regimes in the Comal and San Marcos River Systems

Final Hardy Report to the Edwards Aquifer Recover Implementation Program

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Overarching Comments

The San Marcos and Comal river systems and associated human and natural communities represent a complex, linked ecosystem. Over time both river systems have adjusted to a number of new controlling variables (e.g., increased water use, impervious cover, introduction of non-natives, increased recreation, and other factors).

Overall, there are no serious flaws or errors in the report and recommendations based on our understanding of the charge given to the authors. However, there are significant omissions, as discussed below that may compromise the validity of the findings on a long-term basis. Assumptions of the approach are well documented and are reasonable given present understanding of aquatic ecosystems. The tools and methods of analysis employed, with respect to habitat modeling, are appropriately used and based on best available information. The acknowledgement of data gaps and uncertainties is commendable. Aquatic ecosystems are very complex and even though considerable effort has been expended to understand the Comal and San Marcos River systems, much is still unknown and developing a functionally complete comprehension of the system is a high standard to achieve. Studies such as this are intended to minimize or manage uncertainty – not eliminate it. Within this constraint, appropriate knowledge gaps were identified and addressed by suggested monitoring and adaptive management recommendations.

The Hardy report focuses on the potential effects of degraded habitat in a relatively short period of time (a single drought year). Though long-term drought may not have been experienced in recent history, prospects for an extended drought (possibly associated with the effects of global climate change) are real. If the flow criteria analyzed in the report are intended to be institutionalized for a long period of time or in perpetuity, analysis of the cumulative effects of longer term drought periods would be appropriate.

The application of the models to produce flow-habitat relationships and temperature time-series outputs are accepted practice. The models used were all appropriate and appear to have been properly calibrated or adapted for use in this study. The report identifies many of the readily apparent potential threats to these populations and habitats. Accepted methodological approaches were used to analyze the relationships between critical environmental attributes (habitat suitability and temperature) and flow levels. Most of the important limitations to the analyses and assumptions upon which data interpretations were based were clearly articulated, which strengthens the conclusions and recommendations provided in the report.

The overall approach of using simulated model outputs in combination with observed and empirical data is to be commended. Combining the physical habitat modeling with the temperature modeling represents the state-of-the-art for carrying out these types of studies. The temperature modeling was improved by using recent (2009) empirical data along with the vegetation distribution using historical vegetation mapping results.

Intensive sampling, model calibration, and 2-D simulations of habitat were completed for both systems. Considerable detail is presented, including vegetation cover maps, habitat suitability, and reach maps illustrating ranges of hydraulic habitat suitability over a range of flows for selected species. These analyses were well done. Interfacing field data gathered by wading and by boat and with topographic data from LiDAR represents the state-of-the-art and allows for simulations of flow over the entire flow range from low flow onto the flood plain. Illustrations and information tables were clear and useful. Apparently no simulations of seasonal habitat periodicity or inter-annual habitat suitability were developed. However, it appears that all information necessary for such simulations was available.

The conclusion "that the flow regimes being considered by EARIP will provide adequate protection for aquatic resources given the underlying assumptions and the mitigation measures proposed by the EARIP have been successfully implemented" is supported for survival population levels by the data presented under apparently average climatic conditions. However, recovery after such stressful conditions cannot be assured by evidence presented thus far and should be the focus of adaptive management. Only after critical analyses comparing the proposed regimes over different seasons and under differing conditions of water supply and climate can the conclusion that the same "minimum flow regimes" applied to all years would provide adequate protection and recovery. Applying one set of "minimum flow regimes" to future years should be considered an interim measure pending more study of the system dynamics and biological detail.

It appears as if the current report was constrained somewhat by the scope of the work. To obtain a better understanding of the probability of persistence faced by the organisms studied, additional information and analyses would be helpful. Our technical review team previously made recommendations relative to this needed information. See the team's previous report dated 5/10/2010 where we recommended, "Full characterization of the system hydrology: past, present, and potential including all elements: magnitude, duration, frequency, timing, and rate of change is necessary. Establishing water year categories through 1) development of annual flow duration curves, 2) delineating water year strata (e.g. dry, normal, wet), 3) classifying each water year of the period of record into a specific stratum, and 4) then using that classification in a time series analysis to develop adaptive water management strategies would help refine recommendations. Additionally, hydrologic data should be stratified for water quality analysis according to cool, normal, and hot climatic conditions."

In particular, there appear to be considerable threats posed by secondary impact mechanisms – some of which were mentioned but most of which were not directly studied. Additional work is needed to address issues such as the threats posed by non-native fishes and parasites and prospects for aquatic vegetation collapse at low flows. Though vegetation disturbance associated with human recreation is logically suspected of inhibiting recovery of TWR in the San Marcos River, it is unclear if the level of impact has been directly studied or quantified. Threats posed by these and other sources at low flows may be as great as or greater than the availability of WUA and physical habitat in which organisms may live.

The report provides an appropriate level of technical documentation on the modeling approaches and evaluation of the proposed minimum flow regime targets adopted by the EARIP for a similar instance as the drought of record. We note the presumption that a drought will mirror a previous one in climatic intensity or with the same combination of factors (water quality parameters same as in 1950's, watershed conditions similar (e.g., impervious cover), connectivity constraints similar, biotic interactions similar (e.g., invasive species threats the same), demand for water and recreational demand the same, etc), does not seem probable. These facts underscore the need to look at more than WUA and physical habitat.

The analyses in this report also focused on the potential effects of known threats that exist now or have existed in the past. A thorough assessment of future risk might look to identify potential effects of factors that appear likely to exist or increase in the future. Such factors would include the prospects for considerably more recreational use of the San Marcos River than currently occurs. Studies might also be done of potential effects of contaminated groundwater entering the systems studied here through the numerous springs that feed these environments. Clearly, it is impossible to minimize or eliminate all uncertainty associated with managing for the long-term persistence of endangered species and the reality is that for all the potential risks we can identify today, there are others that are impossible to foresee. The recommendations section of this report offered appropriate suggestions for future study that should be considered to help minimize risks of persistence associated with Texas Wild Rice (TWR) and Fountain darters.

The report also limited its analysis to the lowest recorded flows of record. While an even more severe or extended drought would not be desirable, it would be useful to analyze lower flows for longer periods. Such information would help managers deal with future pressures to allow restriction of flows to even lower levels if and when such public pressures develop. Given the rate of population growth in this part of the U.S. and state, such condition seems likely.

