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Rebuttal Report in the Matter of Rangen Inc. - Availability of Spring Flow and Injury to Water Rights

Prepared for:

Rangen, Inc.

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Introduction

Expert reports on the water call by Rangen Inc. were submitted by Charles Brendecke of AMEC, Bern Hinckley and Thomas L. Rogers for the Idaho Ground Water Appropriators, Inc. (IGWA) and by Gregg Sullivan of Spronk Engineers for the City of Pocatello.

This report responds to various assertions in the reports by Brendecke, Sullivan, Spronk and Hinckley. A separate report addresses comments by Bryce Contor.

Specifically, we assert that the water rights issued by IDWR for the Rangen facility and the administration of those define and treat the entire Rangen Spring as a single source. The historical water measurement data, upon which the determinations of impacts from junior ground water pumping are determined and which were utilized for ESPAM 2.1 model calibration are correct.

The operation of the Rangen facilities for aquaculture research and fish production are consistent with the standard of care in the industry and the diversion facilities are reasonable, hydraulically adequate, and approved by IDWR. Multiple uses of the spring resource within the Rangen facility enhances water use efficiency and prevents operational waste within the system.

The geologic framework of the Rangen Spring is not anomalous compared to other springs emanating from the ESPA in the Thousand Springs area and the hydrogeologic conceptual model of the spring as modeled by IDWR with the ESPAM2.1 model is consistent with the known geology and ground water modeling protocols. Hypothetical interpretations of the Rangen Spring geology offered by IGWA consultants Hinckley and Brendecke are not justified and different conceptual models, as proposed by IGWA consultants, are incorrect. The total Rangen spring source, the Martin-Curren Tunnel outflow and the spring outflow through the talus, as developed for the Rangen water supply and authorized by valid State water rights, is the regional ESPA and should be modeled as such.

These expert reports can be characterized as a sudden reversal of a decade of open and collaborative ESPAM model development led by IDWR and with the cooperation and oversight of the members of the ESHMC, including Brendecke and Sullivan.

The ESPAM 2.1 ground water model is the best tool available for evaluation of responses and impacts to the ESPA from changes in water use. This model has been fully and adequately calibrated and validated by IDWR and the development guided and evaluated by the ESHMC, the members of which are eminent and qualified ground water modelers, hydrologists, and engineers.

The calibration of the ESPAM 2.1 ground water model utilized measured historical spring flow as targets to allow the automated calibration software, PEST, to obtain the best-fit (minimum sum of squares of deviations) of the simulated output and water levels in the ESPA. Rangen Spring historical calibration period discharge was a target in the PEST calibration. All of the Director's requirements for IDWR adoption of ESPAM2.1 have been met. These requirements include model calibration, validation, uncertainty analysis and comparison to ESPAM1.1.

Modification of the ESPAM 2.1 model to unilaterally reflect alleged differences in local geology without evaluation of impacts on other springs in the system is not justified. The utilization of alternative ESPA models, reflecting only differences in local geology of one spring with re-calibration of the modified model is not justified. The ESPA aquifer is a coherent hydraulically interconnected water body and manipulation of individual components (springs) without regard to the impact caused by re-distribution of flow through the aquifer is not justified and does not provide other water users any opportunity to evaluate impacts on their water sources.

IGWA consultants developed what they termed alternative ESPA models, the alternatives being changes to the geology of Rangen Spring, including simulation of a hydraulic barrier one or two miles long, down gradient of the Rangen Spring model cell, assumption of two separate springs within the Rangen Spring cell, addition of head target data, and arbitrary weighting of the importance of the more recent measured Rangen Spring total flow in the calibration process. There were apparently at least eight (8) different model configurations which were evaluated prior to selection of a representative alternative model. Results and documentation of alternative models #3 and #8 were the only model data provided for evaluation. Simulation runs using ESPAM2.1 and the two alternative models show that there is essentially no difference in the impact of curtailment of junior pumping to mitigate for impacts to the June 15, 1962 Rangen water right using the three models. Any differences between the simulated impact on Rangen Spring of curtailment using the alternative models and ESPAM2.1 are the result of application and manipulation of a trimline.

These expert reports introduce new and unvetted ideas, data, analyses and assertions in an inappropriate venue where they can neither be utilized nor explored objectively. They provide incomplete data for their "alternative models" without sufficient explanation as to why some results are included and others are not. And all of the "alternative model" curtailment scenario results are post-processed with the so-called "trimline" procedure, an arbitrary process for excluding data that is a non-scientific, administrative procedure that is inappropriate to introduce into groundwater modeling discussions and essentially renders the results useless and incomparable the standard IDWR curtailment modeling scenarios.

Our analysis of these reports and the alternative models presented concludes that they do not contradict the efficacy of IDWR's calibrated ESPAM 2.1 for quantifying the impact of junior well pumping on model boundary spring flows such as Rangen Spring. Quantifying these impacts is one of the key reasons ESPAM was developed and was used as a guiding objective during ESPAM calibration and uncertainty analyses. In fact, if the "alternative models" are used with the trimline post-processing filter removed, they actually reinforce the accuracy and robustness of the IDWR ESPAM 2.1 model.

As a result these reports have no impact on our opinion that the IDWR ESPAM 2.1 is still the best science available for understanding and quantifying the impacts of junior well pumping on spring flows tributary to the ESPA. IDWR should continue to use ESPAM 2.1 to estimate the reduction in spring flows at

Rangen Spring due to junior ESPA well pumping. Furthermore, the open and collaborative model (ESPAM2.1) that has worked so well should continue to be used. The alternative modeling and hydrogeology ideas and data should be introduced into the ESHMC as previous efforts have done, where it can be vetted and utilized constructively to enhance the ESPAM system.

The best estimate of the impact of junior pumping on Rangen Spring is the unmodified output from ESPAM 2.1. Utilization of a trimline of any percentage magnitude, justified by an unsubstantiated estimate of ground water model uncertainty, arbitrarily limits the true hydraulic impact of junior pumping and is not hydraulically or statistically supported. There has never been an uncertainty analysis performed on ESPAM2.1 or any ESPA ground water model to support the use of a trimline as currently configured.

B. Water Measurement Adequacy, Water Rights, SRBA Decreed and Permit Points of Diversion

The historical flow measurements made by Rangen personnel at the facility have been done correctly and are accurate and adequate for the purposes for which they have been used, including the historical 1980-2008 Rangen Spring complex flows for the IDWR ESPAM 2.1 calibration efforts.

The operation of the Rangen facilities for aquacultural research and fish production are consistent with the standard of care in the industry and the diversion facilities are reasonable, hydraulically adequate, and approved by IDWR. Multiple use of the spring resource within the Rangen facilities enhances water use efficiency and prevents operational waste within the system.

