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David J. Bandrowski

Trinity River Restoration Program, U.S. Bureau of Reclamation, dbandrowski@usbr.gov

Yong G. Lai

Technical Service Center, U.S. Bureau of Reclamation, ylai@usbr.gov

D. Nathan Bradley

Technical Service Center, U.S. Bureau of Reclamation, dnbradley@usbr.gov

Josh Murauskas

Anchor QEA LLC, jmurauskas@anchoragea.com

Dave Gauman

Trinity River Restoration Program, U.S. Bureau of Reclamation, dgaeuman@usbr.gov

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2D Hydrodynamic Based Logic Modelling Tool for River Restoration Decision Analysis: A Quantitative Approach to Project Prioritization

David J. Bandrowski¹; Yong G. Lai²; D. Nathan Bradley²; Josh Murauskas³; Dave Gaeuman¹

¹Trinity River Restoration Program, U.S. Bureau of Reclamation, Weaverville, CA, USA; dbandrowski@usbr.gov and dgaeuman@usbr.gov; ²Technical Service Center, U.S. Bureau of Reclamation, Denver, CO, USA; ylai@usbr.gov and dnbradley@usbr.gov; ³Anchor QEA LLC, Wenatchee, WA, USA; jmurauskas@anchorqea.com

Abstract: In the field of river restoration sciences there is a growing need for analytical modelling tools and quantitative processes to help identify and prioritize project sites. Two-dimensional (2D) hydraulic models have become more common in recent years and with the availability of robust data sets and computing technology, it is now possible to evaluate large river systems at the reach scale. The Trinity River Restoration Program (TRRP) – Bureau of Reclamation in Northern California is now analyzing a 40 mile segment of the Trinity River to determine priority and implementation sequencing for its Phase II channel rehabilitation projects. A comprehensive approach and quantitative tool has recently been developed to analyze this complex river system referred to as: 2D-Hydrodynamic-Based Logic Modelling (2D-HBLM). This tool utilizes various hydraulic output parameters combined with biological, ecological, and physical metrics at user-defined spatial scales and flow discharges. These metrics and their associated algorithms are the underpinnings of the 2D-HBLM habitat module used to evaluate geomorphic characteristics, riverine processes, and habitat complexity. The habitat metrics are further integrated into a comprehensive Logic Model framework to perform statistical analyses to assess project prioritization. The Logic Model will analyze various potential project sites within the 40 mile restoration reach by evaluating connectivity and key response variable drivers. The 2D-HBLM tool will help inform management and decision makers by using a quantitative process to optimize desired response variables with balancing important limiting factors in determining the highest priority locations within the river corridor to implement restoration projects.

Keywords: *2D Hydraulic Modelling, Quantitative Prioritization, Evaluation Metrics, Logic Modelling, Statistical Analysis, and River Restoration*

1 INTRODUCTION

Effective river restoration prioritization starts with well-crafted goals that identify the biological objectives, address underlying causes of habitat change, and recognizes that social, economic, and land use limiting factors may constrain restoration options (Bechie et. al. 2008). In addition, effective management actions need to be tied to a Structured Decision Making (SDM) process that connects decisions to objectives (Hammond et al. 1999, Clemen and Reilly 2001). Applying natural resources management actions to the SDM process, like restoration prioritization, is essential for successful project implementation (Conroy and Peterson, 2013). This paper describes a river restoration prioritization approach that links together two-dimensional (2D) hydraulic modelling with desired response and limiting factor metrics into a statistical model framework. This river restoration tool, referred to as two-dimensional hydrodynamic-based logic modelling (2D-HBLM), will analyze and evaluate key biological, physical, and ecological desired responses in relation to various limiting factors comprising of physical and social constraints. In this paper, we will demonstrate how this approach can be effectively applied to a large river restoration program to help prioritize projects systematically and objectively.