As will be discussed below under *Specific Comments*, improvements to the physical habitat modeling could have been realized through model validation (hydraulic and habitat) and time-series analysis (hydrology, suitable habitat, and temperature). Demonstrating changes to habitat through time during both the assumed drought of record and for the entire period of record would have provided better context. Also, providing additional benchmarks, such as comparing the suggested minimum flows of the Edwards Aquifer Recovery Implementation Program (EARIP) to both the historical and naturalized flows would have been beneficial. Such analyses could be particularly informative by examining the period from the late1980's to present when intensive biological monitoring has been ongoing. Comparisons between the phenology of biological species and hydrology/habitat variability over this time period should be conducted.

The results contained here suggest that higher absolute minimum flows might be appropriate. Setting such conservative standards now could make it easier to achieve needed (higher) flow levels than trying to increase minimum flow levels in the future if the need for such protective flows was documented. A time series analysis that looked at a series of repeated droughts over a more extended period would help clarify potential effects.

While the title of the report is, "Evaluation of the Proposed Edwards Aquifer Recovery Implementation Program", it appears the report simply demonstrates that the proposed minimum flows provide sufficient habitat (quantity and quality) for short-term survival of selected species and life stages. A true evaluation of the implementation program requires comparative analyses as suggested in our specific comments to meet the stated objective of recovery and long-term persistence of the species. As such, we suggest the title be modified to more accurately reflect the relatively narrow scope of the studies presented therein.

The report should address in some way all of the technical components (hydrology and hydraulics, biology, geomorphology and physical processes, water quality, connectivity) emphasized by the 2001 National Research Council review of "The Science of Instream Flows: A review of the Texas Instream Flow Program". Without some discussion of each of the components by default the report leads to the assumption that hydraulic habitat and water temperature are the primary limiting factors in these river systems. The report should provide a discussion and present logical arguments as to why the other components are not limiting during recent historical times. Particular attention to seasonality and periodicity of flow events since the late 1980's when intensive monitoring started would be enlightening. In addition, evidence should be presented on the potential low dissolved oxygen levels during low flow events when combined with extremes in high ambient air temperatures. The modeling capability presented would certainly support such analyses.

An adaptive management approach is necessary if the resilience of this system is to be maintained. Hydrology is a critical aspect linking the ecology and human systems. As such attention to flow regimes and habitat dynamics is critical for additional research, not only to establish specific habitat relationships but to establish and track habitat and population responses over time to ensure not only short-term survival but species recovery.

Specific Comments on Final Hardy Report

Page 1, Introduction

The report introduction states that it will focus evaluations on the “minimum flow regime targets adopted by the Edwards Aquifer Recovery Implementation Program during a similar instance as the drought of record”. The report should clearly state the goals, objectives, and questions addressed within this report. For example, "...the proposed minimum flow regime targets adopted by the Edwards Aquifer Recovery Implementation Program..." mentioned here and throughout the report, needs a concise definition, in terms of hydrology. It would be beneficial to provide a brief discussion on the minimum flow targets and the rationale for how they were derived. If this information is provided elsewhere in this text or other documents, it should be referenced here.

An excellent point is made that: *"These flow regimes cannot be sustained indefinitely (i.e., beyond the time period associated with the drought of record) without irreparable harm to the resources and/or placing these aquatic resources at unacceptable levels of risk."* This points out the need for a hydrology time series analysis to define when the drought of record (DOR) is happening versus times when flows are higher. An important piece of the recovery plan would include setting criteria indicating flows have moved into a DOR triggering implementation of the proposed minimum flow(s). The flow values used for minimums (6 months at one number, 6 months at another slightly higher number) are not flow regimes, simply two minimum flows, which may allow for short-term survival but not for recovery and long-term persistence of the species in question.

A quotation of the charge made to the report authors by the EARIP should be included. The report presumes that a drought will mirror a previous one in climatic intensity and with the same combination of factors (water quality parameters same as in 1950’s, watershed conditions similar (e.g., impervious cover), connectivity constraints similar, biotic interactions similar (e.g., invasive species threats the same), demand for water and recreational demand the same, etc). This does not seem probable and may compromise the long-term validity of the technical analysis provided here.

The report stresses that the flow regimes modeled were specifically chosen to ensure short-term survival of the aquatic resources in the San Marcos and Comal river systems, to ultimately ensure “recovery potential”. This caveat is important and is stressed in the report. The review team is concerned that the report was restricted to focus on only solitary drought events. Given that the Edwards Aquifer Recovery Program is aimed at “recovery “ and the Texas Water Plan emphasizes comprehensive instream flow studies (See Table 3-1, Sample Questions to Guide Technical Evaluations, in NRC, 2001 The Science of Instream Flows A Review of the Texas Instream Flow Program), a broader approach integrating longer term hydrologic characteristics could have been taken. The drought cycle is a part of the overall hydrologic condition. To ensure flow regimes will provide for the long-term protection, enhancement, and recovery (where necessary) of the aquatic resources within these rivers would necessitate analysis of the habitat conditions *after* the drought cycle as well. What is important to establish is the dynamics of species survival; what conditions are necessary to restore viability, what conditions constitute a threshold? Additional hydrologic analysis (e.g., scenarios bracketing past drought flows with even more extreme events or variations) would increase the view of system behavior and the breadth of potential impacts examined. Comprehensive investigations of the variation in hydrology and water quality as well as simulated habitat variability to search for potential associations with events of high stress and conditions necessary for population recovery would be appropriate to include in the study approach.

Page 1, Background

This section presents some basic historical flow information for both the Comal and San Marcos Rivers. Clearly there have been considerable seasonal and inter-annual variations in water flow in both systems, but the extent of this variation is not well developed. Emphasis is placed on the flow during the extreme drought periods of the 1950's. No discussion is given (pro or con) of the need to develop simulations approximating the physical habitat and water quality conditions during that period for comparison with more recent years when intensive biological monitoring has taken place. Other factors that should be included, and are at least by inference, are the need for connectivity (for organisms to escape potentially lethal habitats and re-colonize depleted areas following drought) and geomorphology (or the need to minimize or avoid fluvial geomorphic processes/bedload transport in parts of the study area) during low flow periods.

Page 2, Background - Comal River

Hydrologic information (for the Comal and San Marcos rivers) is an important element in understanding the drought flow condition and relevance of flow recommendations; however this information appears lacking in the report. A table showing the minimum, maximum, and average flow at defined points or gages on both of the streams should be included.