Brendecke criticizes Rangen's flow measurement accuracy with a statement that is extracted from the memo by Cindy Yenter to Karl Dreher (December 15, 2003). The statement was based on Ms. Yenter's site visit on November 24, 2003 during which she compared Rangen's reported flows in the CTR and Large raceways with measurements which she and Brian Patton took on the day after the flows were measured by Rangen. Ms. Yenter reported that the Rangen measurements on the previous day were 10% to 12% lower than her measurements. Ms. Yenter reported that she did not actually observe the Rangen employee measuring the flow in the CTR and Large raceways, but attributed the likely difference to the error caused by the use by Rangen employees of a metal 2 inch wide ruler to measure the head on the weir as compared to a standard staff gage. If a 'standard staff gage' as used by Ms. Yenter it is a Leopold and Stevens enamel Type C staff gage, 2.5 inches wide as compared with the 2 inch wide metal ruler used by Rangen. Use of a gage of different width to "stick" a weir or, in this case, the flow over dam boards, is highly unlikely to cause a 10% to 12% difference in calculated discharge. Table 5-4 from Brater and King (967) and included in Appendix A shows the calculated error in discharge for various sized weirs as a result of errors in measurement of the head. The weir boards on the Rangen CTR raceways for measurement of discharge are, on average, about 2 inches wide. When a staff gage or ruler is used to measure the head on a weir, the bottom of the gage is placed on the upstream edge of the board and turned so that the velocity of overflow causes the water surface to 'run up' on the gage. This maximum 'run up' is measured to account for the velocity head. The difference in 'run up' on a 2 inch wide gage as compared with the 'run up' on a 2.5 inch wide gage cannot be more than 0.01 feet. This run up is equal to the velocity head over the boards as calculated by the formula, $hv=v^2/2g$ where hv is the velocity head, v is the overflow velocity, and g is 32.2 ft/sec^2 or gravity. The over flow velocity for average heads of 0.4 ft as measured on the CTR boards is less than 2 ft/sec and the calculated velocity head, hv, is less that 0.06 ft. It is therefore not likely that the error or difference in heads measured using a 2 inch wide ruler versus a 2.5 inch staff gage would be as much as 0.01 feet. The difference in discharge, if the 'error" in staff gage reading is 0.01 ft, would therefore be less than 4 percent and not 10 to 12 percent. Ms Yenter indicates that Brian Patton applied the Francis formula individually to each set of data which included different widths of boards on each raceway and measurements of head at three points across the width of the boards. It is significant that flow measurements over 2 inch wide boards violates the assumption on which the Francis formula is based. Standard weir formulas assume a sharp crested weir is in place and not a 2 inch thick board. Studies conducted on flow over check boards at the ends of raceways on aquaculture facilities indicate that the weir coefficient that should be used for flow over check boards, is near 3.09 as compared to the standard Francis formula, which assumes a sharp crested weir with a coefficient of 3.33 (USBR Water Measurement Manual, 1967). King and Brater, (Appendix A) 1967 compiled research on broad crested weir coefficients which shows a weir coefficient for use on a broad crested weir of approximately 2 inch width of 3.08. This would be applicable to flow over check boards with heads between 3 and 4.5 inches. This difference in weir coefficients between the standard suppressed rectangular weir with C=3.33 and the more appropriate 3.09 results in a difference of 8%. The Rangen discharge table comports with a weir coefficient of about 3.08 (BCB report)

Sullivan also indicates that the memorandum from Cindy Yenter to Karl Dreher of December 15, 2003 contained "insufficient information as to fully understand why IDWR concluded that the Rangen staff was under-measuring the flows through the hatchery raceways". This conclusion is warranted. In fact, the statement by Ms. Yenter is based on comparison by IDWR staff of one measurement of flow through the Large raceways not made on the same day as the measurement reported by Rangen staff. The comparison is flawed also because IDWR staff utilized the discharge rating curve for a standard sharp crested weir when in fact the flow was over dam boards, which is best represented by a modified weir coefficient resulting in a discharge rating similar to that utilized by Rangen personnel.

Sullivan also indicates that the difference in measured flow from the Martin-Curren Tunnel, which IDWR began measuring in 1993, and the total flow through the hatchery is the flow that originates below the tunnel. This is an incorrect observation in that, the flow from the Martin-Curren Tunnel flows into a concrete box from which several irrigation pipes convey part of the flow to irrigation interests or to the hatchery. Depending on the level of discharge from the tunnel, any excess flow from the box overflows into the talus slope and appears as flow at the toe of the slope and has not originated below the tunnel. Any calculation of the 'flow originating below the tunnel' utilizing this assumption is incorrect. So, Sullivan's assertion that Martin-Curren Tunnel flows averaged 40 percent of the total Rangen flow during 1993-2011 and 30 percent of the total Rangen flow since 2001 is likely in error.

Utilization of monthly average flow data to evaluate whether or not there was or could be beneficial use of a water right neglects the shorter term fluctuations in discharge which are characteristic of all springs in the Thousand Springs area. For instance, Sullivan indicates (P12, Sullivan Report) that the reported monthly average flow in April 1977 was 35.2 cfs and this is far less than would have been necessary to supply any portion of Rangen' April 12, 1977 priority water right. However, the model calibration data set as shown as utilized by IDWR shows values higher than 35.2 cfs during 1977. 1977 was the lowest single year flow record in the Snake River basin and this is reflected in the 1977 and 1978 flow records for most springs emanating from the ESPA.

Sullivan's analysis of Rangen Spring Flow records and estimates of water utilization from the Spring source implies that , in order for beneficial use to be effected, the total water right must be present at all times and must be utilized in some part of the facility to meet some beneficial use criteria. Figure 4-10 which Sullivan has compiled shows Total Unused Flow as compiled from monthly Idaho Power Hatchery Production Summaries and Total Rangen flow reported by Rangen and Martin-Curren Tunnel flow reported by IDWR. The assumption was that the Unused Total Flow is equal to the Total Rangen Flow minus the greater of the flows measured in the (Troughs plus Small Raceways), Large Raceways or CTR Raceways. This assumption implies that any water available from the source at any time that does not flow through a production facility is, in fact, unused or not beneficially used and is therefore a measure of inefficiency or waste. This assumption reflects an un-familiarity with the operation of aquaculture facilities which require periodic harvesting and movement of stock within the facility which results in temporary non-use of specific raceways or rearing facilities.

Use of the historic flow measurement data collected by Rangen staff are accurate for water rights analysis and for the development of ground water model calibration targets.

C. Facilities operations, Diversions, Multiple Use, and Waste within System

Historic IDWR water rights administration and ESPAM2.1 modeling treat the Rangen Spring flow as a single spring source that includes Martin-Curren Tunnel and lower talus spring discharge. The Rangen diversion structures effectively deliver the available water for use in the facility, where it is put to efficient use according to standard aquaculture practices.

The Martin-Curren Tunnel issues from the basalt comprising the upper member of the Glenns Ferry formation. The tunnel was excavated nearly horizontal into the basalt in order to enhance existing spring flows. This construction is similar to the construction of the many ganats or karezes which have been in use for hundreds of years in Pakistan, Afghanistan, Iraq, and Iran and across the arid regions of southwestern Asia. The horizontal tunnel intercepts the sloping water table, providing a hydraulic gradient toward the tunnel and induces additional flow out of the tunnel. This was and is a standard procedure which has been utilized to develop and enhance flow from various major springs issuing from the ESPA (Crystal Springs, White Springs, Hoagland Tunnel). The impetus by early irrigators (1884-1908) to enhance the existing spring by excavating the Martin-Curren Tunnel was the presence of a significant amount of flow from the spring at or near the elevation of the tunnel mouth. Current geologic evaluations and interpretations are not adequate to conclude that the Martin-Curren Tunnel outflow is separate from the flows emanating from the lower talus slope. Idaho Code 42-230b states the definition of a well as, "Well' is an artificial excavation or opening in the ground more than eighteen (18) feet in vertical depth below land surface by which ground water of any temperature is sought or obtained. There is no statutory definition of a "horizontal well". The water rights for the source of water for the Rangen facility are decreed as springs and not a well or wells.

Capture of water from the stream just downstream from the talus slope (headwaters of Billingsley Creek) would require pumping into the small raceways and then re-use of the pumped water in the large raceways causing oxygen depletion in the large raceways. There is no indication in any of the beneficial use exams conducted by IDWR for any of the Rangen water rights that the diversion system is inadequate or unreasonable. To our knowledge, there are no aquaculture facilities on springs issuing from the ESPA that utilize pumping for primary water supplies. The risk of pump failure is too high and, even though the concept may be hydraulically feasible, the risk and water quality degradation has not been deemed a feasible alternative by the commercial trout industry.

Pumping water out of Billingsley Creek into the small raceways and thence into the Large Raceways would result in water quality impacts on available Large Raceway and CTR Raceways and would require interruptible electrical power, which represents a risk to the reliability of continuous flow through the raceways. The fact that use of pumped water for commercial aquaculture is not utilized in the Thousand Springs area indicates that the industry realizes the risks involved with this type of source and has opted not to utilize pumped water.

D. Geologic Interpretations and Conceptualization

Brendecke and Hinckley present hypothetical geologic interpretations as the basis for ESPAM2.1 conceptual changes. The geologic data they rely on are generally too sparse and uncertain to provide clear and convincing evidence in support of their concepts. Furthermore, much of the geologic information has little bearing on the modeling of impact to the Rangen Spring caused by junior ground water pumping. Hinckley presents three main geologic interpretations and implies that they are controlling factors on the influence of ground water pumping on spring flow. Three concepts he puts forth are hypothetical concepts of the base of the Quaternary basalts, a reinterpretation of the potentiometric surface, and a concept that the eastern rim of the Hagerman Valley acts as a barrier to ground water flow.

