CUMULATIVE HYDROLOGIC IMPACT ASSESSMENTS ON SURFACE-WATER IN NORTHEASTERN WYOMING USING HEC-1; A PILOT STUDY[1]

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Abstract: The Surface Mining Control and Reclamation Act of 1977 requires that areas in which multiple mines will affect one watershed be analyzed and the cumulative impacts of all mining on the watershed be assessed. The purpose of the subject study was to conduct a cumulative hydrologic impact assessment (CHIA) for surface-water on a watershed in northeastern Wyoming that is currently being impacted by three mines. An assessment of the mining impact's affect on the total discharge of the watershed is required to determine whether or not material damage to downstream water rights is likely to occur as a result of surface mining and reclamation. The surface-water model HEC-1 was used to model four separate rainfall-runoff events that occurred in the study basin over three years (1978-1980). Although these storms were used to represent pre-mining conditions, they occurred during the early stages of mining and the models were adjusted accordingly. The events were selected for completeness of record and antecedent moisture conditions (AMC). Models were calibrated to the study events and model inputs were altered to reflect post-mining conditions. The same events were then analyzed with the new model inputs. The results were compared with the pre-mining calibration. Peak flow, total discharge and timing of flows were compared for pre-mining and post-mining models. Data were turned over to the State of Wyoming for assessment of whether material damage to downstream water rights is likely to occur.

Additional Key Words: reclamation, coal mining, modeling, ephemeral, Powder River Basin, Little Thunder Creek.

Introduction

CHIA

The Powder River Coal Basin in northeastern Wyoming contains some of the most abundant coal reserves in the world. The eastern and most active portion of that coal basin lies primarily in Campbell and Converse Counties, which have been undergoing large-scale mining activity. A 1994 assessment indicated that 18 surface-coal mines were active in the eastern Powder River coal basin (Vogler et al., 1995). The expected recovery of coal from the areas leased to the mines is nearly seven (7) billion tons of coal (Vogler et al., 1995). Areal extent of the leases of the mines ranges from approximately 900 to 13,000 acres with an average lease of 7,345 acres per mine (Vogler et al., 1995). These figures do not include possible future leases and westward expansion of the mines.

Mining of this extent and magnitude in an area require special analyses to determine the potential impacts of mining on the hydrologic regime of the area. The Surface Mining Control and Reclamation Act, United States Public Law 95-87 (SMCRA) requires that the involved states and parties complete an "assessment of the probable cumulative impact of all anticipated mining in the area to the hydrologic balance specified in section 507(b) (ii). The regulatory authority and the proposed operations are required to be designed to prevent material damage to the hydrologic balance outside the permit area; [SMCRA sec..510(b)(3)]." The State of Wyoming Department of Environmental Quality / Land Quality Division (DEQ/LQD) has the responsibility to satisfy the requirements of the Wyoming Environmental Quality Statutes, and the Wyoming Department of Environmental Quality, Land Quality Division 1996 Rules and Regulations. Chapter 1, Section (b-d) states

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"Material damage to the hydrologic balance" means a significant long-term or permanent adverse change to the hydrologic regime."

The interpretation of this idea that guided the development of the CHIA was that material damage is most likely to occur as a result of disturbances to water rights in the impacted water supplies. The result of that interpretation is that the surface-water modelling efforts associated with the CHIA have centered on determining possible impacts to the quantity of surface-water available to downstream users.

Little Thunder Creek Pilot Study

In 1994, it was determined that one drainage basin, should be studied in considerable detail to determine the most appropriate approach to modeling potential impacts for all the drainages in the Powder River Basin. This area, known as the pilot study area, consisted of the Little Thunder Creek Drainage.

The Little Thunder Creek Drainage in the south-central portion of the Powder River Basin (Figure 1) is approximately 250 square miles in size and is being affected by three surface coal mines. The purpose of this study was to assess the best methods of modeling the impacts of surface mining on the quantitiy of surface-water in the post-mining environment. Methods developed in the Little Thunder Creek Drainage and presented in this report will be applied to the remainder of the CHIA for the Powder River Basin.

The study area is considered to be semi-arid with mean annual rainfall between 11 and 12 inches (Martner, 1986; WRDS, 1992). Annual precipitation can vary widely from year to year (Apley, 1976; WRDS, 1992). Sixty to eighty percent of the annual precipitation falls between March and August, most in the form of high-intensity thunderstorms that can vary widely in intensity and duration over short distances (Schaefer, 1982). Most of the remaining precipitation (20-40%) comes in the form of snow from November - March (Martin et al., 1988; Apley, 1976; Hadley and Schumm, 1961).

The vast majority of the mapped streams in the area are ephemeral (Lowry et al., 1986; Knutson, 1982; Martin et al., 1988). There are some reaches of stream channel that intersect ground water and flow at very low rates for part of the year (Knutson, 1982; Martin et al., 1988). All other flow is in direct response to snowmelt, rainfall, or stream augmentation. Drainage patterns in the study area are almost exclusively dendritic (Knutson, 1982).

HEC-1

The surface-water modeling for the CHIA pilot study area was conducted using HEC-1 in a platform or "front end" developed by BOSS International called the Watershed Modeling System (WMS) (BOSS Int. 1996). HEC-1 is a rainfall-runoff and flood-prediction model developed by the United States Army Corps of Engineers (ACOE). HEC-1 tracks rainfall through the entire surface water system but water lost to infiltration is eliminated from the model (ACOE 1990). HEC-1 requires that the watershed be divided by the user into discrete catchments, called hydrologic response units (HRUs), that should respond to a precipitation event in a more-or-less uniform manner. The channels through those HRU's are then represented as another component of the system. HEC-1 is also capable of including reservoirs and diversion withdrawals and returning flows as components of the system. Each HRU, channel segment, reservoir, and diversion requires a unique set of descriptive parameters. A number of techniques may be used to represent any particular aspect of the hydrologic system. These techniques are generally well-known and accepted algorithms that require unique input parameters (ACOE 1990).

HEC-1 is considered to be a lumped parameter model. This type of model combines a wide range of related variables into a single parameter. Each HEC-1 parameter therefore can represent a large group of related basin or channel characteristics; hence the input parameters represent a wide range of possible conditions and are subject to interpretation based upon the best available information.