Clearly there is a flow level below the proposed minimum threshold at which endangered species in this system are extirpated. It would be helpful if this analysis could identify the approximate flow level at which this might occur to, at a minimum, emphasize the fine line that may exist between the proposed flow regime and the "extirpation" flow level. Such information may help the EARIP understand the need to possibly increase the minimum flow they have proposed in order to minimize the risk of permanently losing these species.

The document states, "*During the drought of record…*". This would be a good place to clearly provide criteria upon which a DOR would be based. We are unable to find the definition for the acronym "EAA". This should be provided.

Spring flows ceased for 144 consecutive days in 1956; fell below 60 cfs for more than 100 days, and also fell below 40 cfs for over 40 days. The low mean daily flow was 26 cfs; other low flows were observed in 1989 (62 cfs), 1990 (46 cfs), and 1996 (83 cfs). Comal riffle beetles and fountain darter were apparently extirpated during this drought period. Clearly, the low flow period in 1956 was substantially lower than low flows experienced subsequently. The report states that low flows after the 1956 period did not extirpate riffle beetles, fountain darter, drypoid beetles, or the Peck's cave amphipod. This is apparently the rationale for the proposed low flow thresholds of 30 cfs for no more than 6 months with increased pulse flows to 80 cfs for the following 6 months. These proposed low flow regimes appear to have been developed before habitat studies were done. The rationale and process for the derivation of the low flow regimes in most studies is based on hydrologic modeling or another process. As a premise for this low flow study, the basis upon which thresholds were developed should be explicitly provided in the report. Without this specific documentation, it is difficult to ascertain the real risk associated with these flow regime proposals, even qualitatively.

Page 2, Background - San Marcos River

As noted above for the Comal River, more complete hydrologic information should be provided. Criteria upon which a DOR would be based should be provided.

The lowest recorded discharge was 46 cfs in August 1956, which also had the lowest monthly average flow recorded (54cfs). Mean monthly discharges between 1955 and 1956 were between 54 and 77 cfs. Importantly, no quantitative data exist for the response of the target aquatic resources over this extended low flow period. Since the 1980's, Texas Wild Rice has sustained populations during all subsequent low flow years, even in the face of impacts from recreation, high flow scour events, and non-native species. Viable populations have been maintained during the extended low flow period in 2009. Low flows examined by the Hardy study were set for 45 cfs for no more than 6 consecutive months, with pulse flows increased to 80 cfs during the following 6 months. Without explanation for the basis of these low flows, we have the same concerns we identified for the Comal River noted above.

Page 2-4, Background - EARIP Drought of Record Low Flow Regimes

Again, it is still not clear how the DOR is defined in terms of a flow value. Figure 1 is apparently showing the DOR begins sometime around the flow corresponding to January 1, 1947 and ends sometime around 1959. Is this the defined time period for the DOR? Does this mean when flows in the San Marcos River drop to 175 cfs this is the trigger for a DOR? As noted previously, there should be a section in the report that deals with hydrology and specifically there needs to be more discussion on what constitutes a DOR in terms of flow values.

Page 4, Methods

The methodological approach described in this section is very thorough and informative. The level of detail contained in these studies is exceptional and appears to facilitate the kind of analyses that are needed to effectively understand the consequences of different flow regimes. Intensive sampling, model calibration, and 2-D simulations of habitat were completed for both systems. Considerable detail is presented, including vegetation cover maps, habitat suitability, and reach maps illustrating ranges of hydraulic habitat suitability over a range of flows for selected species. These analyses were well done. Interfacing field data gathered by wading and by boat and with topographic data from LiDAR represents the state-of-the-art and allows for simulations of flow over the entire flow range from low flow onto the flood plain. Illustrations and information tables were clear and useful. Apparently no simulations of seasonal habitat periodicity or inter-annual habitat suitability were developed. However, it appears that all information necessary for such simulations was available.

Page 4, Methods - Vegetation Mapping

Mapping techniques to create vegetation polygons with dominant and subdominant species and joining with hydrodynamic modeling grids to assign roughness values and vegetation class attributes are an excellent application of the science.

Page 6, Methods - Topographic data reduction and computational mesh generation.

Combining topographic maps, LiDAR, and in-channel shots is standard, thorough modeling practice. The 2nd sentence under this topic reads like LiDAR was used within the wetted channel (standard LiDAR does not penetrate through the water surface), but is resolved in the following sentence with the use of in-channel bed topography. It is common when LiDAR data and field data obtained using survey gear are combined to find inconsistencies in the elevations where data sets overlap. If there were inconsistencies in this study, then the manner in which they were resolved should be reported. Figure 4 shows the process of going from raw data points to contour map to good effect.

Page 7-9, Methods - Hydraulic Modeling

This is standard, thorough 2-D modeling practice. Figure 5 shows close match between observed and predicted water surface elevation (WSE). Table 1 shows a thorough and complete data set. The roughness values listed here all appear reasonable and within expected ranges for each vegetation or substrate type.

Page 9, Methods – Habitat Suitability Criteria (HSC)

The HSC curves for TWR, two non-natives aquatic vegetation species, and darters reflect recent research (Saunders et al. 2001, BioWest 2010a&b) and integrate additional information (empirical observations of darter depth utilization). Modifying the suitable depth criteria for darters as described here is appropriate and a credit to the authors to confirm the need for this.

The HSC curves were adopted from other studies and were well documented. No evidence is presented in this report of any testing of the adopted HSC curves as to their efficacy in describing species distribution at various simulated flows. For studies evaluating endangered species and proposed instream flows for implementation within critical water supply settings such as the Edwards Aquifer verification/validation, demonstration of habitat simulation agreement with species observations is called for (see National Research Council, 2008. Hydrology, Ecology, and Fishes of the Klamath River Basin). If such verification/validation was done by the original authors of the HSC curves then reference to the fact should be included. Academic aquatic scientists and ecosystem modelers have become quite critical of instream flow studies in recent years due to the lack of proper calibration and verification of model use in stream systems. These scientists point out that model calibration and verification/validation has become established practice in water quality modeling for over three decades and is of equal importance for hydraulic and suitability aspects of riverine habitat modeling.

When very low velocity levels (0-1fps) are within the optimum suitability range for some target species, verification of velocity data sets for simulated high flows would lend a high degree of credibility to the simulated velocity distributions produced by 2-D hydrodynamic modeling.