These hypothetical concepts, while adding locally significant complexity, do very little to change the major regional aquifer behavior observed and accurately simulated by the calibrated IDWR ESPAM 2.1. Even though they may influence locally ground water flow direction and rates they are not the primary controlling factors on the relationship between regional ground water pumping and Rangen Spring discharge.

The USGS recently published a circular aimed at correcting common misconceptions about depletion caused by ground water pumping (Barlow and Leake, 2012). In this publication, the authors identify four misconceptions, one of which is described as, *"Misconception 2. Depletion is dependent on the rate and direction of water movement in the aquifer."*

The fundamental hydrogeologic principals controlling depletion of the Rangen Spring flow are that:

Widespread ground water pumping causes a regional decline in aquifer head;

Regardless of ground water flow direction or velocity, head declines caused by pumping propagate as pressure changes;

Head decline or pressure change propagation is controlled by aquifer properties of transmissivity and storage coefficient. These properties create large regional areas that affect discharge of springs in the Thousand Springs area, including Rangen Spring.

When evaluating the depletion caused by large areas of pumping within the ESPA, the aquifer properties are dominated by horizontal propagation of stresses. Because of this, depletion caused by ground water pumping is accurately and appropriately modeled by ESPAM2.1 as a single layer, confined aquifer.

The USGS summarizes these points:

"The independence of depletion and rates and directions of groundwater flow in most systems allows calculation of depletion by a number of different methods. These methods include analytical solutions, superposition models, and groundwater-flow models (see "Analytical and Numerical Modeling" section). In using either analytical solutions or superposition models, the natural rates and directions of groundwater flow are ignored." (Barlow and Leake, 2012)

The sources of data cited by Brendecke (Farmer, 2009 and 2011) show that the hydrology of the subsurface indicates aquifer material that creates large areas of contribution to the Thousand Spring area spring discharges. These large areas of contribution are the primary controls on the interaction between junior pumping within the areas of contribution and the spring discharge rates. Furthermore, it is these highly complex features referenced by Brendecke that interconnect the primary aquifer of the ESPA.

When he presents his interpretation of the bottom of the Quaternary basalts, Hinckley uses it to define the bottom of the "primary aquifer". He acknowledges that there is some flow within the Tertiary sedimentary layers and basalt layers. He presents geologic data indicating high transmissivity in the upper part of the Tertiary basalts. While describing localized geologic conditions, Hinckley summarizes them in his Figure 8. Hinckley describes the data on this figure in the following way:

> *"Contouring distant from control points and in areas with only "less-than" control points is hypothetical, presenting an interpretation consistent with the available data, but more conceptual than precise." (Hinckley, 2012)*

The "less-than" control points Hinckley refers to are 11 wells up to 14 miles away from Rangen where the well does not reach the bottom of the Quaternary basalt, and yet Hinckley uses these wells to plot the bottom of the Quaternary basalt. West of Rangen, the vast majority of Hinckley's data are these "less-than" control points and are not appropriate, accurate, or reliable data for this sort of interpretation. His hypothetical representation of the subsurface calls into question all of the conclusions based on it and does not represent clear and convincing evidence of the "highly localized conditions" repeatedly referenced by Brendecke and Hinckley.

Hinckley further misrepresents the influence of the local geology on Rangen Spring flows when he discusses the available ground water level data. On page 13, Hinckley states,

"Groundwater flow directions on this and other figures in this report are inferred based on perpendicularity to equal-head contours. In basalt aquifers, this generalization is more appropriate over larger areas than at very local scales." (Hinckley, 2012)

This is a true statement and is supported by the tracer study work presented by IDWR tracer study results (Farmer and Blew, 2011). Localized groundwater flow in the basalt dominated ESPA is controlled by preferential flow through localized high transmissivity zones. Additional complexities may be added by faults that can act as either preferential flow paths or barriers. The data available in the area of the Hagerman Rim are too geographically sparse to determine the influence of these localized conditions. ESPAM2.1 appropriately approximates the hydrogeology as a regional system that is interconnected by all of these locally complex flow features. Hinckley supports this claim with his statement:

"Although data density in the area is insufficient to delineate local gradients in detail, the contouring of Figure 16 offers an interpretation that is more consistent with the available data than previous mapping." (Hinckley, 2013)

Hinckley's Figure 16 relies on a subset of the IDWR November 2011 synoptic sampling data (IDWR, 2012). The reason to perform a synoptic sampling is to have one comprehensive data set that is collected at the same time by one team of scientists collecting the data. This approach allows for greater quality control and continuity of hydrologic conditions during the data collection. In his reinterpretation of the synoptic data, Hinckley selectively removed water levels that he interpreted to be from a deeper, disconnected aquifer. He then added in additional data points collected at different time periods. Two measurements were within 2 months of the synoptic sampling, and one measurement from 4 years prior. Inclusion of the data point from 4 years prior is particularly problematic and inappropriate because the data from this well shows variability and decline in water levels (IDWR hydro.online, 2013).

In support of his theory that the Hagerman Rim is a barrier to ground water flow, Hinckley describes the Hagerman Rim as a "westward termination of groundwater flow". It would be more accurate to state that the Hagerman Rim is the location where ground water discharges through the rim as spring flows. The Hagerman Rim does not restrict subsurface flow anywhere where there are Quaternary Basalts, transmissive Tertiary sediments, or transmissive Tertiary basalts are near the rim. Current and historic spring locations are evidence of this. A rise in ground water head would cause more water to flow out of the Hagerman Rim. Anecdotal evidence (personal communication with Frank Erwin, June 21, 2012) indicates that many more springs existed near Rangen in the past.

As supported by Hinckley's statements and the available data inappropriately used in his report, the localized geologic complexity in the Rangen area cannot be accurately resolved. Furthermore, this localized complexity contributes to the connection between the Rangen Spring and its' regional area of influence, the ESPA. Section E.2. of the BCB report presents the analysis of the relationship between regional water levels and Rangen Spring flows supports the connection of the regional ESPA to the Thousand Springs area. These objective, measurable data refute the hypothetical theory put forth by Hinckley that localized geologic features disconnect Rangen Spring flows from the impacts of regional ground water pumping.

E. ESPAM 2.1(Development, ESHMC, Adequacy, Calibration)

ESPAM2.1 is the culmination of decades of ESPA ground water research and model development. The ESHMC has provided guidance and oversight to create an open environment for fair and technically sound model development. The model objectives are best summarized by the IDWR modelers in their final report.

"A primary objective of the model development and calibration was the characterization of the interaction between the aquifer and the river. Although thousands of aquifer water level observations were used during the model calibration, the model was optimized for prediction of hydrologic impacts to the river and to Group A and B springs. The model can be used to provide a general sense of groundwater to groundwater impacts; however, the model is best used for prediction of impacts to surface-water resources resulting from regional groundwater use or from changes in the magnitude, timing, and spatial distribution of aquifer recharge." (IDWR, 2012)

ESPAM 2.1 adequately simulates the outflow of the spring system at Rangen which includes flow from the Martin-Curren Tunnel and the remaining flow emanating from the talus slope the total of which is the source of water for the Rangen water rights. It is not necessary to 'separate' the individual flows since they both originate from the regional system and are included in the source for the SRBA decreed water rights.

Spring discharge is affected by changes in water use by surface water entities including conversions to sprinkler irrigation from surface irrigation, ground water pumping for irrigation, and variations in irrigation water requirements over the ESPA. These affects are regional perturbations in the net flux or input to the ESPA and all springs emanating from the ESPA respond to these changes. The input data set to the ESPAM 2.1 model incorporates these temporal changes and the model simulated output reflects these regional impacts and changes in water budget. These man-made temporal changes in water use do not impair the use of ESPAM 2.1 to simulate impacts to Rangen Spring due to junior ground water pumping.

Constant model thickness and constant transmissivity are model assumptions accepted by the ESHMC as a necessary simplification of the natural system. Accepting this does not preclude the usefulness of model results. The high quality of model predictions at the Rangen Spring is evidence that the model is appropriately conceptualizing the regional water system that contributes to the flow conditions at the springs.