All too often restoration actions are site specific without considering and evaluating ecosystem scale processes, protection of existing high quality habitats, or an understanding of the effectiveness of specific restoration techniques (Roni et. al. 2002). With over two decades of scientific literature and applied practice, the restoration community has a thorough understanding of the role of channel morphology in the formation of physical habitats (Montgomery and Buffington 1998) and the relationship between hydraulic parameters of depth and velocity to habitat quantity and quality (Singh 1989, Lamouroux 1998, Stewart et. al. 2005, Saraeva and Hardy 2009, Goodman et. al. 2010). The understanding of geomorphic processes and physical habitats have been integrated into models to assess hydraulic relationships quantitatively (Schweizer et. al. 2007, Dunbar et. al. 2012) and eco-hydraulic questions through prediction-based simulations (Bovee 1982, Gore et. al. 1998, Milhous et. al. 1999). Model utilization requires restoration science not only to embrace uncertainty (Darby and Sear 2008, Hillman et. al. 2008, Wheaton et. al. 2008), but to integrate bio-physical diversity, variability, and complexity into river management (Brierley and Fryirs 2008). Evaluating tradeoffs and examining alternatives to improve fish habitat through optimization modelling (Null and Lund, 2012) is not just a trend but rather the scientific strategy management needs to embrace and apply in its decision framework.

The overall approach of this reach-based prioritization is to evaluate the river system through integration of 2D hydraulic modelling, quantitative metric evaluation, and statistical logic modelling within a broader adaptive management and SDM framework. The topics described below include: overview of 2D hydraulic modelling, application of the 2D model on the Trinity River, development of the habitat module quantitative metrics, and approach to the logic model framework.

2. OVERVIEW OF 2D HYDRAULIC MODELLING

Stream flow modelling is one of the most widely used tools to understand how hydraulic conditions change between discharges and how they are related to fish habitat (Bovee, 1982; Milhous et al., 1989). Building on the early use of one-dimensional (1D) models, 2D hydrodynamic modelling has been widely used for evaluating hydraulic habitat data (e.g. water depth, water velocity, and substrate size). 2D models can be operated on a finer scale than 1D models and they can better predict hydraulics in near-shore habitat and across large-scale roughness features (Waddle et al., 2000). 2D models can more accurately predict water velocities and depths at local scales due to the ability to calculate both longitudinal and cross-sectional velocity distributions (Crowder and Diplas, 2000). Sample applications of 2D hydrodynamic models for habitat evaluation include Tharme (2003), Wheaton et al. (2004), Stewart et al. (2005), Mingelbier et al. (2008), Yarnell et al. (2010), Waddle (2010), and Hatten et al. (2013).

In recent years, the trend has been to use a 2D model to represent the roughness elements at the individual boulder scale (e.g., Waddle 2010), since riverine salmonid species are found to use flow obstructions as velocity shelters to minimize exertion and thus expend the minimum amount of energy while foraging and resting (Bjornn and Reiser, 1991). Boulder placement and the use of large wood are techniques of river restoration commonly used to provide increased diversity of velocity patterns in generally uniform river channels. Accurate modelling of such areas can provide better information about the extent of habitat in rivers and tools for design of constructed habitats.

In this study, we adopt SRH-2D (Sedimentation and River Hydraulics) as the two-dimensional depth-averaged hydraulic model that was developed at the U.S. Bureau of Reclamation. The hydraulic flow modelling module, documented by Lai (2008; 2010), has been widely used for evaluation of river projects. The robustness and accuracy of SRH-2D have been proven with a wide range of model verifications, as well as many project applications, at both Reclamation and external institutions. SRH-2D has a few unique features which make it ideal for engineering river applications. First, SRH-2D uses a flexible mesh that adopts the arbitrarily shaped element method of Lai et al. (2003) for geometric representation. In practice, a hybrid mesh normally uses quadrilaterals in the main stream and near structures and triangles in the floodplain and transition zones. The hybrid mesh achieves the best compromise between accuracy and computing efficiency and such a mesh is relatively easy to generate. Second, SRH-2D adopts very robust (stable) numerical schemes with a seamless wetting-drying algorithm. Reliable solutions may be obtained with the primary tuning parameter of Mannings n . Third, SRH-2D solves the 2D depth-averaged St. Venant dynamic-wave equations using an implicit solution scheme and unstructured meshes with arbitrary mesh cell shapes. It solves both steady and unsteady flows over all flow regimes (subcritical, supercritical or transcritical flows).