The primary output from HEC-1 is a set of hydrographs that represent the discharge at the outlet of each individual component of the system. These hydrographs are translated into graphical output by the WMS front end. The resulting graphical output is then compared to observed data to determine the accuracy of the model. It should be noted that HEC-1 was originally designed as a flood-prediction program and, as a result is designed for large flows; consequently does not always accruately predict small flows. The wide use and acceptance of this model by the hydrology profession, and the relatively small amount of data required to run HEC-1 outweighed the limitations of the model. Any model selected would be based upon certain unique assumptions and have such limitations.

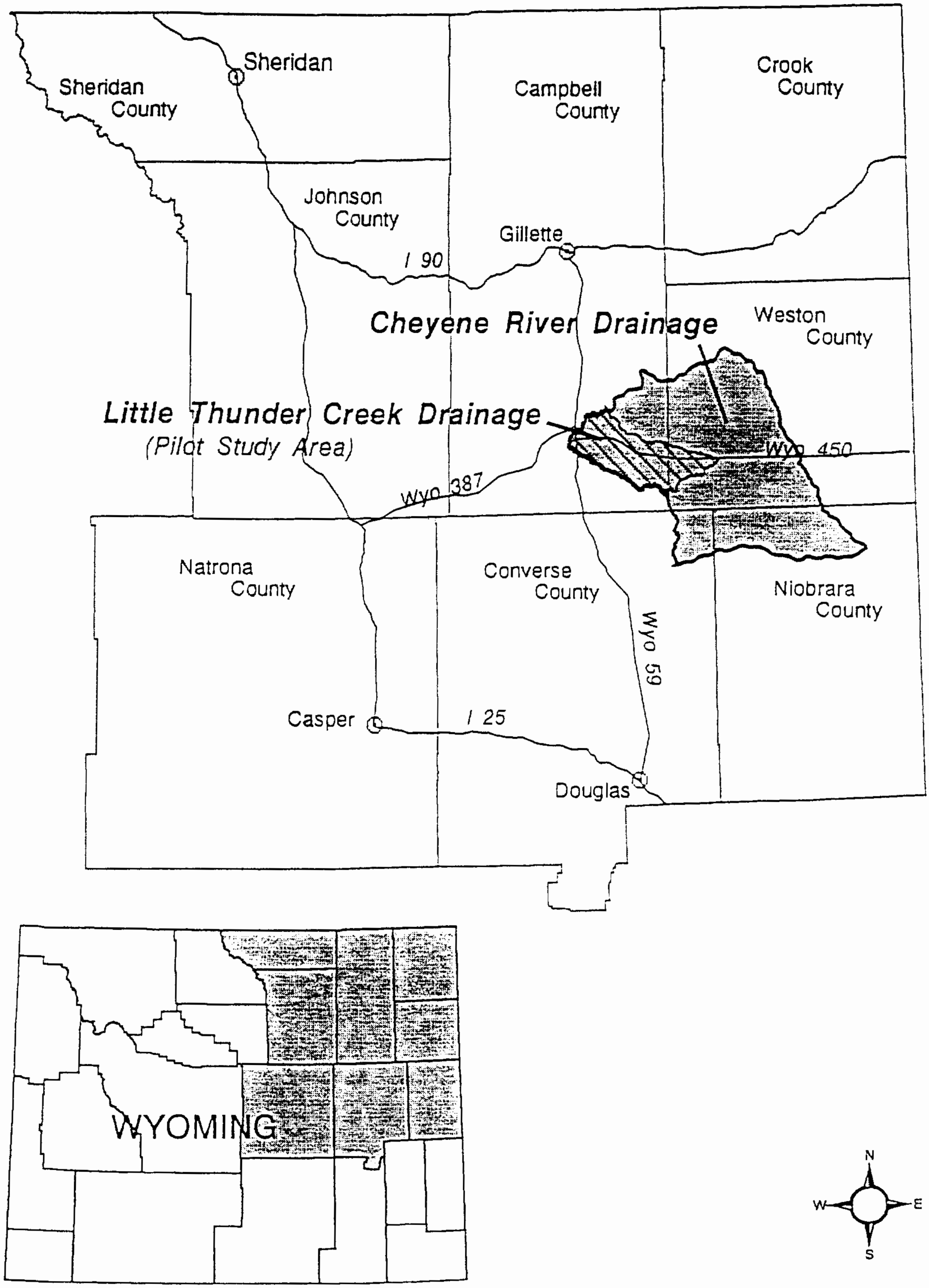

Figure 1. The counties of northeastern Wyoming that are wholly or in part within the Powder River Basin. The Little Thunder Creek pilot study area (250 mi^2) is identified as part of that portion of the Cheyenne River drainage that is included within the CHIA study area.

Methods

Data Acquistion

The acquisition and analysis of appropriate data sources for the Little Thunder Creek Drainage basin was the first and most important step in conducting the CHIA for the pilot study area. Data pertaining to the soils, vegetation, hydrography, mine permit areas, precipitation, and discharge were gathered and compiled from a variety of sources available through the Wyoming Water Resource Center's Water Resources Data System (WRDS) and Geographic Information System (GIS) Laboratory at the University of Wyoming. Data were also obtained from the Coal Permitting and Review (CPR) data base and the mine permit applications on file with the State of Wyoming DEQ / LQD.

Precipitation. The ephemeral nature of stream flow in the Little Thunder Creek watershed necessitated the acquisition of hourly precipitation and discharge data for the area. Precipitation data were gathered from gages located on mine sites in the study area as well as from National Weather Service (NWS) stations in the vicinity. Those stations recording at greater than 1 hour intervals were disregarded for purposes of determining rainfall patterns but were retained for determining total precipitation and general climatic tendencies in the surrounding areas.

Twelve precipitation stations had adequate data to be used in the pilot study. Consistency in operation varied from station to station but an adequate distribution of stations was available for at least four storms between 1978 and 1980. The hourly precipitation data of these 12 stations were analyzed and only those stations with consistent records were used to determine the total precipitation for a given storm. Hourly records for each station were used to establish the rainfall distribution through time for each HRU.