ESPAM2.1 has a large number of parameters, which is by design, and approved by the ESHMC. A large number of parameters does not equate to increased likelihood that the model is not unique, especially if specific calibration techniques are employed. ESPAM2.1 was calibrated using PEST automated calibration software and a powerful technique that allows for (and even encourages) the use of a large number of parameters. Large numbers of parameters and the procedures used during ESPAM2.1 calibration are common practice when using PEST to calibrate groundwater models.

ESPAM2.1 was designed to predict total Rangen Spring flows and cannot differentiate the Martin-Curren Tunnel. The IDWR modelers and the ESHMC are considering changing some of the ESPAM springs from one drain to two drains.

Brendecke makes the statement, "ESPAM2.1 simulates conditions that are not physically possible and conditions that are in direct opposition to observed conditions..." This is unjustified and a dramatized textual attempt to skew the reader's opinion of ESPAM2.1. The claim of impossibility of ESPAM2.1 simulated conditions is unjustified and an over exaggeration of the required and commonly accepted modeling practice of simplifying assumptions. Hinckley and Brendecke provide no data to support the claim that ESPAM2.1 is in direct opposition to observed conditions. The use of the words "direct opposition" is not a scientifically sound description.

Relative to the other springs, the Rangen Spring flow predictions are both accurate and precise. In the 1980-2008 calibration period, the mean difference between the observed and modeled Rangen Spring flows is reported as 0.04 CFS with a mean absolute error of 4.57 CFS. We discuss identified inaccuracies with the lower flow predictions in our report in section C.5. of our report.

A thorough evaluation of uncertainty does involve other components in addition to a predictive component. The predictive component attempts to quantify the range of specific simulated output as a result of allowing calibration within a specific range of the objective function. As outlined in the expert report of Brockway, Colvin and Brannon (BCB report), the result of the IDWR predictive uncertainty analysis, proposed by Doherty, the author of the PEST program, does provide a measure of the calibrated model's ability to simulate output within a reasonable range of the objective function. The best estimate of the simulated output is the result from the calibrated model for which PEST has minimized the objective function. Changing hydrogeologic parameters at specific locations to prevent "improper conceptualization" of geologic and hydraulic conditions is speculative at best and should not be conducted arbitrarily without a thorough model-wide evaluation of all parameters. IDWR decided, and the ESHMC agreed, that a full uncertainty analysis which would likely involve a Monte Carlo approach was not achievable and not mandatory. Changing the geologic parameters and configuration in ESPAM2.1 for a particular spring without evaluating all other spring configurations and recalibrating would not be justified.

Alternative conceptual models could be proposed providing that adequate evidence exists to justify alternative concepts. However, any proposed alternative model should be vetted and receive a thorough review and approval by qualified hydrologists and ground water modelers before being utilized for administrative purposes.

The AMEC alternative models further support that the ESPAM2.1 is a robust model and that using any of the models above to evaluate full ESPA curtailment show virtually identical results for Rangen Spring flow impacts. Put another way, the non-unique models created by AMEC come up with the same predictions. As further demonstrated by Brendecke's work, it is the arbitrary application of a "trimline" that results in different predictions. This further illuminates the non-technical and problematic nature of a "trimline".

F. AMEC Alternative Models and Curtailment Analyses

Brendecke has developed alternative models to test the impact of conceptual and calibration changes to ESPAM2.1. These changes are based on the hypothetical concepts put forth by Hinckley and have not been vetted in an open, collaborative environment such as the ESHMC.

Improving the ESPAM to better reflect geologic complexity is an effort that IDWR and the ESHMC are currently addressing. In doing so, the IDWR modelers and the ESHMC are weighing the benefits of adding complexity to the ESPAM based on available data. When enough clear and convincing data are not available to guide a conceptual model, a modeler is required to make assumptions.

Alternative calibrated models, as defined by Brendecke, include hydraulic barriers to east-west ground water flow patterns, not substantiated by indisputable hydrologic and hydraulic evidence; weighting of arbitrary segments of the calibration spring discharge data set, and reconfiguration of the drain cell treatment in an attempt to reflect multiple aquifer sources for which adequate evidence is lacking. One could arbitrarily configure the spring hydrogeologic parameters so that curtailment would beneficially produce almost any percentage of curtailed depletion. Utilization of an arbitrary 10% trimline or any trimline is not justified since use of the trimline, which is model specific, drastically reduces the defined curtailment area within the common ground water boundary. Use of a 10% trimline with ESPAM 2.1 reduces the contributing irrigated area to Rangen Spring from ground water pumping to 406 acres out of a potential 479,199 potentially curtailed acres within the common ground water boundary on the ESPA. Similarly, the potential curtailed discharge within the common ground water boundary on the ESPA to the Rangen July 1962 priority water right is estimated at 17.13 cfs. (IDWR Rangen Scoping). Utilization of a 10% trimline reduces the curtailed discharge to 0.19 cfs within the 406 acre curtailed area or 1.1% of the common ground water ESPA discharge from junior ground water pumping. This arbitrary reduction to only 1.1% of the junior ground water pumping affecting the Rangen Spring cannot be justified hydrologically or hydraulically and can only be justified by a desire to minimize the required mitigation for impact to the Rangen water rights.

ESPAM 2.1 was configured (number of drain cells and calibrated elevation) in a manner similar to all other A &B springs in the Devil's Washbowl to King Hill reach of the Snake River. The decision to utilize one drain within the model cell representing Rangen Spring was made by IDWR and reviewed by ESHMC because geologic data and information indicates that a two-drain configuration is not warranted. The purpose of utilizing two-drain configurations is not necessarily because there is geologic evidence to support two different spring sources but to allow PEST more latitude to better simulate the range of measured spring flow over the calibration period.

It should be noted that ESPAM 2.1 has been calibrated with measured total spring discharge ranging from over 50 cfs to just over 10 cfs or a range of about 40 cfs. This range in measured and simulated response is an adequate range to support predictive simulations required for evaluation of curtailment or other mitigation measures. Simulations of impacts from the Rangen water call using ESPAM2.1 predict an impact of up to 18 cfs for curtailment of the July 12, 1962 water right over the entire aquifer. This simulated change in spring flow is not "radically different from those extant in the model calibration period" so the ESPAM 2.1 model can be expected to represent and predict accurately the expected behavior of the aquifer and springs due to this magnitude of flux change. Brendecke (p 6-8) concludes that "Relatively minor changes in ESPAM2.1 conceptualization, made to more closely reflect the local conditions at Rangen, result in model predictions that differ substantially from those of ESPAM2.1." The proposed 'minor changes in model conceptualization' are not in any sense minor.

Table 6.1 of Brendecke's report shows what he characterizes as "...model predictions that differ substantially from those of ESPAM2.1." This table shows the comparison of ESPAM2.1 and two alternative models which predict the impact of curtailment using the unjustified and technically inappropriate "trimline". The spring flow predictions presented in Table 6.1 range from 0.01-0.21 cfs. These flow amounts would be extremely difficult to measure in the field and are very likely under the predictive precision of the model. Brendecke's statement that his alternative model produces 5% of the ESPAM2.1 result is misleading. The change is small in volume, and the result was primarily due to the number of acres curtailed. The alternative model curtailed 24 acres compared to 406 acres curtailed using ESPAM2.1. In addition, model runs using Brendecke's alternative model showed virtually no difference from ESPAM2.1 predictions of Rangen Spring flow when using a full ESPA curtailment. The alternative model presented by Brendecke actually further verifies that the ESPAM2.1 model is an accurate and appropriate predictor of impacts to Rangen Spring flow from regional junior ground water pumping.

The alternative models proposed by Brendecke confirm the results of ESPAM 2.1. Table 1 shows the results and comparison of curtailment model runs utilizing ESPAM 2.1 and alternative Models #3 and #8. All three of the models were run to determine the simulated impact on Rangen Spring from curtailment of ground water rights in the ESPA junior to July 13, 1962, IDWR procedures and protocol were use for all three model runs with the models run in steady state and superposition model. Table 1 indicates that the steady state response at Rangen Spring not significantly different for any of the three models. If anything, the ESPAM 2.1 model is conservative in its prediction of the curtailment response to Rangen.