3. APPLICATION OF THE 2D MODEL ON THE TRINITY RIVER

The Trinity River is an ideal location for an applied scientific assessment of a reach based model due to the wealth of robust data sets that span large spatial and temporal scales. The Trinity has been monitored consistently for decades and has been surveyed at high resolution as required for two dimensional hydraulic modelling. A seamless Digital Terrain Model (DTM) that integrates terrestrial and bathymetric topography is the basis of the 40 mile hydraulic model. The DTM for the Trinity consists of airborne LiDAR topography and boat-based sonar bathymetry across the entire reach (Woolpert 2013) that has been validated to a 95% vertical accuracy confidence of 0.320-foot RMSEz (Root Mean Square Error) for LiDAR and +/-0.686-foot RMSEz for sonar. This validated accuracy is based on extensive quality control field measurements consisting of 40 channel spanning cross-sections and 849 independent GPS-RTK check shots along the Trinity. The DTM has been certified by a professional licensed land surveyor and exceeds both National Map Accuracy and American Society of Photogrammetry and Remote Sensing (ASPRS) Standards.

In addition to topographic data sets, aerial imagery orthophotography has been collected in multiple years and serves as the foundation data set for geospatial mapping on many projects including the 2D hydraulic modelling mesh generation. Two model meshes were developed for this project: a coarse mesh to use for model calibration (the calibration mesh) and a denser mesh to use for the actual assessment (the habitat mesh). Both meshes are hybrid meshes that use rectangular elements in the main and side channels and triangular elements in areas that are dry at most flows. The calibration mesh contains approximately one quarter the number of elements as the habitat mesh across the 40 mile reach on the Trinity River.

The calibration mesh was developed from channel bank lines digitized from the aerial imagery data set (Figure 1). The complexity and curvature of the channel dictated length of elements in a reach. Long straight reaches contain longer elements, Tight bends and areas of complex morphology contain shorter elements.

Figure 1. An example of the calibration mesh on the Trinity



The width of main channel mesh elements is 1/8 of the local channel width. Side channel mesh elements are 1/3 of the local side channel width. Calibration mesh elements range from approximately 10 to 50 feet in length and 5 to 25 feet in width. The mean area of calibration mesh elements is 284 square feet.

The habitat mesh was developed by dividing each calibration mesh element into four elements. Channel elements in the habitat mesh range in width from approximately 1 foot to 10 feet. The mean area of habitat mesh channel elements is 71 square feet.

The sole calibration parameter available in SRH-2D is the channel roughness, represented by Mannings n. Increasing channel roughness by increasing the value of Mannings n has the effect of raising the water surface elevation and reducing flow velocity. Decreasing channel roughness has the opposite effect. The calibration data we used are water surface elevations measured during the bathymetric survey at seven different discharges ranging from 500 cfs to 4500

cfs. About 91% of the model error (modelled elevation vs. observed elevation) is within +/- 0.5 feet and the error is symmetrically distributed around zero. This error is similar to the error in the bathymetric data collection.

4. HABITAT MODULE QUANTITATIVE METRICS

The 2D hydraulic model has been run for approximately 20 different discharges cases, ranging from 300 cfs to 14,000 cfs. All the output data from each of the discharges will be exported from the hydraulic model into an evaluation tool referred to as the habitat module. This module calculates and organizes key hydraulic variables and quantitative metrics throughout the river into three spatial scales: 1) Panel-Based (Panel); 2) Cross-Sectional (XS); and 3) two-dimensional spatial (2D). The hydraulic output metrics are comprised of biological, ecological, and physical process algorithms used to evaluate a diverse range of riverine characteristics. The Panel spatial scale are 200 meter equal distant lengths and are based off a sampling protocol system currently being used on Trinity by the monitoring program called Generalized Random Tessellation Stratification (GRTS). Across the entire 40 mile reach, there are 319, 200 meter panels. Each unit length segment referred to as a “panel”, which could be replaced with the term “reach”, and at times in this paper they are used interchangeably. In addition to the panel based output format, the habitat module will also calculate similar hydraulic variables and metrics at automatically generated cross-sections and at the model mesh element center (2D-spatial output).

Hydraulic Variables and Metrics - A series of standard hydraulic variables will be one the primary outputs calculated at each discharge. These include water depth, wetted width, wetted area, velocity, width-depth ratio, and slope. Each of these variables will be calculated in both the panel and XS output formats. In order to perform statistical-based analyses within the Logic Model (the following step) the various hydraulic output data per panel need to be synthesised into average or mean values in order to have one number per variable per panel. One method to capture the range of values will be to calculate the standard deviation across the panel to take into account min-max values, and exclude outlier data. The second output type is hydraulic-based metrics used to evaluate biological, physical, and ecological functions to assess desired response. The other calculated metrics are to evaluate limiting factors from physical or social constraints. The metrics are broken into the following categories: 1) Biological; 2) Ecological; 3) Physical; and 4) Constraints.