Page 15 -19, Methods - Physical Habitat Quantity and Quality, *Non-native vegetation Control*

Analysis of habitat for TWR and *Hydrilla verticullata* and *Hygrophila polysperma* allowed for an effective examination of non-native vegetation control areas. The basic approach for control was to, 1) remove non-native plants from existing optimal TWR stands and 2) remove non-native vegetation within a 2-meter buffer of occupied optimal TWR stands but additionally constrained by TWR having a greater suitability than the modeled non-native species.

These approaches seem reasonable given the data that exists. One caveat comes from Liebig's "law of the minimum" that states it doesn't matter how much habitat is provided, if that is not the limiting factor for the TWR plants in those areas (see http://en.wikipedia.org/wiki/Liebig's_law_of_the_minimum). There are always limits, and layers of limits; i.e., remove one limitation, and the next one becomes important. Any physical entity with multiple inputs and outputs is surrounded by layers of limits (Meadows 2008). However, what is often confounding is that the limits may shift – in other words, limits to the

TWR may shift in response to stand size or some other dynamic factor. None of this argues against the approach taken, but merely expresses caution about expectations of results of the non-native vegetation control efforts. Lastly, the areal significance of *Colocasia esculenta* may suggest some further research for this species, especially if the habitat-guided control efforts for other plant species are even moderately successful.

Explanation of the analysis and accompanying graphics (Figures 10-12) were informative. As with any major field project (potentially removing over 25,000 m^2 of non-native vegetation qualifies as 'major'), converting the plans to implementation will be key. Applicability of the data, particularly under approach 2), where data accuracy is a critical element of a 'correct' decision, will likely require exploratory pilot efforts to work through field decisions before attempting targeted control work on a large scale.

Page 15, Methods - Physical Habitat Quantity and Quality, *Fountain Darters – Riverine Sections*

When carrying out flow-habitat modeling, there are several ways the HSC data can be used with the hydraulic data. In this instance the authors chose to use the geometric mean approach. This is a commonly used calculation method but it would be beneficial to provide the rationale for using this approach over other approaches. Validation of habitat model output by comparing suitable and unsuitable habitats with empirical data illustrating fish distributions would lend credibility to both the HSC and geometric mean composite suitability computations.

Habitat metrics can be expressed in a number of ways. For example, relating WUA as a percentage of the maximum observed WUA at each simulated flow would allow readers to better relate the WUA at each flow to the maximum that can be expected at a study site over the entire range of flows simulated. This may or may not change the overall conclusions of this report but would allow readers to better gauge the relative merits of the proposed minimum flow levels to other flow levels. Presenting the information as percent of total surface areas is, however, acceptable. It would be beneficial to provide the rationale for choosing this metric.

Page 15, Methods - Physical Habitat Quantity and Quality, *Fountain Darters – Lake Sections*

It is appropriate to recognize the limitations of applying flow-habitat models in lake environments and the need to use another approach, such as wetted area and depth, as used in the report. Relying on reservoir water quality models in lake systems is also commonly used.

A minor point, but use of the term "optimal" here and throughout the text is misleading and suggestive that all aspects of "habitat" have been captured. The term "habitat" can be very broad and encompassing. As a consequence, a more technically correct term might be "maximum observed suitable habitat." This change does not affect the validity of any interpretations or analyses, but would simply relate the attribute(s) being described more precisely.

Conducting analyses based on determination of WUA is widely accepted and used in virtually all instream flow studies. However, it is important to note that the relationship between the amount of WUA and numbers of target organisms is variable and imprecise between different rivers, segments, and species. The amount of WUA provides a good indication of the relative suitability of physical habitat for an organism and one would generally expect organisms to fare better and possibly expand in response to more WUA; but there is no guarantee of such outcome or steady state relationship between this factor and numbers of organisms. This is largely due to the fact that "habitat", as noted above, is comprised of a large universe of dynamic factors and processes that influence organisms. Certainly maximizing physical habitat (WUA) is the desired goal. Analyses based on the amount of WUA can help reduce or manage uncertainty, but such studies do not eliminate it or guarantee a particular outcome. It is axiomatic that physical habitat modeling is necessary but is not sufficient to provide a complete understanding of the species' ecology.

Page 16, Methods – Physical Habitat Quantity and Quality, *Texas Wild Rice – Theoretical Optimal and Suboptimal Area*

As noted above it would be beneficial to provide the rationale for using the geometric mean of the component depth over other approaches.

Overall, the approach described here is exceptional and should provide an appropriate and useful analysis.

Pages 17-19, Methods – Physical Habitat Quantity and Quality, *Non-native vegetation*

It is unclear if non-native vegetation density is constant year round or between years. Additional information about the abundance and distribution of non-native vegetation on an intra- and inter-annual basis would strengthen conclusions about the adequacy of the target flows for ensuring persistence of TWR. It would also be useful to include information on the growth and spread of these plants and TWR. This information would allow the reader more understanding of the feasibility of and need for physically controlling these plants as a way to facilitate the long-term persistence of TWR. The basic strategy and logic presented in the text is reasonable, though it is unclear why a 2 meter buffer is of greater utility than another size of buffer. Is this driven by the size of polygons used in modeling or a known life history feature of TWR or the non-native vegetation species? Clarification of these questions is needed.

The described approach for identifying most suitable areas for non-native vegetation removal and TWR expansion is a judicious and appropriate strategy that has merit over blanket removal of non-native vegetation.

Page 20, Methods - Temperature modeling

A glaring omission from this section is any discussion of the potential effects of global climate change on probabilities of achieving thermal or hydrologic conditions described in this report. Given the uncertainties associated with the effects of global climate change, a credible discussion of the probability associated with future annual thermal patterns and precipitation characteristics is warranted. At a minimum, the report should acknowledge the elevated uncertainties that may be experienced in the short (decadal) and longer terms.

Another missing component that should be included here or in an expanded water quality section would incorporate other water quality considerations, both surface and ground water inputs. At the low flow levels proposed by the EARIP, even small changes in some pollutants that could enter these systems from either surface or ground water could significantly affect the persistence of the organisms studied here. The potential impact should at least be acknowledged in the final report. Future studies should more specifically address this issue.

The last sentence of this paragraph notes that adverse thermal conditions should not exceed 6 months, but this seems based more on professional judgment than data analysis. Professional judgment is most acceptable in many situations; however this is where a time-series analysis would be possible and beneficial.