Table 1 July 13, 1962 superposition, steady state, full curtailment results from ESPAM 2.1, AMEC-3, and AMEC-8

Model	Steady State Response at Rangen (cfs)
ESPAM 2.1	17.9 cfs
AMEC-3	18.5 cfs
AMEC-8	18.0cfs

Determination of selected contributing model cells for the alternative models illustrate the irrational nature of arbitrarily eliminating model cells from inclusion in the contributing aquifer area for springs.

Table 2 shows a comparison of response functions to Rangen (Cell No. 42, 13). Model cells listed were identified by IDWR as the contributing model cells to Rangen Springs for Scoping Calculations evaluated for ESPAM 2.0. Cells with a more than 0.5% change in the response functions as determined by the different models are highlighted.

Table 2 Response of Rangen Spring to Pumping at Various Model Cells (Response Functions)

Model Cell	ESPAM 2.1	AMEC-3	AMEC-8
40, 13	9.5%	9.7%	9.5%
41, 13	10.5%	10.7%	10.4%
41, 14	9.5%	9.7%	9.5%
42, 12	11.6%	8.2%	10.1%
42, 13	16.0%	15.9%	15.5%
42, 14	10.7%	10.8%	10.5%
43, 13	9.5%	9.1%	9.1%

Table 2 shows that only one model cell (42, 12) shows a significant difference in the percentage of contribution from any of the seven model cells identified by IDWR as contributing cells. Cell 42, 12 is the cell down-gradient of the Rangen Spring and down-gradient of the hydraulic barrier inserted in alternative models #3 and #8 by Brendecke. Again, there is no basis for the selection of non-contributing cells proposed as the 10% criteria for exclusion was identified by IDWR for ESPAM 1.1 because of potential errors in the Snake River Gage readings.

Therefore, when the AMEC alternative model output is taken as a whole (with and without the application of a trim line), it actually indicates that it is only the trim line method that has an unacceptably large arbitrary and uncertain behavior, and it indicates that the ESPAM 2.1 base model is robust and stable in terms of the relationship between pumping stresses and spring flows. All the alternative model output provided by AMEC used a trimline. When compared to ESPAM 2.1 output using a trimline, Brendecke showed wide variations in the results. However, this is an artifact of a trimline approach that excludes all but a tiny fraction of the original model results. As commonly known by engineers and scientists, comparing two very small numbers at the limits of the precision of the system can create an appearance of variability and uncertainty. On the other hand, as shown above, when comparing the full AMEC alternative model output to the full ESPAM 2.1 model output without a trimline, there is still very good agreement on the impacts of junior pumping on Rangen Spring flows.

IDWR (Sukow, 2012) performed an evaluation of model linearity and the appropriateness of using a superposition model.

"The superposition version of the model is expected to be acceptable for simulation of curtailment of groundwater pumping, managed recharge, most ESPA water right transfers, and mitigation activities including conversions from groundwater to surface water irrigation, the Conservation Reserve Enhancement Program (CREP), and voluntary reductions in irrigation." (Sukow, 2012)

IDWR compared five different curtailment scenarios, including one with a 1/1/1961 curtailment date. They found that the difference between superposition ESPAM2.0 curtailment models and those using a fully populated model were less than 1% for the spring flow predictions. This is an indication that the non-linearity issues raised by Brendecke do not adversely affect the accuracy of the spring flow predictions and that curtailment modeling using a superposition model is appropriate.

G. Unjustified Application of the "Trim Line"

Use of any statistical parameter to limit the result of a ground water model simulation, if not justified by some recognized statistical parameter and applied in a defensible manner should not be considered. Brendeke and Sullivan consistently utilize what might be termed a one-way exclusion parameter (trimline) to limit the liability of junior ground water pumpers for mitigation of impacts to the Rangen water rights. This one-way exclusion parameter assumes that no junior ground water pumping which does not impact the Rangen Spring flow by 10% or more at steady state is not, in fact, impacting the Rangen Spring flow. Not only is the concept of a 'trimline' not hydraulically justified, the arbitrary assignment of a 10% exclusion limit is not justified by any statistically recognized procedure and certainly not by any rigorous statistical uncertainty analysis. We are not aware of any statistics textbook or publication which even mentions the term 'trimline'.

To infer or conclude that any deferred pumping as a result of curtailment of junior ground water pumping that does not benefit the calling spring or target spring is 'waste' implies a short-sighted view of the ESPA system. Granted that target curtailment for mitigation is not efficient, however, the deferred pumping impact that shows up in adjacent springs or as Snake River reach gain is not 'wasted'. All springs and reach-gains in the ESPA/Snake River system have shown declines over the last 50 years and most of these sources either have water rights for irrigation, aquaculture, hydropower, or aesthetic, recreation, and wildlife purposes. Supplies for these water rights have been impacted; any increases in these sources can be beneficially utilized and are therefore not 'wasted'.

Brendecke's assertion that the 'uncertainty derives from use of a regional model to predict discharge from a particular spring outlet at the edge of the aquifer system' is an erroneous assumption. ESPAM2.1 is a regional model and calibration of target springs shows that it is capable of adequately simulating spring flow responses from regional changes in water use (Appendix B, BCB report). Correlations of Rangen Spring historical discharge and other target springs with individual wells as much as 11 miles away exhibit excellent correlation coefficients (R^2) (Appendix C, BCB report). Measured seasonal discharge and testimony of the Watermaster and Rangen employees attest to the seasonal response of the springs to the commencement and cessation of irrigation on the Northside Canal lands and to ground water pumping up-gradient of the springs.

H. Conclusions and Recommendations

The overarching conclusion of this report is that nothing presented in the AMEC, Spronk, or Hinckley reports, refutes ESPAM2.1 as being the best available science for the evaluation of junior ground water pumping impacts at the Rangen Spring. The results of ESPAM2.1 modeling indicate that a full ESPA curtailment of junior ground water pumping would be a hydrologically feasible mitigation of the impact to Rangen Spring.

Nothing presented in the aforementioned reports changes the opinions originally presented in our BCB report. Our opinions contained in this report are summarized as follows:

1. Pumping by junior ground water rights impacts the exercise of Rangen water rights 36-02551 (priority July 13, 1962) and 36-07694 (priority April 12, 1977).
2. There is insufficient spring flow available to operate the Rangen facility and that the available Rangen Spring flows are being utilized appropriately and efficiently according to the adjudicated water rights. There is no evidence of wasted water.
3. Rangen staff historical measurements have been collected accurately.
4. Historical measurements are adequate for use as calibration target data for ESPAM2.1.
5. The source of ESPA water for Rangen's water rights includes flow from the Martin-Curren Tunnel and the talus slope below it.
6. Rangen's water rights are decreed as springs and not as a well or wells.
7. Rangen's diversion structures are efficient and appropriate for aquaculture use of water.
8. Use of water within Rangen's system is in accordance with standard aquaculture practices.
9. The geologic interpretations presented by Hinckley are not applicablelapplicable when evaluating ESPAM2.1's ability to predict the impact of junior ground water pumping on the Rangen Spring.
10. The geologic interpretations of Hinckley are hypothetical and rely on sparse data which is inappropriately used in some cases.
11. ESPAM2.1 has been developed in an open and peer reviewed manner to have appropriate simplifications and assumptions that result in accurate predictions of the impact of junior ground water pumping on the Rangen Spring.
12. IDWR has appropriately designed ESPAM2.1 and that, according to IDWR model documentation, *"...the model was optimized for prediction of hydrologic impacts to the river and to Group A and B springs."* Rangen is a group B spring.
13. IDWR has demonstrated that the superposition version of ESPAM2.1 is accurate for curtailment scenarios and that there is very little difference in the superposition and fully populated model results.
14. The "trimline" has no technical justification and should not be applied.
15. The best estimate of impact of junior ground water pumping on the Rangen Spring is the unaltered output of ESPAM2.1.
16. The similarities between the results from alternative models presented by Brendecke and results from ESPAM 2.1 prove that ESPAM2.1 is a robust model. Even when inappropriate changes are made to the conceptualization of the model, it predicts virtually the same Rangen Spring response to full ESPA curtailment of junior ground water pumping.
17. The alternative model results also point out that it is the arbitrary and technically unjustified application of a "trimline" that causes variability in predictions of Rangen Spring flow impacts.