Biological Metrics - The primary metric and the currently accepted most limiting factor for the Trinity River and many other restoration programs is juvenile rearing habitat. Fry and Pre-smolt critical rearing habitat is and will be computed from the hydraulic model using Habitat Suitability Criteria (HSC) developed for the Trinity River specific to the life stage and species (Goodman et. al. 2010). The metric for this habitat is Area_fry and Area_smolt based on meeting depth and velocity requirements determined by field validated HSC values. Adult holding habitat is a separate metric that will be the distance calculated from the each panel's centroid location to a location where the depth of water is greater than a certain user-defined value. The Dist_adult metric type looks for depths in the river that are indices of adult holding location.

Ecological Metrics - One of the major goals and objectives for the TRRP is to restore riparian function using both revegetation techniques and process-based natural regeneration from seed dispersal and hydrograph interactions. The riparian corridor is vital for ecosystem health and is a link to multiple habitats for aquatic, terrestrial, and avian species. A diverse and healthy plant community within the riparian zone is vital for restoration success and is the basis for the following metric. Area of Vegetation (Area_Veg) is based on a user-defined parameter specifying the appropriate height range above the water surface elevation. This is calculated per panel and at each flow and is determined as the amount of dry ground area from height x to height y above the specific water surface elevation corresponding to the specific discharge being evaluated.

Physical Metrics - Restoration activities on the Trinity River include flow and sediment management intended to promote the dynamic fluvial processes that create diverse physical habitat and rejuvenate the aquatic ecosystem. Several of the physical process metrics output from the habitat module are specifically designed to support an assessment of the potential for a given stream reach to achieve restoration goals with minimal mechanical intervention. The remaining physical process metrics quantify the existing geomorphic complexity in the reach under the assumption that existing complexity indicates that the panel is likely to be geomorphically active. The fluvial processes involved in the maintenance of high-quality habitat are tightly linked to sediment supply and sediment transport capacity. Scour and fill processes, in which the elevation of the stream bed or bar surface changes dynamically through time, creates topographic complexity, maintains substrate quality, and rejuvenates riparian vegetation. Lateral erosion of the banks facilitates planform adjustment and

contributes to the formation of alcoves, sloughs, and complex bar features. Although the habitat module cannot address questions about sediment supply, its output includes four metrics intended to assess the sediment transport capacity within a panel and its spatial variability. The simplest of these is Tau_avg, the panel-averaged shear stress. A large Tau_avg value indicates that the panel is characterized by relatively high shear stresses and so may have a high capacity to erode and transport sediment. That average value is complemented by Tau_dev, the standard deviation of the shear stresses, which indicates whether shear stresses in the panel tend to be spatially constant or spatially variable. As for process-oriented metrics, Tau_avg and Tau_dev are computed over a domain defined by left and right edge polylines provided by the user. It is recommended that, for process metrics, these edge lines correspond to the edges of the bankfull channel. More detail on the spatial variability of shear stress is provided by dTau_dL. This metric is defined by the slope of the shear stress gradient along the flow direction at each node in the 2D mesh. It identifies where shear stress is locally increasing or decreasing, and so indicates where local scour or fill might be expected. In addition to node-by-node output, the average of the absolute values of dTau_dL across all nodes is output for the panel as a whole. That average can be interpreted as an indicator of whether changes in the shear stress field within the panel occur abruptly, or whether they change gradually over longer distances. StreamP_V and StreamP_SS are measures of the total stream power within a panel, one is velocity based and another is shear stress based representing the rate of energy dissipation against the bed and banks of a river. Stream power at each transect or within the panel, is another indicator of local sediment transport capacity. Because it is a transect-based metric, it provides a convenient means for evaluating longitudinal changes in transport capacity and identifying subdivisions of the panel where deposition or erosion might be expected. Additional physical complexity metrics include Vorticity, Flow Direction Change (Flow_Dir), Hydraulic Cross-Over (Crossover), Wetted Edge Length (Edge_Len), and Sinosity. These remaining metrics assess the complexity of the flow field within the local reach or panel. The Vorticity metric calculates the angular velocity of a fluid particle and can be computed as a spatially distributed parameter at the panel scale or 2D output. Vorticity is a kinematic property of the flow field which, at each point, measures twice the angular velocity of a fluid particle. Flow_Dir represents the percent of wetted flowing area per panel going in the downstream direction. "Downstream" direction is defined as the one along the thalweg within the panel and is a measure of the flow direction change. The Crossover parameter represents the number of times the thalweg crosses the channel centerline of channel and is another representation of channel sinuosity. Edge_Len is the total edge length of wet-dry boundaries within a panel and reflects complexities of flows around islands, boulders, etc.