Water quality was restricted to water temperatures. Given the sophistication of the study otherwise, it is surprising that other constituents were not addressed, especially dissolved oxygen. Average monthly and even daily time steps for this parameter are not sufficient when looking at the potential dynamics of plant stands, associated fish species (fountain darter), and sediment oxygen demand. Extreme oxygen deficits are highly possible at these low flows and can cause imperceptible mortalities to fishes, especially small, young life stages.

Thermal death criteria for specific life stages for all species should be provided.

Page 21, Methods – Temperature Modeling, Comal water temperature modeling, *Model Structure*

The QUAL2E model used was calibrated by the senior author and published and has been in use since. It incorporates headwater (7) and point load locations (44) to represent various springs in the system. As such it represents an established tool with adequate testing and refinement.

Page 21, Methods – Temperature Modeling, Comal water temperature modeling, *Assumed spring flows for Comal headwater and point loads*

The revision of flow rates for specific springs as a function of total Comal River discharge incorporated 8 years of field monitoring by EAA and work of Guyton Associates (2004), who analyzed historical water levels and spring flows for the 1948 to 2001 period. Assumptions and adjustments adopted within the report, based on the additional information from these sources, seem reasonable.

It is unclear why 74.51 F was used as the constant flow on page 24 and why this level of precision (hundredth of a degree) was appropriate. Additional clarification is needed.

Page 24, Methods – Temperature Modeling, Comal water temperature modeling, *Assumed flow splits for Old and New Channel*

Table 12 - Showing the historic flow splits along with the preferred flow splits would be informative. The rationale for splitting the flows for the simulated model runs seems appropriate given the information provided. However, it would be informative to understand the historical flows in terms of differences from the flow splits being used for modeling.

Page 27, Methods – Temperature Modeling, Comal water temperature modeling, *Climate Data and Model Calibration*

Air temperatures for the 1956 meteorological year would enhance the utility of Figure 16, to show the relative similarity and differences between modeled air and water temperatures and the air temperatures occurring during the historic low flow year. Old Channel simulations (Figure 18) seemed to represent the critical excursions into or past the larval threshold differently than New Channel across from Landa Park Office (Figure 19) or the Landa Lake near Spring Island (Figure 20). There were at least 7 observed temperature readings in the Old Channel that were higher than the threshold and simulations; at least 4 of these occurred where the simulation did not reach past the threshold and the observed values did. In the New Channel, the simulations exceeded the observed values and 18 times exceeded the threshold when the observed values did not. At Landa Lake the observed high values generally exceeded the simulations but did not reach above the larval threshold temperature. The under-estimates are a concern, particularly in the Old Channel, which appears to be a critical habitat area. Additional discussion explaining these dynamics and related consequences would be helpful.

The water temperature modeling in this report relies heavily on the previous application and calibration of the QUAL2E model reported in 2009 (recalibrated from Bartsch et al. 2000). However, significant changes in the hydrology of the system have been included in this report. Therefore some discussion of recalibration of the QUAL2E model in this new setting seems appropriate. Was the model recalibrated to better fit the empirical data or simply used with new hydrology? In Figure 18, simulated high temperatures do not seem to provide a good fit to empirical data in Landa Lake.

On page 28, the report references a USGS gage on the Comal River, but the gage location is not provided here, nor is it apparent on any figures provided to this point. As noted previously, it would be helpful to include more information on and from any and all gages on the Comal River (and San Marcos).

Page 30, Methods – Temperature Modeling, *San Marcos water temperature modeling, <u>Model Structure</u>*

Significant changes in the hydrology of the system have been discussed in this report. Therefore discussion of recalibration of the QUAL2E model in this new setting seems appropriate. Again, was the model recalibrated to better fit the empirical data or simply used with new hydrology? An even poorer fit (both maximum and minimum) for the San Marcos Thompson Island is illustrated in Figure 28. If recalibration was done and this is the best fit that could be made considering the other sites for simulations then discussion to that effect would be appropriate. Time series simulations of water temperatures over the period of intensive biological monitoring would be informative. Recalibration should be done given the new hydrology. Time series using the recalibrated model would require additional partitioning of years and seasons of the record into periods of dry, normal/average, and wet hydrology and hot, normal/average, and cool air temperature conditions. Much of this information is apparently available from stream gage and airport weather records.

Page 30, Methods – Temperature Modeling, *San Marcos water temperature modeling, <u>Assumed spring flows for San Marcos headwater and point loads</u>*

There is a lack of quantitative data on individual spring flow discharges to assign specific flow rates over the range of San Marcos discharges. This mandated that individual spring flows within Spring Lake were treated as a single incremental flow and this is a straightforward treatment of the constraint posed. From Table 13: only two of the 6 headwater (1) and point load (5) discharges for the San Marcos River are assumed to vary as total discharge decreases over the range of flows studied (130-45 cfs): Spring Lake Headwater and Incremental inflow Reach 1, for reasons noted above Interpretation of results should refer back to this limitation. This uncertainty may limit the precision of the conclusions.

The QUAL2E model is widely used and appears to have been properly calibrated and run for this study. Another model that might be considered and could offer significant benefits for other determinations discussed later in this report is the QUAL2K model (see http://www.epa.gov/athens/wwqtsc/html/qual2k.html). This model is a modernization of the former model but offers some expanded modeling features that include, among other things, use of unequally spaced reaches; simulation of attached bottom algae, light extinction as a function of algae, detritus, and inorganic solids; and simulation of pathogen removal as a function of temperature, light, and settling. Use of QUAL2K would likely not change the recommendations provided in this report but could help the authors or others address elements such as pathogen management and vegetation survival under low flow conditions in future reports.

Page 33 Methods – Temperature Modeling, *San Marcos water temperature modeling, <u>Assumed spring flows for San Marcos headwater and point loads</u>*

As noted above, descriptive information about the San Marcos River gage as well as more detailed hydrologic information from the gage would be helpful.

Pages 36-67, Results and Discussion

The habitat modeling results provided for the San Marcos River are impressive and thorough. Quantification of additional areas for TWR with removal of two non-native species shows the peak gain occurs at 100 cfs. Analysis of optimal and suboptimal habitat as the foundation for expansion of TWR into stable areas of unoccupied optimal habitat is a proactive application of science in an adaptive management framework. The 2-D mapped areas of TWR physical habitat provide a visual basis for relating the results and also necessary information for actually planning field operations. The report also provides quantitative information on the potential gain in TWR habitat through removal of two non-native plants, which comprise 2 of the 3 most common and abundant non-native plants documented. A conservative approach is proposed and seems prudent. The only caveat to this is obvious: proceed slowly, (spatially more isolated, smaller plots) making sure that the removal of non-native species, particularly within TWR stands, did not set up unintended conditions which exacerbate the invasive characteristics of the targeted plants. Documentation of conditions before, during, and after removal are paramount for later diagnostic efforts should something go awry.