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Appendix

Water Quality Monitoring of Billingsley Creek Head Water and Lower Tunnel Slope

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where S is defined as follows:

$$S = \frac{a_2 \sqrt{H_2}}{a_1 \sqrt{H_1}} \tag{5-52}$$

In Eq. (5-52), a_2 is the weir area corresponding to H_2 and a_1 is the weir area corresponding to H_1. Mavis also presented some interesting data which resulted from tests made in 1717 by Poleni. It was found that Poleni's results agreed within 2 to 4 per cent with the Mavis data.

The author has plotted the curves shown in Fig. 5-5 based on the results of the work of Villemonte and Mavis. Information regarding the experimental arrangements for the 90° V-notch weirs and rectangular weirs is given in the following table. It may be noted that the channel widths differed for the two

	Mavis	Villemonte		
Channel width........	4 ft 0 in.	3.02 ft		
P for 90° V-notch weirs	1 ft 6 in.	2.0 ft		
P for rectangular weirs	1 ft 10 in.	2.0 ft	1.0 ft	1.25 ft
Widths of notches of rectangular weirs...	1 ft 3 in.	3.02 ft	0.5 ft	1.00 ft

sets of tests, that P was different for all cases, and that rectangular weirs of four different widths were tested. Curves 1 and 2 are composite curves based on the results of the two investigators for the 90° V-notch weirs and the rectangular weirs, respectively. Curves 1 and 2 differ by no more than 1 per cent from the test results.

Because Eqs. (5-50) and (5-51) both indicate that Q/Q_1 is a function of $(H_2/H_1)^n$, the author has prepared curve 3, which is an average of results obtained from Eqs. (5-50) and (5-51). Results obtained from either equation differ by less than 1 per cent from curve 3. Curve 3 may be used to compute the discharge of a submerged sharp-crested weir of any shape. This curve is also in reasonable agreement with the results of the investigations summarized by Vennard and Weston, as well

as with data presented by Stevens.[1] It should be noted, however, that for some of the weirs tested, the results could be represented more closely by an equation differing slightly from Eqs. (5-50) and (5-51) and by a curve differing slightly from curves 1 to 3. Therefore, if great accuracy is essential, it is recommended that the particular weir, or a similar one, be tested in a laboratory under conditions comparable with field conditions. In using the curves shown in Fig. 5-5, it is recommended that H_1 be measured at least $2.5H_1$ upstream from the weir and that H_2 be measured beyond the turbulence caused by the nappe.

Example 5-4. Determine the discharge of a 90° V-notch weir if H_1 is 0.9 ft, H_2 is 0.3 ft, and $Q_1 = 2.5H_1^{2.5}$.

a. Use curve 1 of Fig. 5-5.

$$Q_1 = 2.5 \times 0.9^{2.5} = 1.92 \text{ sec-ft}$$
$$\frac{H_2}{H_1} = \frac{0.3}{0.9} = 0.333$$
$$\frac{Q}{Q_1} = 0.972 \text{ (from curve 1)}$$
$$Q = 0.972 \times 1.92 = 1.86 \text{ sec-ft}$$

b. Use curve 3 of Fig. 5-5.

$$\left(\frac{H_2}{H_1}\right)^n = (0.333)^{2.5} = 0.064$$
$$\frac{Q}{Q_1} = 0.972 \text{ (from curve 3)}$$
$$Q = 0.972 \times 1.92 = 1.86 \text{ sec-ft}$$

Example 5-5. Determine the discharge of a parabolic weir if H_1 is 0.8 ft, H_2 is 0.4 ft, and $Q_1 = 2.0H_1^{2.0}$.

$$Q_1 = 2.0 \times (0.8)^{2.0} = 1.28 \text{ sec-ft}$$
$$\left(\frac{H_2}{H_1}\right)^n = \left(\frac{0.4}{0.8}\right)^{2.0} = 0.25$$
$$\frac{Q}{Q_1} = 0.89 \text{ (from curve 3)}$$
$$Q = 0.89 \times 1.28 = 1.14 \text{ sec-ft}$$

Weirs Not Sharp-crested

Sharp-crested weirs, if used to obtain discharge records for comparatively long periods, are difficult to maintain. The

[1] J. C. Stevens, Experiments on Small Weirs and Modules, *Eng. News*, Aug. 18, 1910.

crest is likely to become dulled or rusted, or it may be damaged by floating ice and debris. Under such conditions it may be advisable to use a weir with a thicker crest. It is often convenient to use an existing weir or overflow dam for measuring discharges. Weirs of various dimensions and shapes are used in hydraulic structures. When designing such structures it is important to be able to estimate approximately the discharges over these weirs (p. 2-15).

The amount of water which will pass over a weir, not sharp-crested, depends to a large extent upon its sectional form and the shape of its crest, and it is necessary to resort to experiment to determine the discharge over any particular shape. Inasmuch as the number of shapes of weirs is unlimited, it is not to be expected that experimental data are or ever will be available for them all. There are available, however, the results of several series of experiments on weirs of different cross sections which furnish much valuable information for determining discharges over weirs of the same or similar shapes.

The available experiments are not extensive enough for a comprehensive study of the effect of velocity of approach on weirs not sharp-crested. The coefficients given in this chapter probably apply more accurately where the velocity of approach is not high. From a consideration of sharp-crested weirs it appears that discharges, for high velocities of approach, will be somewhat greater than is given by formula (5-10).

Since experimental conditions will seldom be duplicated in practice, it is probable that errors may result from the general use of the coefficients given in this chapter. Extreme accuracy, however, is not always necessary in design, where uncertainty as to the exact quantity of water to be provided for may exist.

The problem of establishing a fixed relation between head and discharge, for weirs not sharp-crested, is complicated by the fact that the nappe may assume a variety of forms in passing over the weir. For each modification of nappe form, there is a corresponding change in the relation between head and discharge. The effect of this condition is more noticeable for low heads.

The nappe may undergo several of these modifications in succession as the head is varied. The successive forms that appear with an increasing stage may differ from those pertaining to similar stages with a decreasing head. The head at which the changes of nappe form occur varies with the rate of

change of head, whether increasing or decreasing, and with other conditions.

Among weirs of irregular section there is a large class for which, from the nature of their section, the nappe can assume only one form unless drowned. Such weirs, it is suggested, may, if properly calibrated, equal or exceed the usefulness of the thin-edged weir for purposes of stream gaging, because of their stability of section and because the thin-edged weir is not free from modification of nappe form for low heads.

Broad-crested Weirs. A weir approximately rectangular in cross section is termed a broad-crested weir. Unless otherwise noted, it will be assumed to have vertical faces, a plane level

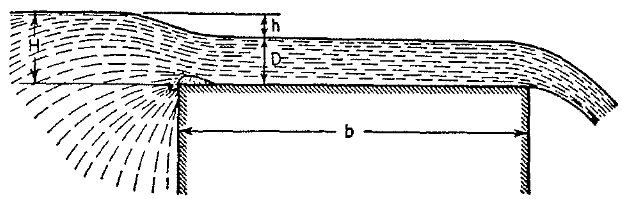

FIG. 5-6. Broad-crested weir.

crest, and sharp right-angled corners. Figure 5-6 represents a broad-crested weir of breadth b. The head H should be measured at least $2.5H$ upstream from the weir. Because of the sharp upstream edge, contraction of the nappe occurs. Surface contraction begins at a point slightly upstream from the weir.

The discharge over broad-crested weirs is usually expressed by the equation

$$Q = CLH^{3/2} \tag{5-10}$$

Experiments on broad-crested weirs have been performed by Blackwell, Bazin, Woodburn, the U.S. Deep Waterways Board, and the U.S. Geological Survey. These experiments cover a wide range of conditions as to head, breadth, and height of weir. Considerable discrepancy exists in the results of the different experimenters, especially for heads below 0.5 ft. For heads from 0.5 to about 1.5 ft the coefficient becomes more uniform, and for heads from 1.5 ft to that at which the nappe becomes detached from the crest, the coefficient as given by the different experiments is nearly constant and equals approximately 2.63.