Discharge. One United States Geological Survey (USGS) continuous gage was located on the main channel of Little Thunder Creek approximately 12 miles east of the mine permits and approximately 24 river miles downstream. The hourly stage measurements for the station were obtained and converted to discharge readings using the stage-discharge rating tables for the station. The adjustments used for the daily average were applied to the hourly stage in order to determine discharge.

Model Development

Model Structure. The pilot study area was divided into 33 HRUs, based upon analysis of surficial geology, soils, vegetation, mine permit locations, gaging stations and hydrography. Hydrographic divisions based upon the mapped channel networks were used to further delineate the HRU's. Areas of uniform vegetative and soil cover were grouped within an HRU whenever possible.

The 33 HRU's identified for the Little Thunder Creek watershed include 6 that are non-contributing areas. These non-contributing areas are large enclosed playas or dry lakes. They have a unique drainage area that happens to fall entirely within the drainage of Little Thunder Creek. It is highly improbable that any of these playas would fill to the point of overflow and contribute to discharge in Little Thunder Creek. Therefore, they were removed from the model. Twenty-seven HRU's were identified that actively contributed to runoff.

The model developed for Little Thunder Creek includes only two reservoirs. The two reservoirs included in the model are large reservoirs on the main channel that were deemed to be large enough to model explicitly. These reservoirs are both present in the post-mining models. It was assumed that the parameters input for the reservoir to be removed by mining would adequately represent the terrain features that are to replace it.

Rainfall-Runoff. The U.S. Natural Resource Conservation Service (NRCS) Runoff Curve Number method was used to estimate runoff from each HRU. These numbers express a rainfall-runoff relationship for an area. A curve number of 100 represents a complete runoff of all rainfall. Lower numbers represent less runoff from an area. Incorporated in each curve number is an initial abstraction or amount of rainfall required to saturate the top of the soil and to fill surface storage. The same ground is represented by different curve numbers depending upon antecedent moisture conditions (AMC). Chow (1964) indicates that for the normal range of antecedent moisture conditions, the difference between dry (AMC I) conditions and wet (AMC III) conditions can be as large as 15 curve numbers. It should be noted that the conditions identified as AMC I, AMC II, and AMC III in this report do not correspond exactly with those described in Chow (1964). They should be read, for the remainder of this report, as expressions of the relative antecedent conditions for each of the four precipitation events in question. They do not represent the antecedent conditions described by Chow (1964) as AMCs I, II, and III.

Unit Hydrograph Method. A number of Unit Hydrograph methods are available in HEC-1. The authors chose the unit hydrograph method associated with the NRCS runoff curve numbers. This approach assigns a lag-time to each HRU. The lag-time given approximates the time that will elapse between precipitation and runoff.

Channel Routing. The Muskingum-Cunge Routing method was chosen to represent the channel components of the pilot study area. The Muskingum-Cunge method was considered to be more robust with regard to irregular channel shapes and textures (ACOE 1990). The other method that was considered was the kinematic wave method. That method requires the same input parameters as Muskingum-Cunge but was considered to be overly dependent upon regular channel shapes and conditions. The kinematic wave method is more stable at low flows and was used when necessary for areas and times of low flow or when numerical instability in the Muskingum-Cunge method became too great (ACOE 1990). Muskingum-Cunge parameters include: channel shape, channel length, channel slope, Manning's "n", and channel side slope. Greatest channel width was estimated from the width near the gage. Upstream channel widths were estimated for each channel reach relative to the decreasing contributing areas.

Storm Selection. There are 4 years during which hourly precipitation and hourly discharge are available for the pilot study area. The area is well represented during the water years of 1978-1981. However, this period represents a period of active mining in two of the three mines. Mining in the basin started around 1977. The data from 1978-1981 is being used to represent pre-mining conditions. It is assumed that the more obvious hydrologic impacts of active mining are reflected in the methodology.

Precipitation and discharge data were arranged into time series formats so that a direct comparison of the two could be made at each time stamp. The hourly records were then compared to determine which rainfall-runoff events were most likely to provide consistent, well distributed and accurate data. The events chosen were then prepared for entry into HEC-1. Four storms were chosen to represent a variety of antecedent moisture conditions (Chow 1964). Dry conditions (AMC I) were represented by a storm in early July, 1978. Wet conditions (AMC III) were represented by a storm in May of 1980. Two storms (1978-1979) were chosen to represent intermediate moisture conditions (AMC II.

Antecedent moisture conditions were determined for each storm by analyzing the daily precipitation and temperature values for a nearby meteorological station. Precipitation for the thirty days prior to the first hourly precipitation of each storm were totalled and compared to one another. These values, along with temperature data from the same 30 day period, were then used to establish the relationship between the storms with regard to antecedent moisture conditions. Antecedent conditions, along with other parameters, were then used to determine curve numbers within each catchment or hydrologic response unit (HRU).

Reservoir Impacts. Antecedent moisture condition, in conjunction with contributing area, was also used to simulate reservoir storage in each HRU. The number of reservoirs present in the drainage (as represented by water rights) was too great for each reservoir to be modeled separately. It was decided that contributing area would be adjusted to reflect the impact of reservoir storage on an HRU. The locations of water rights were plotted for each HRU. Visual analysis of these plots generated approximations of how much of the contributing area was impacted by reservoir storage. The percentage of the HRU that was impacted was estimated and applied to a formula developed for the three antecedent conditions listed in Chow (1964). The contributing area was reduced by the percentage of the area impacted by the reservoirs. During dry conditions (AMC I) the reservoirs were assumed to be 20 percent full and the amount of impacted area reduced by 20 percent. Fifty percent of capacity was assumed for intermediate conditions (AMC II) and the impacted area was reduced by 50 percent. Seventy percent of capacity was assumed for wet conditions (AMC III) and the impacted area reduced by 70 percent. Contributing area was thus reduced more for dry conditions than for wet. This method was developed to represent storage in the basin considering antecedent conditions, practicality and accuracy. It is assumed that by never reducing the impact to absolute zero and never increasing it to its maximum that the contributing area changes would reflect the effect of many small reservoirs reaching overflow at different times.