The highest predicted suitable habitat generally occurs somewhat away from the stream margins both at 45 and 80 cfs. These results suggest that potentially high quality areas in these regions currently not occupied by TWR should be considered for planting or priorities for non-native vegetation removal as discussed below.

Another potential explanation, one that does not necessarily negate the report recommendation, is that there is another limiting factor in these areas, other than the measured habitat. For example, the distributions of the TWR may reflect unique hydraulic conditions (e.g., inside of bends), which are a function of channel shape and the helical flows of water, sediment, and nutrients.

Another explanation of the distribution of TWR could relate to the overall regime of flows; that this current distribution of TWR is an expression of longer term prevailing conditions, and that the stand itself modifies habitat when provided a range of flows within which to exist. Time series analysis of the habitat for this species would help establish the basis for comparison of flow regimes (hydrologic time series wed with HSC curves) and an estimate of the impact on habitat conditions for any particular arrangement of flows. It would also allow diagnostic analysis of notable population events, especially when coupled with a wider array of potentially impacting factors (e.g., outbreaks of invasive species, extreme temperature events, recreation activities, sediment, nutrients, etc.). While the report is clearly addressing its stated charge, 'evaluation of the proposed minimum flow regime targets during a similar instance as the drought of record', documentation of the habitat resulting from the entire hydrologic regime, and any subsequent modifications of flows, are not provided. Adaptive management, so clearly called for and which was initiated by this substantial effort, would benefit from formal analysis of the target populations of interest and the flow/habitat time series which supports them. Gaps in understanding these systems would become clearer as well.

Page 37, Results and Discussion – San Marcos Physical Habitat Modeling, *Texas Wild Rice, Simulated TWR Optimal versus Suboptimal Physical Habitat*

Analyzing WUA data as a function of maximum WUA instead of as a function of stream surface area appears as if it would show a greater rate of change at the low flow range of interest. This presentation of the data likely would not change the overall conclusion but could strengthen it.

The word "strongly" is subjective and probably not appropriate; however, the overall conclusion that TWR may expand into areas of unoccupied suitable areas that remain suitable over a wide range of flows is a reasonable conclusion.

Page 40, Results and Discussion – San Marcos Physical Habitat Modeling, *Texas Wild Rice Simulated TWR Optimal versus Suboptimal Physical Habitat*

The headers for Table 15 are unclear. It appears the second column should have "simulated" added to the header and in the third column, "2009 mapped" should be added to the header. The same correction appears needed for Figure 35.

Page 42, Results and Discussion – San Marcos Physical Habitat Modeling, *Texas Wild Rice Potential TWR expansion with removal of H. verticillata and H. polysperma*

Use of the word "strongly" is subjective and unsupported. There is no information in simulations in this report that relate to the long-term persistence of TWR under any conditions, though a time series analysis of physical habitat and temperature would be helpful.

The conclusion of both providing adequate flows and removal of non-native vegetation is compelling. However, long-term monitoring is needed to confirm the indication that proactive planting and non-native vegetation removal would lead to long-term persistence of TWR. Other mechanisms may be at work influencing the growth and abundance of these organisms other than WUA as evidenced by the fact that the non-natives encroached on TWR in the past and could do so again. Though the assumption that non-native vegetation removal has a "high" potential for increasing TWR abundance, there are no data in the report that relate to this probability. This does not change the basic conclusion brought forth here that this activity may have merit and should be explored by managers.

Pages 43-47, Results and Discussion – San Marcos Physical Habitat Modeling, *Fountain Darters - Simulated Fountain Darter Physical Habitat*

The results illustrate the value of the habitat modeling represented in this report. Potential changes of vegetation resulting from flow regime changes were not specifically included, but the results show the spatial influence of depth and velocity over the range of discharges. The sophistication of modeling analysis is evident: after providing the information indicating relatively small reductions of darter habitat between the examined flow ranges (45-80 cfs) the authors the necessity to implement adequate control measures to protect the vegetation community, to reduce potential secondary impacts on darters.

The last paragraph of this section of the report makes the appropriate point that the proposed flow regimes seem likely to provide enough WUA/habitat to ensure persistence of TWR and that other measures to control secondary impacts such as those associated with recreation and non-native fishes are equally or more important elements in a recovery program. The following section of this report addresses potential effects associated with temperature at low flow, but there may be other water quality issues to monitor and manage as well. Such impacts could conceivably arise from surface or ground water and their impacts would be greater at lower flow. If these potential secondary impacts have not yet been identified or managed, they should be the subject of future consideration and study.

Page 45, Results and Discussion – San Marcos Physical Habitat Modeling, *Fountain Darters*, *<u>Simulated Fountain Darter Physical Habitat</u>*

We agree with the conclusion that "*the combined suitability of darter habitat shows incremental increases as the discharge increases and that the spatial mosaic remains relatively constant."* However, we do not follow the logic that it *"...is in part related to integration of vegetation in the calculation of the combined suitability which remains fixed over all ranges of simulated discharges."* Unless the coding of the mesh is changed at each independent run of the model for each discharge, the vegetation, or substrate coding, is always constant in these models. We can't tell what actual velocities were measured at the flows of interest from the report, but suggest that if habitat remains relatively constant over a range of modeled discharges, then it is likely the velocity HSC curve is relatively constant at these low flows (see Figure 9). A sensitivity analysis can be run where vegetation is included as input to the model and then do another run of the model with the vegetation component removed. Results should be somewhat similar with the only difference being the scale on the Y axis (habitat units). The statement that *"Potential changes in vegetation as a function of flow regime within the San Marcos River were not considered in these analyses"* provides needed explanation of what was done.

It is reasonable to exclude Spring Lake from the WUA analysis since the modeled output in lakes is typically insensitive to changes in flow rate.

Whenever WUA curves show a monotypic increase in habitat relative to discharge, there should be a discussion presented to explain the shape of the WUA curve. It would be beneficial to know what the natural (no human alteration to the flow) range of discharge is for these reaches of the river. Is it reasonable to expect maximum habitat occurs at flows greater than 250 cfs? These animals evolved in the natural range of flows since the last ice age and it would helpful to know if flows greater than 250 cfs are overbank flows, or rarely occur, etc. The known biology of the animal and the shape of the WUA should be discussed.