When the head reaches one to two times the breadth, the nappe becomes detached and the weir becomes essentially sharp-crested. The effect on discharge of roughness of the crest can be computed by applying the principles of flow in open channels.

In order to put the results of the various experiments in a form convenient for use, Table 5-3 has been prepared by graphically interpolating the results of all experiments, giving more weight to those of the U.S. Geological Survey. This table should give values of C within the limits of accuracy of the original experiments. Table 5-1 gives three-halves powers of numbers.

The effect of rounding the upstream corner of a broad-crested weir is to increase the discharge for a given head. Table 5-4 gives a résumé of experiments on this type of weir. The effect of rounding the upstream corner on a radius of 4 in. is to increase the coefficient C approximately 9 per cent. Coefficients by Woodburn[1] for flat weirs with rounded upstream corners and gently sloping crests are given in Table 5-5*a*.

Blackwell experimented with three weirs 3.0 ft broad having a slightly inclined crest. Inclining the crest appears slightly to increase the coefficient of discharge. The results of these experiments are rather inconsistent, especially for low heads. Table 5-5*b* has been obtained from Blackwell's experiments. Sloping the top of a broad-crested weir makes it similar to a triangular weir with the upstream face vertical. The coefficients given in Tables 5-6 and 5-7 will therefore be helpful in selecting coefficients for broad-crested weirs with sloping crests.

If the upstream corner of a weir is so rounded as entirely to prevent contraction, and if the slope of the crest is as great as the loss of head due to friction, flow occurs at critical depth, and discharge is given by the rational formula

$$Q = 3.087 L H^{3/2} \qquad (5\text{-}53)$$

For further discussion of flow at critical depth, see Sec. 8. It should be noted that $C = 3.087$ is the maximum value of the coefficient that is obtainable for broad-crested weirs under any conditions.

Weirs of Triangular Section. Figure 5-7 represents the cross section of a weir having the upper face vertical and the lower

[1] J. G. Woodburn, Tests on Broad Crested Weirs, *Trans. ASCE*, vol. 96, 1932.

face inclined downward, the two faces meeting in a sharp angle which forms the crest.

Bazin has experimented with weirs of this type, 2.46 ft high, having various slopes of the downstream face. The coefficients resulting from those experiments are given in Table 5-6.

It will be observed that the coefficient for a given slope, in each case shown by the experiments, is nearly constant for heads above 0.7 ft. It seems fair to assume, therefore, that these values could be extended to higher heads with reasonable assurance. The average values of the coefficients given in

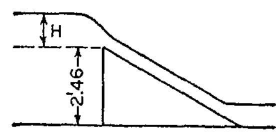

FIG. 5-7. Triangular weir.

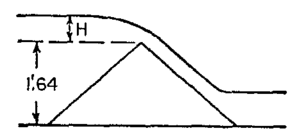

FIG. 5-8. Triangular weir.

Table 5-6, for heads above 0.7 ft, were plotted logarithmically and found to fall very accurately on a straight line. This line was then extended to include slopes of 20 horizontal to 1 vertical, from which the values given in Table 5-7 were taken. Table 5-7 may be used for computing discharges over weirs of the types shown in Fig. 5-7 for heads above 0.7 ft. These coefficients are to be used for broad-crested weirs with inclined tops only when the breadth is sufficient to prevent the nappe from springing clear. In the latter case the weir becomes in principle a thin-edged weir.

Bazin also experimented with weirs of triangular cross sections 1.64 ft high, having both faces inclined (Fig. 5-8). Coefficients covering the range of these experiments are given in Table 5-8.

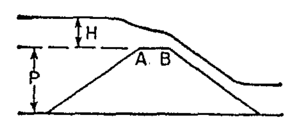

FIG. 5-9. Trapezoidal weir.

Weirs of Trapezoidal Section. Figure 5-9 represents a weir of trapezoidal section with both upstream and downstream faces inclined. Experiments on this type of weir were made by Bazin and the U.S. Deep Waterways Board. Bazin's experiments were all on weirs 2.64 ft high, the breadth of crest AB varying from 0.66 to 1.32 ft. Experiments on two

Table 5-3. Values of C in the Formula $Q = CLH^{3/2}$ for Broad-crested Weirs

Measured head in feet, H	Breadth of crest of weir in feet										
	0.50	0.75	1.00	1.50	2.00	2.50	3.00	4.00	5.00	10.00	15.00
0.2	2.80	2.75	2.69	2.62	2.54	2.48	2.44	2.38	2.34	2.49	2.68
0.4	2.92	2.80	2.72	2.64	2.61	2.60	2.58	2.54	2.50	2.56	2.70
0.6	3.08	2.89	2.75	2.64	2.61	2.60	2.68	2.69	2.70	2.70	2.70
0.8	3.30	3.04	2.85	2.68	2.60	2.60	2.67	2.68	2.68	2.69	2.64
1.0	3.32	3.14	2.98	2.75	2.66	2.64	2.65	2.67	2.68	2.68	2.63
1.2	3.32	3.20	3.08	2.86	2.70	2.65	2.64	2.67	2.66	2.69	2.64
1.4	3.32	3.26	3.20	2.92	2.77	2.68	2.64	2.65	2.65	2.67	2.64
1.6	3.32	3.29	3.28	3.07	2.89	2.75	2.68	2.66	2.65	2.64	2.63
1.8	3.32	3.32	3.31	3.07	2.88	2.74	2.68	2.66	2.65	2.64	2.63
2.0	3.32	3.31	3.30	3.03	2.85	2.76	2.72	2.68	2.65	2.64	2.63
2.5	3.32	3.32	3.31	3.28	3.07	2.89	2.81	2.72	2.67	2.64	2.63
3.0	3.32	3.32	3.32	3.32	3.20	3.05	2.92	2.73	2.66	2.64	2.63
3.5	3.32	3.32	3.32	3.32	3.32	3.19	2.97	2.76	2.68	2.64	2.63
4.0	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.70	2.64	2.63
4.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.74	2.64	2.63
5.0	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.64	2.63
5.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.64	2.63

Table 5-4. Values of C in the Formula $Q = CLH^{3/2}$ for Models of Broad-crested Weirs with Rounded Upstream Corner

Name of experimenter	Radius of curve in feet	Breadth of weir in feet, B	Height of weir in feet, P	Head in feet, H									
				0.4	0.6	0.8	1.0	1.5	2.0	2.5	3.0	4.0	5.0
Bazin	0.33	2.62	2.46	2.93	2.97	2.98	3.01	3.04					
Bazin	0.33	6.56	2.46	2.70	2.82	2.87	2.89	2.92					
U. S. Deep Waterways	0.33	2.62	4.57	....	2.77	2.80	2.83	2.92	3.00	3.08	3.17	3.34	3.50
U. S. Deep Waterways	0.33	6.56	4.56	....	....	2.83	2.83	2.83	2.82	2.82	2.82	2.82	2.81

Table 5-5. Values of C in the Formula $Q = CLH^{3/2}$ for Broad-crested Weirs with Crests Inclined Slightly Downward

(a)

Crest	Energy head = H_e								
	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.5
Level	2.78	2.79	2.80	2.81	2.82	2.83	2.85	2.85	2.85
Slope = 0.004	2.95	2.94	2.93	2.92	2.91	2.90	2.88	2.87	2.87
Slope = 0.026	3.07	3.06	3.05	3.04	3.03	3.02	3.00	2.99	

(b)

Slope of crest	Length of weir in feet	Head in feet, H						
		0.1	0.2	0.3	0.4	0.5	0.6	0.7
12 to 1	3.0	2.58	2.87	2.57	2.60	2.84	2.81	2.70
18 to 1	3.0	2.91	2.92	2.53	2.60	2.80	2.74	2.62
18 to 1	10.0	2.52	2.68	2.73	2.80	2.90	2.80	2.68

Table 5-6. Values of C in the Formula $Q = CLH^{3/2}$ for Weirs of Triangular Cross Section with Vertical Upstream Face and Sloping Downstream Face