Constraint Metrics - In contrast to the metrics described above, which quantifies desired benefits, the constraint metrics evaluate limiting factors throughout the project reach. There are many limiting factors including: bedrock, topographic constraints, land ownership, access, infrastructure, and realty. The primary hydraulic-based metric is the topographic constraint that assesses feasibility and constructability factors. The topographic constraint metric is calculated by differencing the water surface at the discharge being evaluated with the surrounding topographic terrain at a user-defined distance from the river centreline (both right and left). The metric will calculate the height or elevation differential and the volume of the material needed to lower the surrounding topography to match water surface elevation, as a way to determine level or constructability

5. APPROACH TO THE LOGIC MODEL FRAMEWORK

Once the hydraulic variables and metrics have been calculated within the habitat module and synthesized for each of the 319 panels, the data will be then analyzed within a comprehensive statistical tool, referred to as the "Logic Model". The Logic Model will be the component within the 2D-HBLM process that analyses the data statistically and links together desired responses with limiting factors to result in prioritized areas of the river. Quantitative approaches have long been recognized as a key to improving processes (Box and Myer 1986). Modelling, hierarchical ordering of effects, and identifying key relationships and root causes for deficiency is commonplace in manufacturing (Harry and Schroeder 2006) and increasingly in biological sciences (Dassau et al. 2006; Huang et al. 2009). The Logic Model will utilize such approaches to assess key measures and relationships followed by integration of desired responses and limiting factors to inform prioritization. The objective of the Logic Model is to assimilate professional judgment, 2D modelling outputs, and empirical data to objectively prioritize restoration projects.

Measures used in the Logic Model include 2D output hydraulic variables, along with calculated metrics and empirical data selected using professional judgment prior to analysis. Desired responses include those measures that would represent improvements or ideal conditions for natural productivity of wild salmon, such as quality, connectivity, and complexity (Roni et al. 2002). Conversely, limiting factors represent measures that would constrain the ability to implement restoration projects (e.g., access or infrastructure). The distinction between desired responses and limiting factors is important in that the Logic Model is intended to prioritize restoration projects where the need, relative benefit, and practicality are optimized.

Data used in the Logic Model will be examined prior to statistical modelling. Both desired responses and limiting factors will be reduced to a set of uncorrelated variables using Principal Component Analysis (SAS Institute 2008). This step is intended to minimize the issue of multicollinearity in further analyses, particularly with predictor variables (Saab 1999). Desired responses and limiting factors will be further analyzed for spatial autocorrelation since standard statistical techniques assume independence among observations. For example, preliminary evaluations show that suitable fry habitat has a partial autocorrelation with at least the two preceding panels at 4500 cfs. Quantitative approaches used in the Logic Model will need to compensate for the relationships among neighboring panels to ensure that parameter estimates and significance tests yield reliable results (Isaak et al. 2010).

The principal components of desired responses will be analyzed using multiple regression techniques to identify key predictor variables derived from empirical observations. Variables with a significant effect on the desired response will be subsequently used to estimate expected habitat suitability within each panel. Data will be integrated using two approaches in the final stages of the Logic Model. First, a multiple measures approach will be used to evaluate desired responses in a compensatory manner, where a higher ranking in one measure can compensate for a lower ranking in another. For example, the Logic Model should target a panel or set of neighboring panels that have low rearing habitat or complexity, but high connectivity, riparian availability, constructability, feasibility, and high potential for relative change. The variables identified by Principal Component Analysis, as described above, will be ranked relatively among all 318 panels and the product of each score will be used for a combined score for ranking. Details and weighting factors will be evaluated and discussed after preliminary results are available. Secondly, a k-means cluster analysis will be used to group like panels (SAS Institute 2008). For example, five clusters shown in Figure 4 above and Table 1 below represent panels most closely related based on fry habitat, redds, planform area, and bedrock area derived from empirical data and 2D model outputs at 4500 cfs. Assuming that bedrock and planform area represent practicality to implement projects with potential to improve rearing habitat, it would appear that the 8 panels in cluster #3 would represent ideal locations for improvement (i.e., relatively high planform area and low bedrock, but high redd counts and lower than expected fry area on average).