Pages 47 to 51, Results and Discussion – San Marcos Physical Habitat Modeling, *Fountain Darters*, *<u>Implications of Temperature on Fountain Darters</u>*

The temperature discussion is excellent. The detailed discussion refines the habitat suitability for fountain darters in various areas of this spring and addresses or explains the recent findings of other research. Conclusions related to the decreased viability of habitat for reproduction and recruitment in the river below Rio Vista are provided and have important implications during drought.

The graphical data presented generally support the conclusion that the flow regime being considered in the San Marcos River will provide adequate habitat quantity and quality necessary to provide protection for this species during similar instances as the drought of record. However, comparisons made with assumptions of differing climatic conditions would be valuable (e.g. dry water year and hot climate year, etc.). These comparative analyses including potential effects on dissolved oxygen are needed as well as simulations over seasons and years to evaluate recovery after critical droughts.

It is widely recognized that temperature modeling of natural systems based on laboratory data is problematic but it is the standard practice. It is also common to have some observed data where temperatures exceed thresholds and the animals persist. However, given the intent is to protect species from extirpation, it is a good approach to use consistent metrics and apply a measure of precaution. There are inherent errors in models and since this exercise was designed to stay above a "thermal death" line, erring on the side of caution is warranted.

The horizontal lines in Figures 41 to 45 should have a label of "increased larval mortalities" on the graphs or supporting text in the figure caption. On page 50, reference to reaches 1 and 5 do not appear to be the subject of data presented in Figure 42. Also on page 50, the statement that ambient air temperature in the spring of 2009 was about 75F may be correct but there is no citation or other data to indicate where this number came from or whether it is the correct value to reference.

Page 51, Results and Discussion – Comal River

Physical habitat modeling again is well done and illustrated with detailed habitat maps and graphs. The general conclusion is that sufficient darter habitat will be maintained. Many caveats are given and emphasis directed toward the need to control non-native species, ensure flow through the old channel, and protect vegetation. Indeed, survival of some, if not most, organisms during potential drought conditions similar to the 1950's appears likely under the proposed 'minimum flow regimes". Recovery following such stressful events is not demonstrated and generates uncertainty when combined with potential water quality conditions.

Page 51, Results and Discussion – Comal River – *Fountain Darters, Simulated Fountain Darter Physical Habitat in Landa Lake*

We agree that populations (adults and juveniles) probably would not die at the temperatures shown, especially if temperatures return to favorable levels during the lifetime of these fish. If favorable temperatures do not return for several years, resident populations may disappear though re-colonization would likely occur from upstream refugia. Recreation-related impacts and other secondary impacts (e.g. invasive species) could be severe at this time and could threaten long-term recovery. Again, this is another case where time series analysis of historic conditions and simulated worst case future conditions (that might be more severe than historic conditions), would provide important information.

Non-native fishes are a relatively new factor that may change the prospects for long-term persistence of fountain darters and the comments made here about their potential effects are valid. Other "new" or evolving factors that may change persistence prospects for darters should be identified as well. Control or removal of non-native fishes (and snails) can at least temporarily reduce pressure on small fishes like darters, but will likely require permanent monitoring and removal by humans. True recovery of endangered species should be such that species can persist on their own over time without the need for continued, regular intervention by humans. Thus non-native species removal should strive for total removal although this is a difficult goal. The uncertainties associated with this management practice speak strongly to the need to maintain the most WUA (and flow) possible to prevent non-native fishes, snails, and parasites from gaining a key advantage in terms of numbers and impacts. In consideration of the potential cascading effects of secondary impacts like these, the assessment provided by this report may be overly optimistic. EARIP managers should make a commitment to long-term monitoring and responsive action to ensure the goals of the program are met.

The second to last sentence in this section (page 58) states that “sufficient darter habitat will be maintained” but it is unclear what level of population existence is expected. It would be helpful if the authors indicated whether “sufficient habitat” relates to minimal persistence, maintaining robust populations, or some other level of abundance.

Pages 58-63, Results and Discussion – Comal River – *Fountain Darters*, *Implications of Temperature on Fountain Darters*

The graphical data presented generally support the conclusion that the flow regime being considered in the San Marcos River will provide adequate habitat quantity and quality necessary to provide protection for this species during similar instances as the drought of record. However, comparisons made with assumptions of differing climatic conditions would be valuable (e.g., dry water year and hot climate year). These comparative analyses including potential effects of dissolved oxygen are needed as well as simulations over seasons and years to evaluate recovery after critical droughts.

Temperature modeling at 30 cfs illustrates conditions that exceeded both darter larval mortality and cessation of viable egg production thresholds in Landa Lake. At 80 cfs a few hours in late afternoon still exceed larval mortality and viable egg production threshold levels. Uncertainty about the possibility for incomplete mixing of the water column raises questions about the reliability of the QUAL2E simulations and leads the authors to believe the model over states the thermal impacts (“likely results in an ‘over stating’ of the thermal impacts in Lower Landa Lake.”). This uncertainty calls for additional analyses incorporating dissolved oxygen in the water quality model simulations. This need is reinforced by reference to Figure 56 showing “that the lower extant of Landa Lake is primarily dominated by mud sediments which can have a high potential for oxygen demand under the right conditions.” The cause for previous extirpations of Comal Springs riffle beetles is not known.

The horizontal line in Figures 50 to 54 should have a label of "larval mortality threshold" or text in the figure caption.

The discussion at the top of page 63 reflects an appropriate use of professional judgment.

Figure 55 shows that the river goes through a golf course, which may have or create water quality issues associated with the addition of nutrients (e.g., nitrogen, phosphorous). This situation provides just one example of the potential risk of water quality impacts from a variety of inputs that need to be explicitly addressed in future studies.

Pages 64, Results and Discussion – Comal River – *Implications of Flow Regime on Vegetation Dynamics*

The discussion related to all factors that can influence the aquatic ecosystem of Landa Lake is thorough and comprehensive *"...directed research on...flow regimes...residence time...velocity fields, on aquatic plant dynamics needs to be undertaken early in the adaptive management process to better inform the adequacy of the flow regimes being contemplated by the EARIP."* It is evident the tools used to date are only a subset of the effort that is required to understand the unique and complex ecosystem of Landa Lake.