Slope of down-stream face	Height of weir in feet, P	Head in feet, H										
		0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.5
Hor. Vert.												
1 to 1	2.46	3.88	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85
2 to 1	2.46	3.48	3.48	3.49	3.49	3.50	3.50	3.50	3.50	3.50	3.51	3.51
2 to 1	1.64	3.56	3.47	3.47	3.51	3.54	3.57	3.58	3.58	3.58	3.59	3.57
3 to 1	1.64	....	2.90	3.11	3.22	3.26	3.33	3.37	3.40	3.40	3.41	3.41
5 to 1	2.46	....	3.08	3.06	3.05	3.05	3.07	3.09	3.12	3.13	3.13	3.13
10 to 1	2.46	....	2.82	2.83	2.84	2.86	2.89	2.90	2.91	2.91	2.92	2.93

Table 5-14. Errors in Weir Discharge Resulting from Errors in Measurement of Head

Discharge in second-feet Q	Error in head in feet	Weir 1 ft. long		Weir 2 ft. long		Weir 5 ft. long		Weir 10 ft. long		Right-angled V-notch wier	
		Head	Per cent. error in Q	Head	Per cent. error in Q	Head	Per cent. error in Q	Head	Per cent. error in Q	Head	Per cent. error in Q
0.05	0.001	0.06	2.6	0.04	4.0	0.02	8.0	0.01	12.0	**0.20**	**1.2**
	0.005		13.2		21.2		41.0		68.0		**6.1**
	0.010		26.6		43.6		85.0		144.0		**12.2**
0.10	0.001	0.09	1.6	0.06	2.6	0.03	5.0	0.02	8.0	**0.27**	**0.9**
	0.005		8.1		13.2		25.0		41.0		**4.6**
	0.010		16.4		26.6		51.5		85.0		**9.1**
0.50	0.001	**0.27**	**0.5**	0.17	0.9	0.09	1.6	0.06	2.6	**0.52**	**0.5**
	0.005		**2.7**		4.3		8.1		13.2		**2.4**
	0.010		**5.5**		8.7		16.4		26.6		**4.8**
	0.050		**27.3**		45.7		89.5				**23.8**
1.00	0.001	0.44	0.3	**0.27**	**0.5**	0.15	1.0	0.09	1.6	**0.69**	**0.4**
	0.005		1.7		**2.7**		5.0		8.1		**1.8**
	0.010		3.4		**5.5**		10.1		16.4		**3.6**
	0.050		17.0		**27.3**		53.6		89.5		**18.0**
2.50	0.001	0.82	0.2	**0.51**	**0.3**	**0.27**	**0.5**	0.17	0.9	**1.00**	**0.3**
	0.005		0.9		**1.5**		**2.7**		4.3		**1.2**
	0.010		1.8		**3.6**		**5.5**		8.7		**2.5**
	0.050		9.1		**14.7**		**27.3**		45.7		**12.4**
5.00	0.001	1.32	0.1	0.82	0.2	**0.44**	**0.3**	**0.27**	**0.5**	**1.32**	**0.2**
	0.005		0.6		0.9		**1.7**		**2.7**		**0.9**
	0.010		1.1		1.8		**3.4**		**5.5**		**1.9**
	0.050		5.6		9.1		**17.0**		**27.3**		**9.3**
10.00	0.001	2.11	0.1	1.32	0.1	**0.71**	**0.2**	**0.44**	**0.3**	**1.75**	**0.1**
	0.005		0.4		0.6		**1.1**		**1.7**		**0.7**
	0.010		0.7		1.1		**2.1**		**3.4**		**1.5**
	0.050		3.5		5.6		**10.6**		**17.0**		**7.3**
25.00	0.001	3.93	0.1	2.45	0.1	**1.32**	**0.1**	**0.82**	**0.2**	2.53	0.1
	0.005		0.2		0.3		**0.6**		**0.9**		0.5
	0.010		0.4		0.6		**1.1**		**1.8**		1.0
	0.050		1.8		3.0		**5.6**		**9.1**		5.0

HANDBOOK OF HYDRAULICS,
BRATER & KING
FIFTH EDITION 1963

Broad-Crested Weir Coefficients

Broad-Crested Weir Coefficient C Values As A Function Of Weir Crest Breadth And Head

Measured Head, H[1] (mm)	Breadth Of The Crest Of Weir (m)										
	0.15	0.23	0.3	0.45	0.60	0.75	0.90	1.20	1.50	3.00	4.50
60	2.80	2.75	2.69	2.62	2.54	2.48	2.44	2.38	2.34	2.49	2.68
120	2.92	2.80	2.72	2.64	2.61	2.60	2.58	2.54	2.50	2.56	2.70
180	3.08	2.89	2.75	2.64	2.61	2.60	2.68	2.69	2.70	2.70	2.70
240	3.30	3.04	2.85	2.68	2.60	2.60	2.67	2.68	2.68	2.69	2.64
300	3.32	3.14	2.98	2.75	2.66	2.64	2.65	2.67	2.68	2.68	2.63
360	3.32	3.20	3.08	2.86	2.70	2.65	2.64	2.67	2.66	2.69	2.64
420	3.32	3.26	3.20	2.92	2.77	2.68	2.64	2.65	2.65	2.67	2.64
480	3.32	3.29	3.28	3.07	2.89	2.75	2.68	2.66	2.65	2.64	2.63
240	3.32	3.32	3.31	3.07	2.88	2.74	2.68	2.66	2.65	2.64	2.63
600	3.32	3.31	3.30	3.03	2.85	2.76	2.27	2.68	2.65	2.64	2.63
750	3.32	3.32	3.31	3.28	3.07	2.89	2.81	2.72	2.67	2.64	2.63
900	3.32	3.32	3.32	3.32	3.20	3.05	2.92	2.73	2.66	2.64	2.63
1,050	3.32	3.32	3.32	3.32	3.32	3.19	2.97	2.76	2.68	2.64	2.63
1,200	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.70	2.64	2.63
1,350	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.74	2.64	2.63
1,500	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.64	2.63
1,650	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.64	2.63

Measured Head, H[1] (ft)	Breadth Of The Crest Of Weir (ft)										
	0.50	0.75	1.00	1.50	2.00	2.50	3.00	4.00	5.00	10.00	15.00
0.2	2.80	2.75	2.69	2.62	2.54	2.48	2.44	2.38	2.34	2.49	2.68
0.4	2.92	2.80	2.72	2.64	2.61	2.60	2.58	2.54	2.50	2.56	2.70
0.6	3.08	2.89	2.75	2.64	2.61	2.60	2.68	2.69	2.70	2.70	2.70
0.8	3.30	3.04	2.85	2.68	2.60	2.60	2.67	2.68	2.68	2.69	2.64
1.0	3.32	3.14	2.98	2.75	2.66	2.64	2.65	2.67	2.68	2.68	2.63
1.2	3.32	3.20	3.08	2.86	2.70	2.65	2.64	2.67	2.66	2.69	2.64
1.4	3.32	3.26	3.20	2.92	2.77	2.68	2.64	2.65	2.65	2.67	2.64
1.6	3.32	3.29	3.28	3.07	2.89	2.75	2.68	2.66	2.65	2.64	2.63
1.8	3.32	3.32	3.31	3.07	2.88	2.74	2.68	2.66	2.65	2.64	2.63
2.0	3.32	3.31	3.30	3.03	2.85	2.76	2.27	2.68	2.65	2.64	2.63
2.5	3.32	3.32	3.31	3.28	3.07	2.89	2.81	2.72	2.67	2.64	2.63
3.0	3.32	3.32	3.32	3.32	3.20	3.05	2.92	2.73	2.66	2.64	2.63
3.5	3.32	3.32	3.32	3.32	3.32	3.19	2.97	2.76	2.68	2.64	2.63
4.0	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.70	2.64	2.63
4.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.74	2.64	2.63
5.0	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.64	2.63
5.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.64	2.63

[1]Measured at least 2.5H upstream of the weir.

Reference: Brater and King (1976).

BROAD CRESTED WEIR COEFFICIENTS

AS A FUNCTION OF WEIR THICKNESS AND HEAD

Brater, E. F. and H. W. King, 1976, *Handbook of Hydraulics*, 5th ed., New York
McGraw Hill Book Company Table 5.3