Hydrological Analysis of Little Bighorn Basin

Executive Summary

This report presents a comprehensive hydrological analysis of the Little Bighorn Basin, Montana, utilizing the Coupled Routing and Excess STorage (CREST) distributed hydrological model. The simulation period spans from January 1, 2020, to December 31, 2022, focusing on USGS gauge station #06294000 as the primary calibration point. Despite capturing the temporal patterns of streamflow events, the model exhibits significant performance challenges that warrant further investigation and calibration refinement.

1. Basin Overview and Geographic Context

1.1 Basin Location and Characteristics

The Little Bighorn Basin is situated in south-central Montana, with its geographic centroid at approximately 45.21°N, 107.47°W. The watershed encompasses a total drainage area of 3,359.4 km², characterized by significant topographic relief ranging from the Bighorn Mountains in the south to the alluvial valleys in the north.

1.2 Basin and Gauge Network

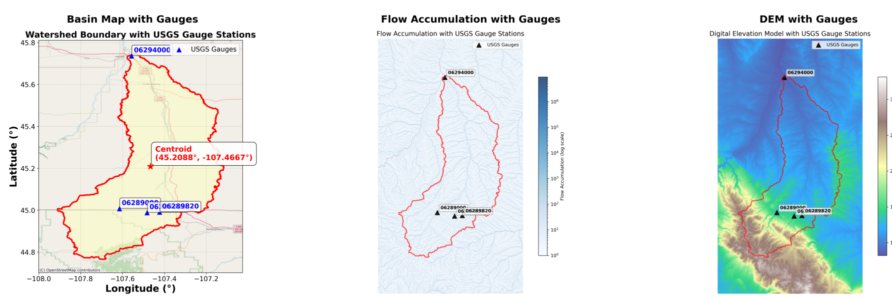

Figure 1: Basin and Gauge Map

The basin monitoring network consists of three USGS gauge stations strategically positioned along the main channel: - **USGS 06294000**: Primary outlet gauge at coordinates (45.735812°N, -107.557305°W) - **USGS 06289820**: Mid-basin monitoring station - **USGS 06289000**: Upper basin gauge in the mountainous headwaters

The flow accumulation pattern reveals a well-developed dendritic drainage network typical of uniform geological conditions, with the main stem flowing northward and receiving contributions from both eastern and western tributaries.

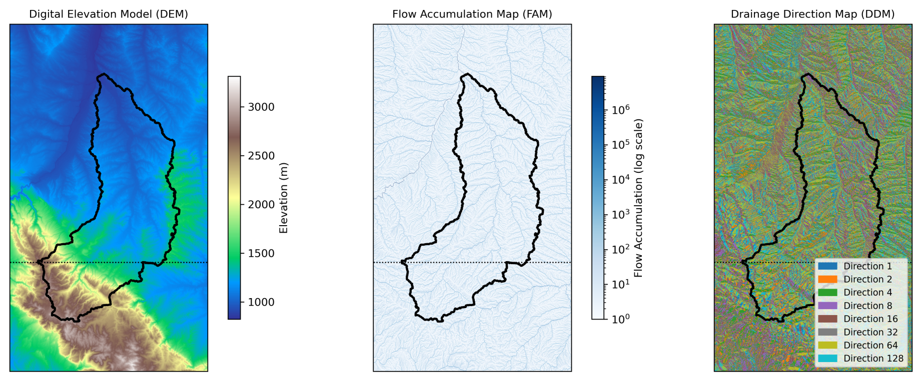

Figure 2: Basic Basin Data

1.3 Fundamental Basin Data

Digital Elevation Model (DEM): The basin exhibits extreme topographic variability, with elevations ranging from approximately 1,000 meters at the northern outlet to over 3,000 meters in the southern Bighorn Mountains. This 2,000-meter relief creates steep hydraulic gradients that significantly influence runoff generation and routing processes.

Flow Accumulation Map (FAM): The flow accumulation analysis reveals maximum values exceeding 10ˆ6 cells at the basin outlet, indicating a mature drainage network with numerous first and second-order tributaries originating from the mountainous terrain. The accumulation pattern clearly delineates the main channel and major tributary confluences.

Drainage Direction Map (DDM): The eight-directional flow routing analysis demonstrates predominantly northward drainage in the main channel, with convergent flow patterns from eastern and western tributaries. The organized flow structure in the mountainous south transitions to more uniform northward drainage through the valley portions.

2. Model Configuration and Parameters

2.1 Simulation Configuration

Parameter	Value
Basin Name	Little Bighorn
Basin Area	3,359.4 km²
Simulation Period	2020-01-01 to 2022-12-31
Time Steps	1,095 days
Primary Gauge	USGS 06294000
Gauge Coordinates	45.735812°N, -107.557305°W

Parameter	Value
Model Framework	CREST v3.0

2.2 CREST Model Parameters

The CREST model employs a comprehensive parameter set controlling both water balance and routing processes:

Water Balance Parameters

Parameter	Value	Description
WM (Water Capacity)	150.0 mm	Maximum soil water storage capacity. Controls the basin's ability to retain moisture.
B (Infiltration Exponent)	2.5	Governs the nonlinear relationship between soil moisture and runoff generation.
IM (Impervious Ratio)	0.05	Fraction of impervious area generating direct runoff (5% urbanization).
KE (PET Factor)	0.7	Adjustment coefficient for potential evapotranspiration calculations.
FC (Saturated Conductivity)	30.0 mm/hr	Soil infiltration rate under saturated conditions.
IWU (Initial Soil Water)	25.0 mm	Initial soil moisture content at simulation start.