Overall, this section characterizes the strength of this report, which is clearly detailed modeling and thorough examination of related factors affecting the results. Specific areas of uncertainty are noted in the report that illustrate this point:

1) Uncertainties related to vegetation response to sustained low flow regimes within Landa Lake and the fact that this represents a potentially significant unknown. The vibrancy of the current vegetation stands over the past decade is related as a positive signal for the resilience of the aquatic plant community;
2) Sediment oxygen demand within Landa Lake and uncertainties related to sediment accumulation and potential impact on the aquatic plant community. The short review of literature in this area is provided to explain this concern and is relevant and insightful;
3) A discussion of vegetation dynamics in shallow lakes, relating the complexity of interactions between dissolved inorganic carbon, periphyton, macroinvertebrates, and fish. The authors conclude, and we agree, that control of non-native species to positively impact the native aquatic vegetation in this system needs to be effective and that directed research on the implications of flow regimes on aquatic plant dynamics needs to be undertaken early as part of an adaptive management process.

The discussion on page 64 is good and adds a measure of accountability to managers to consider a potentially significant threat. Though the information needed to quantify potential effects of low flows on the survival of aquatic plants in general was apparently beyond the scope of this study, the authors make an excellent case for further developing and analyzing this potential threat.

A strong case for pursuing a conservative approach to setting long-term minimum flow levels is made. While analyses in this report suggest that WUA for target species may be acceptable on a short-term basis, the reality is that secondary factors that were not analyzed may pose a greater risk to the persistence of endangered species. The summary paragraph at the bottom of this page (paragraph 5) is precisely on the mark.

Page 67, Results and Discussion – Comal Springs riffle beetle

The statement, *"Our review of the water quality data do not indicate any demonstrable shift in water temperature or quality that would suggest that at these lower flow rates, impacts from water quality would be expected."* is technically correct, but what is not mentioned is that the effects of other water quality factors (pollutants) would be magnified at low flows and could have a negative effect if they were introduced. In addition to pollutants, there are likely negative consequences due potential diel swings of dissolved oxygen.

The discussion following the results shows no discernable impact to the riffle beetle. According to the report, empirical evidence of their persistence over the past two decades is evidence the proposed minimum flows provide for habitat necessary for protection of these species. Concerns expressed are: the implicit expectation of persistence of current water quality conditions, stability in water quality, stability in the surrounding watershed conditions and land use. While evidence supporting these concerns is not provided, we suggest this is not likely the case, even over the past two decades.

Pages 67- 68, Summary

The flow-habitat modeling, the temperature modeling, and the vegetation mapping are state-of-the-art (with the noted exception of a time series analysis). However, the authors very logically and correctly state there is much that is still unknown, particularly in Landa Lake with respect to dissolved oxygen and temperature regimes. While the authors conclude that the proposed flow minimums should result in the survival of the species, there were no evaluations consisting of comparisons among alternative flow regimes. The authors appropriately caveat this conclusion stating *"...these flow regimes are not sustainable on a long term basis..."* The recommended minimums are specific to maintaining adequate habitat conditions for short-term survival of the target species during conditions similar to the drought of record. We agree these flow regimes will likely provide adequate protection for the aquatic resources but only if the underlying assumptions and proposed mitigation measures are successfully implemented.

One of the stated uncertainties is related to vegetation dynamics in Landa Lake. Other uncertainties include the degree to which the hydrodynamic velocity fields may permit cooler water to make it downstream to the old channel culvert system, and whether or not parasite and non-native fish control would be successful. The authors also note the impact of the proposed low flow regime on vegetation stand viability is unknown and this may dynamically impact darters and other species that strongly associate with the vegetation. The call for careful expansion of pilot control efforts for snails and undertaking an aggressive non-native fish program is important given the significance of this resource and the relatively small (tenuous) spatial scale of its existence. This underscores the need for systematic documentation of the population responses to flow regimes, control of non-natives, water quality parameters in addition to temperature, impacts of recreation, and small scale studies of vegetation die-offs.

To establish the theoretical and practical basis for adaptive management, sensitivity analysis of the proposed minimum flows through time series for both hydrology and habitat analyses should be undertaken not only for short-term survival during a drought of record, but of equal importance, conditions for long term recovery.

Given these uncertainties, it is problematic to then suggest*"...that darter populations will persist at reasonable numbers both within Landa Lake and upper reaches of the old channel with the flow regime magnitudes currently being considered."* The level of uncertainty and what is known about populations of darters make it difficult to suggest persistence in perpetuity under these conditions. Clearly on-going monitoring is essential to address the uncertainties.

It is stated, *"We further reiterate the importance that these opinions assume all other mitigation measures are successfully implemented and would include non-native (fish) control, etc.*" It should also be stated that given the uncertainties regarding dissolved oxygen (diel) and thermal connectivity, scientifically credible monitoring (designed to address hypotheses) is absolutely essential to address factors such as ecosystem parameters that were not included in this report, the uncertainties associated with the assumptions of the recommended mitigation measures, and the predicted outcomes of the models that were applied.

Within the San Marcos River, addressing the uncertainty related to successful recreation control for target TWR stands and removal of non-native vegetation represent substantial areas of negative feedback, in both the human and natural systems. A formal adaptive management plan, strategically stepping through modeling, research action, monitoring, and adjustment would be appropriate for all aspects of managing this system.

Pages 69-70, Recommendations

The recommendations given are certainly important. In addition, attention to additional water quality components and research on variable flow regimes and climatic conditions necessary for population recovery after the stresses brought on by critical drought conditions should be an integral component of adaptive management.

The specific recommendations follow from the results and discussion provided within the report and addressing them would generate a better understanding of the systems covered. Further, they would begin to provide information to allow a more proactive approach to management – before a crisis mode is reached. For example, it seems prudent to begin implementation of recreation measures and testing the procedures, spatially, institutionally, and socially before *extreme* drought conditions are reached.

Use of the report results to guide direct management control activities is a logical outcome given the detail and refinement in the report and is laudable. The discussion and recommendation for future research related to vegetation dynamics and control of non-native species and control of flows in the old versus new channels should become the focus of future study as part of the adaptive management strategy. However, expansion of the scale of perspective to TWR, fountain darter, and riffle beetle through time series analysis would further augment proactive management activities, further the understanding of target population dynamics, and allow science (habitat/ecology) based comparison and refinement of the low flow regime proposals. These efforts are absolutely essential in view of the uncertainty of using only flow-habitat and temperature models and the gaps in knowledge that were identified by the authors.

References

Meadows, D. H. 2008. Thinking in systems: a primer. Chelsea Green Publishing Company, White River Junction, Vermont, USA.