Precipitation. Precipitation was an important and flexible variable. The convective nature of most of the storms that impact the study area results in spatially and temporally inconsistent distributions of rainfall. Precipitation depth and temporal distribution was recorded at 5-7 stations within the study area for each storm. A contour map of total precipitation was developed for each storm using GIS plots of the station locations and the contouring capabilities of Surfer (Golden Software Inc 1994).

The contoured map output provided an estimation of storm totals at locations where the data was insufficient or unknown. Most HRU's had multiple contour lines or were in a large area between contour lines allowing a range of acceptable values to be developed. Acceptable values for total precipitation for each HRU were, therefore, estimated for each storm.

The time series data associated with each precipitation station were also used. The gage pattern associated with each HRU was changed between storms as our available stations changed. The choice of the appropriate gage was made based upon proximity of the gage to the HRU. This availability of multiple stations also allowed us to change precipitation patterns for an HRU if it was felt to be necessary. The distribution pattern associated with a particular gage was never altered from the raw data.

NRCS Curve Numbers. NRCS curve numbers represent a runoff pattern that takes into account a great many geomorphic parameters. The information from tables from Chow (1964) was applied to the available surficial geology, soils, and vegetation data using best professional judgment to develop specific curve numbers for each HRU. The mine permit application for the Black Thunder Coal Mine was also analyzed to obtain estimates of the appropriate range of curve numbers for the area. Analysis of the tables indicated that the land types in the Little Thunder Creek drainage would have curve numbers between 55 and 80.
The values obtained from the permit agreed with the authors' analysis of the tables in Chow (1964).

The relationship of each HRU to adjacent or similar HRU's was considered and the curve numbers assigned with these relationships in mind. It was a priority concern for the authors that the values used reflected not only a calibrated fit but the expected relationships between HRU's. HRUs expected to be high in clay soils were assigned curve numbers that were similar to other areas of clay soils but were also substantially different from areas with soils of greater infiltration capacities.

Basin Characteristics. Drainage basin characteristics were also used heavily in calibrating models. The drainage areas of each HRU remained constant throughout the calibration process associated with each storm. The procedure explained above was developed to account for small reservoir storage and antecedent moisture condition by adjusting effective contributing area for each antecedent moisture condition.

Two values associated with the shape of a hydrograph produced by an HRU were regularly used to calibrate the model. Input parameters for each HRU include a recession point and a recession constant. The recession point is the point of inflection in the hydrograph and occurs at the amount of discharge at which the HRU's runoff hydrograph begins an exponential decay. The recession constant is the exponential slope value that controls the rate of the decay. These values are almost completely unknown and were given a relatively wide range of acceptable values.

Mining in the Little Thunder Creek drainage had been initiated in 1976. Certain adjustments to the model were required to reflect the impacts of mining present in the basin at the time of the observed storms used for model calibration. Five of the twenty-seven contributing basins were estimated to have been impacted by mining activities during the time period of the calibration storms. The presence of sediment-retention ponds on these areas indicated that only large precipitation events capable of exceeding the storage capacity of the ponds would produce runoff. Contributing areas for these mined HRUs were reduced 90 percent to account for those values. The diversions built by the mines around their property were not accounted for and stream flow was modeled as if the diversions did not exist. The contributing areas of all the HRUs were returned to their actual values, antecedent storage reductions not withstanding, when generating the "pre-mining" model.

Calibration

Calibration is the process by which the initial estimates of parameters for a model are changed to better fit the observed data. Certain input parameters are not particularly variable for an individual storm and therefore remained constant through the calibration process. Other input parameters are estimates of highly variable characteristics. When values for a parameter are estimated with broad confidence intervals, it is more appropriate to adjust those values to reflect the observed data than it would be to alter parameter values that are more certain.. The greater the uncertainty and or sensitivity associated with a parameter the more likely it was to serve as a valuable calibration tool.

It was necessary to make numerous assumptions regarding the application of the surface-water model. The lumped nature of the parameters in HEC-1 requires the use of professional judgment with regard to the correct values for certain parameters. Most of the parameters used in the model take into account a variety of conditions that must be balanced against one another in choosing an appropriate value.

Process. Calibration of the model to a particular storm was largely an iterative process. The baseline estimates of each parameter were entered into the model. The output from the model was compared to the observed data. Peaks that appear in the model output could be traced up the watershed using WMS's graphical capability, and their point of origin identified. Altering the basin parameters for the HRU of origin would allow the peaks and valleys of the predicted data to be matched to the peaks and valleys of the observed data.

NRCS curve numbers were usually the first parameters to be changed. All reasonable attempts were made to stay within ranges that professional judgment deemed appropriate.

After curve numbers were optimized, total precipitation would be altered to add or subtract water from a particular HRU. Exceeding the minimum or maximum estimates for a given HRU's precipitation total was an option available during the calibration process. If too much or not enough water was available to approximate the observed hydrograph the limits were exceeded to produce an accurate calibration. Altering the amount of water that falls on an HRU was one of the most effective means of matching the predicted discharge to the observed discharge data.

Channel length and slope were held constant because hard data were available regarding those values. Manning's "n" was held constant at 0.036 because we had estimates of "n" for the region (Jensen 1994). While Jensen found large variability in the region with regard to Manning's "n" the authors used the average value found for a particular type of stream (Jensen 1994). The possibility of using Manning's "n" as a calibration variable was considered but it actually had little impact on the overall calibration of the model. Channel width was also held constant for each HRU between the storms.

Lag-time also became an important calibration tool for the model. These times were initially estimated from knowledge of the shape and size of each HRU. Increasing or decreasing the lag time allowed storm peaks to be slowed or moved up in time to better fit the observed data.

Other parameters, such as, the recession point and the recession constant were used to shape the hydrograph once the total volume was approximately correct. The adjustments to the model would be used to generate new hydrographs. Each series of new hydrographs was compared to the previous set and additional adjustments would be made to generate a better fit between the predicted and observed values, and the process would continue. A single calibration could require between 100 and 250 iterations of the process.

Goals. The goal of the calibration process was to generate a model that matched, as closely as possible, the rainfall-runoff relationships within the basin, without entering parameter values that were outside the range of feasibility. A variety of parameter inputs can be used to generate the same hydrograph at the mouth of the stream. It is entirely possible to achieve a well-matched hydrograph for the wrong reasons. During the calibrating process each parameter that was altered was bracketed by values believed by the authors to represent the minimum and maximum acceptable values for that parameter. All possible attempts were made to remain within those limits. There were times, however, when calibration was impossible without exceeding the maximum or dropping below the minimum. Judgment was also critical in maintaining what the authors believed to be the appropriate relationship between components of the system.