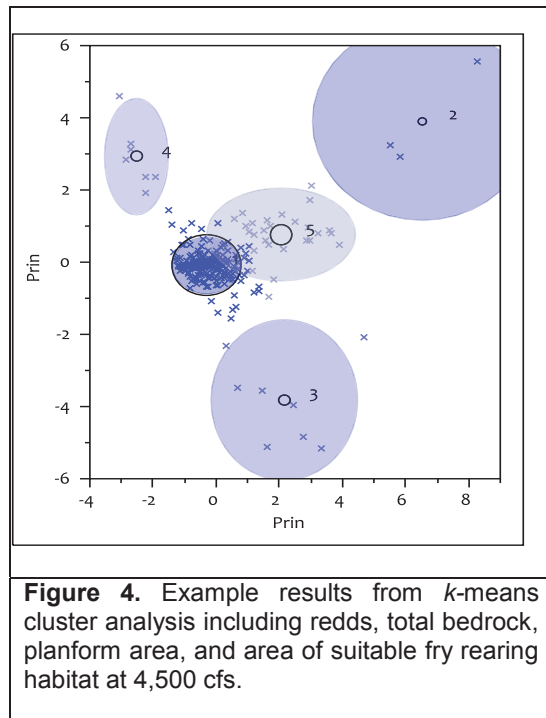


Figure 4. Example results from k-means cluster analysis including redds, total bedrock, planform area, and area of suitable fry rearing habitat at 4,500 cfs.

Table 1. Cluster means from example k-means analysis on data from 2D hydraulic model run at 4500 cfs. Not all 318 panels are included due to missing data in this particular case.

Cluster	Count	Fry habitat (square meters)	Percent redds in system	Planform area (square meters)	Bedrock area (square meters)
1	247	72	0.20%	9,363	70
2	3	3,561	0.03%	18,946	0
3	8	178	3.90%	12,065	0
4	7	83	0.04%	7,370	2,914
5	27	951	0.34%	13,886	30

6. SUMMARY AND REMARKS

In river restoration sciences there are still many information gaps to overcome and a strong need for analytical assessment tools to help answer important questions and test hypotheses. With the development of the 2D-HBLM tool some of these questions are being answered and important information gaps bridged. 2D-HBLM is now providing a quantitative and systematic approach to assessing riverine processes, evaluate project prioritization, and help inform management decisions. A critical step to validating and embracing the results from the 2D-HBLM is to compare the output to pre-defined hypotheses. This hypothesis testing phase will be done using the results from several metrics and statistical outputs for juvenile rearing habitat, the primary response variable and restoration goal. One key hypothesis that will be explored is the relationship of rearing habitat to river complexity. Complexity can be measured and defined using several different approaches, but the proposed method is to take a variety of physical metrics including vorticity, flow direction change, shear stress, edge length, and sinuosity and compare that to rearing habitat for a particular discharge. The hypothesis is that rearing habitat is closely related and has strong statistical correlation to the rivers physical and hydraulic complexity. Once the numerical and statistical modelling components are completed, a comprehensive phase of validation will take place to insure that analytical outputs match up to empirical and qualitative data sets. The approach for this validation will include a multi-disciplinary evaluation of the logic model results compared to empirical field monitoring data collected on the Trinity River over multiple temporal and spatial scales. This ground-truthing effort will help validate the hydraulic model output and statistical prioritization results with field collected data. An additional step will be a collaboration phase with key stakeholders and decision makers to inform them of the results and to seek recommendations for prioritization implementation. It should be noted that this project is currently being implemented and results are forthcoming. Some of the final results and data analysis and synthesis were presented at the IEMS conference in June 2014.

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