An arbitrary standard of accuracy was established for the models. Pre-mining models were established with the goal of being within 15 percent of the observed data with regard to peak discharge and total volume and 20 percent with respect to the timing of the peak flows. It was, of course, desirable to have models that were closer to the observed values and values of plus or minus 5-10 percent were preferred.

Validation. Four storms were calibrated to help insure that the models represented a variety of conditions and that the model adequately reflected the appropriate relationships between HRUs. Antecedent conditions for the four storms were estimated and curve numbers established for the driest and wettest storms. The remaining two storms were calibrated by keeping them between the two outside values with regard to NRCS curve numbers. It was hoped that any substantial errors in our assumptions or methods would be revealed in the process of attempting to calibrate the intermediate storms.

Post-Mining Models

Adjustments were made to the calibrated models to reflect what would have happened had the mines not been in place. The adjusted or pre-mining models were used as a baseline for comparison to post-mining models. For post-mine modelling, the baseline models were adjusted to represent the changes in the hydrologic regime that would result from mining. Both the adjustments to the calibrated model to reflect pre-mining conditions and the adjustments to the pre-mining model to reflect post-mining conditions are speculative in nature.

NRCS curve numbers were changed to reflect the post-mining environment. A general lowering of the ground surface and reduction in overall slope is expected in the post-mining environment. The infiltration rates of the post-mining soils are expected to decrease in the short term due primarily to compaction and reduced vegetative rooting and then slowly return towards a pre-mining level (Martin et al 1988). The types of changes to be made were at times contradictory with regard to the direction of change in NRCS curve numbers. The authors decided that based upon expected changes in infiltration, the overall changes in NRCS curve numbers would be small and positive. Therefore our estimates project a postmining environment of greater runoff. The developed postmining model has an increase of one curve number in all impacted HRUs.

Uncertainty exists, however, as to the direction or extent of the changes and led to additional runs of the models. The first model represents our prediction regarding the most likely post mining condition and has an increase of one curve number in the impacted HRUs. The second model predicts a decrease of one curve number in the affected areas. This bracketing operation creates a type of confidence interval for expected impacts. Similar but more widespread brackets were modeled for changes of two and three curve numbers in each direction. An extreme case scenario model was generated using a change of 4 curve numbers in both directions. It was not expected that any greater alterations in runoff would occur. This bracketing approach will allow for analysis of predicted impacts, greatest probable impacts, and worst case scenario impacts on the hydrographs generated by a given storm.

Other parameters were also changed between the pre- and post-mining models. The largest single difference was the new channel lengths that are to exist in the post mining environment. The new channel lengths and slopes, while not representing great changes, are easily documented alterations to the system. Lag-times were increase by 10 percent to account for reductions in overall slope in the reclaimed areas.

Results

The observed hydrographs and the hydrographs developed during calibration for all four storms are presented in Figure 2. Each storm represented a unique temporal and spatial distribution of rainfall. Few characteristics seemed consistent from storm to storm. The most obvious consistenct being a sharp spike early in the hydrograph and a small dip in the receding tail of the hydrograph. Modeling efforts have indicated that at least part of the early spike is associated with HRU-2, the HRU immediately above the gage.

Storm 1_78

The storm labeled 1_78 started on July 6th at 11:00 AM. It was a small flow event during one of the wettest years on record. After a large event in May, the month of June was relatively dry. Flow from the event in May, however, continued well into June. The dry weather and relatively high temperatures of June, 1978 indicated to the authors that 1_78 would be a good representative of AMC 1. The small reservoirs were treated as they would be for dry conditions and contributing areas were adjusted accordingly. The peak flow and total-volume values used to determine the accuracy of calibration and the magnitude of expected change in the post-mining environment for all four storms are given in Tables 1 and 2. Hydrographs representing the pre-mining conditions and the post-mining conditions with an increase and decrease of one NRCS curve number are presented in figure 3.

Storm 1_78 shows an unexpected increase in total volume in the model using a decrease of 1 curve number. The total-volume figures become repetitive with further decreases in the curve numbers. The low flows fo the receding limb apparently caused instability in the model and produced an unexpectedly-large peak in the receding limb of the hydrograph. This result was unexpected but not surprising. The instability of HEC-1 at low flows was a limitation of the model the authors were unable to avoid.

Storm 2_78

The storm labeled 2_78 started on July 21st at midnight. It was a large flow event that followed storm 1_78 by 15 days. The dry weather and relatively high temperatures of June, 1978 continued in the inter-storm period. The small reservoirs were treated as they would have been for intermediate conditions and contributing areas were adjusted to AMC II values. During the calibration process it became evident that some water was flowing out of the reservoirs on the main channel. In order to match the observed flow, the starting conditions for the reservoirs became part of the calibration process and were altered accordingly. The available storage of the larger reservoirs was adjusted downward from those expected of the other storms to reflect the storage from the 100 year event in May and the storm of 15 days earlier. The calibration process resulted in a general lowering of the NRCS curve numbers from original estimates. The recovery to dry conditions after storm 1_78 was more rapid than we had expected. The NRCS curve numbers are just slightly higher than those used for storm 1_78. The precipitation values generally fell outside the expected ranges with most HRUs receiving less rain than originally anticipated.

Storm 3-79

The storm labeled 3_79 started on June 25th, 1979 at midnight. It is a medium sized event of longer duration. The nature of the hydrograph is unlike the other three storms. Flows do not exhibit the flashy tendencies usually associated with ephemeral systems. Flows peak, decline and then peak again. The unusual aspect is that after the second peak, flows become unusually consistent for nearly two days. After the two days the hydrograph drops off sharply into the familiar long recession tail. Analysis of the precipitation pattern for the area indicate that a second storm occurred in the study area approximately 2 days after the initial precipitation. The last two peaks in the observed hydrograph could coincide with the runoff from that event. With that in mind, the storm was calibrated using only the peaks that occurred earlier than the last two. The comparison of the total volumes for the calibrated and observed hydrographs was cut off after 51 hours when the two hydrographs begin to permanently diverge. This storm does bear some resemblance with the hydrograph produced by storm 1_78. They both include multiple peaks that include more gentle summits than do 2_78 and 2_80.

The year 1979 was dry, especially when compared with 1978. The storm labeled 3_79 was just the third major flow event recorded by the USGS in that water year. The one month period prior to the storm was fairly wet, however. A storm two or three days prior to the event and recorded at a nearby station, deposited substantial amounts of rain in the area. The relatively-wet month preceding the storm suggested that a wet AMC II would be appropriate for this storm. The calibration procedures later indicated that AMC III contributing areas and high AMC II curve numbers were more appropriate.

Storm total values also changed substantially from our initial estimates. The low storm total at the Rochelle station lowered the storm totals for lower HRUs. During the calibration process it was decided that the low storm totals in the lower basin would prevent any calibration. It was decided to ignore the low values of the Rochelle station and move the storm totals higher to be more consistent with the other recording stations in the study area.

Further analysis of the 30 days preceding the storm revealed that it may indeed have been wetter than the authors had anticipated. The initial calibrations of the four storms were done with the idea that 2_80 had wetter antecedent conditions. The end calibration almost brought the contributing areas and NRCS curve numbers up to the level of 2_80. The timing of the rain in the 30 days prior to the studied storm is probably as important as the amount.

The small reservoirs were treated as they would be for wet conditions and contributing areas were adjusted to AMC III values. The available storage of the larger reservoirs was adjusted upward to reflect the depleted storage of a dry year in the Powder River Basin. The previous storms during the month were probably enough to reduce the storage capacity of the small reservoirs throughout the basin. It is doubtful however, that the larger reserivoirs would overflow in response to an event of this magnitude.

Storm 2_80

The storm labeled 2_80 started on June 24, 1980 at 10:00 AM. It was a large flow event with a duration and hydrograph that is more common to ephemeral systems than that displayed by storm 3_79. The hydrograph exhibits the large peaks associated with ephemeral systems that are impacted by largely convective weather patterns. Flows peak, decline and then peak again. The single large peak is followed by the familiar long recession tail.

The year 1980 was intermediate with regard to precipitation. The storm labeled 2_80 was just the second major flow event recorded by the USGS in that water year. Storm 2_80 is an earlier event than the other storms used in the study. The one month period prior to the storm was fairly wet and substantially colder than the other 3 storms. A storm shortly prior to the event and recorded at the Rochelle station, deposited substantial amounts of rain in the area. The relatively wet month preceding the storm suggested that AMC III would be appropriate for this storm. The calibration procedures later indicated that this was a valid analysis. The wet and cold month prior to the storm also suggested that most of the smaller reservoirs would be full and would have experienced little in the way of evaporative depletion.

The small reservoirs were treated as they would for wet conditions and contributing areas were adjusted to AMC III values. The available storage of the larger reservoirs was adjusted downward to reflect the wet spring conditions associated with this storm. The previous storms during the month were probably enough to reduce the storage capacity of the small reservoirs throughout the basin. It is doubtful however, that the larger reservoirs would overflow in response to an event of this magnitude.

Discussion

The current implementation of HEC-1 for this modeling project is somewhat unique in its approach. In most modeling situations, the model is developed with known or closely estimated parameters that are applied to the model to predict an unknown. Predictions regarding real or hypothetical events are based upon that model. These models were first calibrated to observed data, using unknown parameters, and then changed to reflect hypothetical or unknown conditions. Whenever possible, input parameters believed to reflect actual conditions within the watershed were used in the model. If, however, that data provided results that could not be reconciled to the observed discharge data, the input parameters were changed accordingly.

The NRCS curve numbers and the total precipitation for a storm were the "sledgehammers" of the calibration effort. Using those two aspects of an HRU, the total volume of output and the peak flows were approximated. At a certain point however, finer adjustments to the model were required. These finer adjustments usually reflected changes in timing, hydrograph shape, or, to a smaller extent, the peak flow. The parameters discussed in the methods section were the primary tools with which the finer adjustments were made during the calibration process. Lag time, recession point, recession constant, and other parameters were the parameters used to fine tune the calibrations.

The modeling process documented above was an inherently intuitive process. Alterations in NRCS curve number, precipitation storm totals, lag time and conveyance loss were made, based upon interpretation of the WMS output from each model run. It would be well out of the realm of feasibility to assume or assert that these models represent the only possible calibrations. What they represent is the professional analysis of the authors with regard to calibration of 4 storms in the Little Thunder Creek drainage. Models developed by others may be substantially different from those developed here. As is explained below, it is anticipated that the process of calibrating four storms and analyzing them relative to one another allowed the authors to identify any conceptual errors within the algorithms or assumptions used to calibrate and eventually model the basin.

The alteration of parameter inputs from the expected ranges was not an anticipated outcome of the modeling effort; however, it was necessary to the completion of the calibration process. After modeling 200 or 300 runs, it became obvious to the modeller what was required to make the input data fit the observed data. Sometimes this meant going beyond what was initially believed to be a reasonable value. This process also resulted in the conclusion that the initial estimates of reasonable maximum and minimum precipitation values did not account for the tremendous variability in precipitation. Eastwood (1994) established that variability of point precipitation data can vary greatly with relatively small areas. That concept was not well applied to the precipitation contour maps until the calibration process revealed that the estimates for precipitation were well outside the limits of the initial minimums and maximums.

The decision to calibrate 4 storms of varying intensities and magnitudes was primarily based upon the nature of HEC-1. Replicating the antecedent moisture conditions between two storms closely enough to allow validation of one storm by the other would be very nearly impossible. Even if such a match was possible, matching only one storm to the model would neither confirm nor deny the validity of the model-irregardless of the output. A larger sample size would be required to test the validity of the model. The limited number of storms available makes acquisition of an adequate sample impractical at best and impossible at worst.

The primary strength of analyzing 4 storms was that it facilitated the detection of conceptual errors in the model. At times, the observed discharge data and the watershed data input simply could not be reconciled. These discrepancies were believed, at times, to be the product of erroneous data and at other times they were believed to be conceptual problems with the model algorithms. The cause of the discrepancies became more or less irrelevant because the only means of resolving the problems was to alter the input data. If only one storm had been calibrated, the correctness of the model would be dubious. The calibration of 4 models of varying conditions allowed the authors to develop models that were not only correct with regard to the observed discharge data for a given storm, but also correct in the model's underlying concepts. By recreating 4 different hydrographs, the models have, in a sense, been validated relative to one another. The underlying concepts used in the dryest and wettest models were confirmed during the calibration process of the intermediate storms.

Post-mining impacts can be added to the pre-mining models by determining the areas to be impacted, ascertaining post-mining terrain features such as topography or channel lengths, and then altering those values in the model. Curve number changes are largely a function of best professional judgment with regard to the direction and amount of change. Nothing about the model is dependent upon a standardized change in NRCS curve numbers. To the contrary, the authors have provided a wide range of changes based upon the simplist possible assertions. The uniform change in curve numbers for the entire impacted area is the simplist model we could develop. The flexibility of the model is such that a large number of scenarios can be put into place if future conditions warrant.

Acknowledgements

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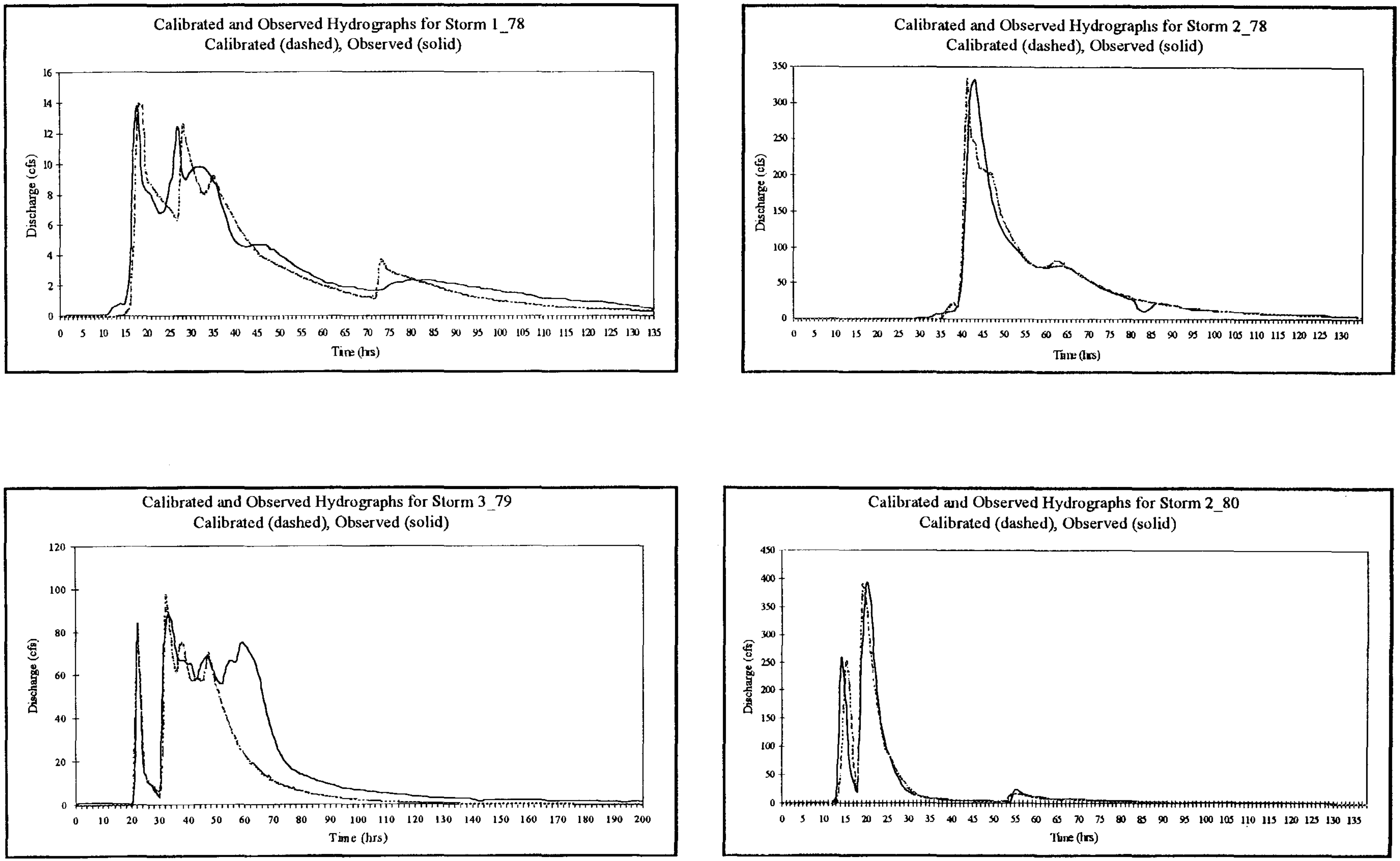

Figure 2. Calibrated and observed hydrographs for each of the four storms selected in the Little Thunder Creek, Wyoming study. Calibrated hydrographs were generated by the HEC-1 models. The observed data was obtained from USGS primary sheet records. Only the first 51 hours of storm 3_79 were calibrated due to the occurrence of a second rainfall event

Table 1. Comparison of peak flow rates in cubic feet per second (cfs) from the observed, calibrated (Predicted), premining and post-mining models. Percentages indicated change between observed and calibrated and between the pre-mining and post-mining models.

Storms	**1_78**	**2_78**	**3_79**	**2_80**
Predicted	13.9	327.5	95.7	387.2
Observed	13.8	332.6	88.5	392.8
% Difference	0.7%	1.5	8.1%	1.4%
Pre-mining	13.9	376.9	93.2	372.4
+1	13.9	414.3	90.1	372.4
% Difference	0.0%	9.9%	3.2%	0%
-1	13.9	331.7	93.2	372.4
% Difference	0.0%	12.0%	0%	0%
+2	13.9	426.9	111.3	372.4
% Difference	0.0%	13.3%	19.4%	0%
-2	13.9	321.6	93.2	372.4
% Difference	0.0%	14.7%	0%	0%
+3	13.9	465.6	127.0	372.4
% Difference	0.0%	23.5%	36.3%	0%
-3	13.9	276.3	93.2	372.4
% Difference	0.0%	26.7%	0%	0%
+4	13.9	470.3	155.5	372.4
% Difference	0.0%	24.8%	66.8%	0%
_4	13.9	305.5	93.2	372.4
% Difference	0.0%	18.9%	0%	0%

Table 2. Comparison of total flow volumes in acre-feet (ac-ft) from the observed, calibrated (Predicted), pre-mining, and post-mining models. Percentages indicated change between observed and calibrated and between the premining and post-mining models. Starred (*) total volumes for storm for the observed and calibrated storm 3_79 are presented for the first 51 hours of the event to eliminate the impact of a second rainfall-runoff event.

Storms	**1_78**	**2_78**	**3_79**	**2_80**
Predicted	30.99	407.95	129.9*	242.70
Observed	33.62	392.41	135.7*	240.66
% Difference	8.49%	3.81%	4.3%*	0.84
Pre-mining	30.48	453.84	189.43	242.65
+1	32.64	480.37	193.27	247.57
% Difference	7.09%	5.85%	2.03%	2.03%
-1	30.54	429.42	176.81	239.25
% Difference	0.20%	5.38%	6.66%	1.40%
+2	33.06	506.26	203.63	252.13
% Difference	8.46%	11.55%	7.5%	3.91%
-2	31.20	407.63	170.29	233.44
% Difference	2.36%	10.18%	10.10%	3.80%
+3	34.82	538.33	214.32	258.54
% Difference	14.24%	18.61%	13.14%	6.55%
-3	31.20	382.90	165.89	229.39
% Difference	2.36%	15.63%	12.43%	5.46%
+4	39.52	562.80	229.47	269.31
% Difference	29.66%	24.0%	21.14%	10.99%
-4	31.20	367.21	162.17	227.33
% Difference	2.36%	19.09%	14.39%	6.31%

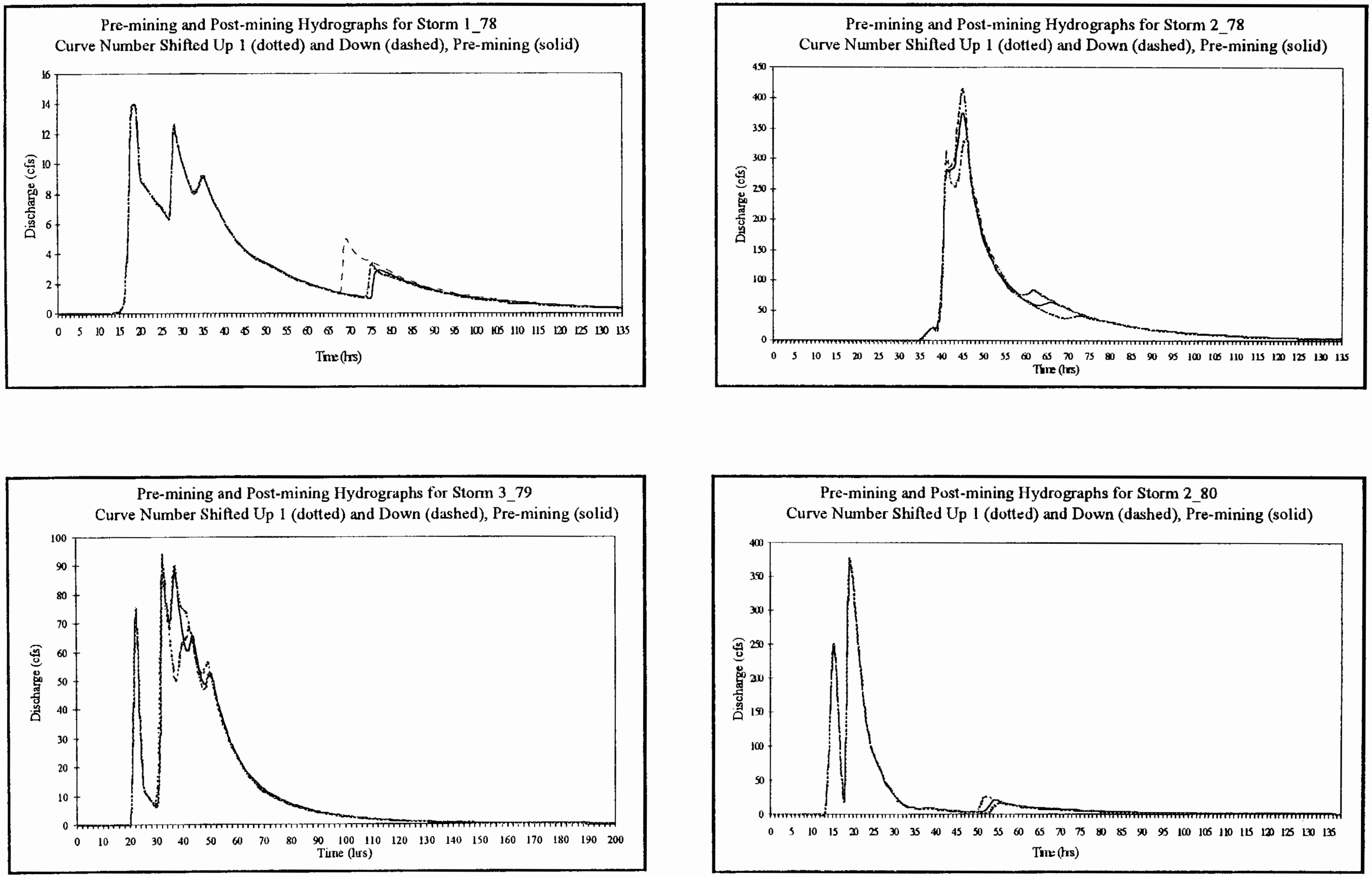

Figure 3..Pre-mining and post-mining hydrographs for each of the four storms selected in the Little Thunder Creek, Wyoming study. The post-mining hydrographs represent possible post-mining conditions with an increase and decrease of one NRCS curve number. The hydrographs are all predicted for the location of the USGS gaging station near the mouth of the stream.

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