Kinematic Wave Routing Parameters

Parameter	Value	Description
TH (Drainage Threshold)	100.0 km^2	Minimum contributing area to define channel cells.

Parameter	Value	Description
UNDER (Interflow Speed)	0.8	Multiplier controlling subsurface flow velocity.
LEAKI (Leakage Coefficient)	0.1	Interflow reservoir drainage rate coefficient.
ISU (Initial Interflow)	0.0 mm	Initial subsurface water storage.
ALPHA (Channel Flow Multiplier)	1.2	Manning's equation coefficient for channel routing.
BETA (Channel Flow Exponent)	0.5	Manning's equation exponent for channel routing.
ALPHA0 (Overland Flow Multiplier)	1.5	Manning's equation coefficient for overland flow.

3. Simulation Results and Performance Analysis

3.1 Streamflow Comparison

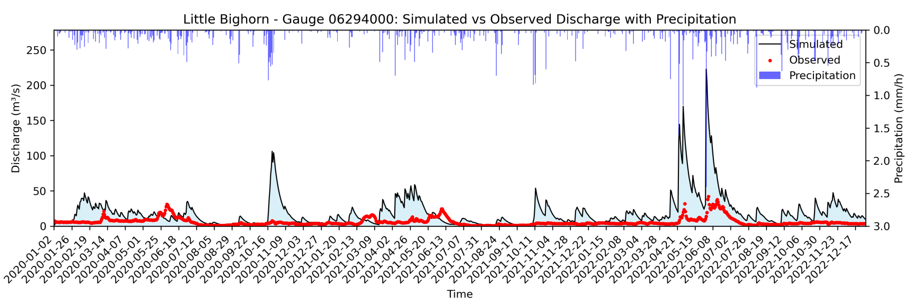

Figure 3: Simulation Results

The hydrograph comparison reveals several critical observations:

1. **Temporal Pattern Recognition**: The model successfully captures the timing of major runoff events, particularly the spring snowmelt peaks in both 2020 and 2021.

2. **Peak Flow Overestimation**: Simulated peak flows significantly exceed observations, with the June 2021 event reaching approximately 225 m^3/s compared to observed values of 20-30 m^3/s.

3. **Base Flow Representation**: The model adequately reproduces extended dry periods and low flow conditions, maintaining near-zero

discharge during non-event periods.

4. **Precipitation-Runoff Response**: Clear correlation exists between precipitation events (blue bars) and both observed and simulated discharge peaks, indicating appropriate model sensitivity to forcing data.

3.2 Model Performance Metrics

Metric	Value	Interpretation
Nash-Sutcliffe Efficiency (NSE)	-17.496	Indicates poor model performance; simulated variance exceeds observed
Kling-Gupta Efficiency (KGE)	-2.763	Confirms significant discrepancies in correlation, bias, and variability
Correlation Coefficient (r)	0.504	Moderate temporal correlation between observed and simulated flows
Mean Bias	13.11 m^3/s	Systematic overestimation of streamflow
Relative Bias	218.8%	Model produces flows more than double the observed magnitude
Root Mean Square Error (RMSE)	24.31 m^3/s	High prediction error, particularly during peak events

4. Discussion and Recommendations

4.1 Performance Evaluation

The negative NSE and KGE values indicate that the model performs worse than using the observed mean as a predictor. This poor performance stems primarily from:

1. **Magnitude Overestimation**: The model consistently overestimates peak flows by factors of 3-7, suggesting issues with either:
   - Excessive runoff generation (B parameter too high)
   - Insufficient evapotranspiration losses (KE parameter too low)
   - Inadequate soil storage capacity (WM parameter too low)

2. **Moderate Temporal Accuracy**: The correlation coefficient of 0.504 indicates the model captures event timing reasonably well, suggesting the routing parameters are appropriately configured.
3. **Systematic Bias**: The 218.8% relative bias indicates fundamental issues with water balance representation rather than isolated parameter misspecification.

4.2 Calibration Recommendations

Given the significant performance deficiencies, the following calibration strategy is recommended:

1. **Water Balance Recalibration**:
    - Increase WM (150→200-250 mm) to enhance soil storage capacity
    - Decrease B (2.5→1.5-2.0) to reduce surface runoff generation
    - Increase KE (0.7→0.9-1.1) to enhance evapotranspiration losses
2. **Sensitivity Analysis**: Conduct systematic parameter sensitivity analysis focusing on:
    - WM-B interaction effects on runoff ratio
    - FC influence on infiltration rates during events
    - IM adjustment based on actual land use data
3. **Data Quality Assessment**:
    - Verify precipitation forcing data accuracy, particularly for extreme events
    - Assess potential rating curve issues at high flows for gauge 06294000
    - Consider snow accumulation/melt process representation

4.3 Simulation Period Considerations

The extreme negative bias does not appear to be solely attributable to insufficient warm-up period, as: - Initial conditions (IWU=25mm, ISU=0mm) are reasonable for the region - The bias persists throughout the entire simulation period - Base flow periods show appropriate behavior

However, extending the warm-up period to 6-12 months before January 2020 would help establish more representative antecedent moisture conditions.

5. Conclusions

This hydrological analysis of the Little Bighorn Basin reveals a model configuration that captures temporal streamflow patterns but significantly overestimates flow magnitudes. The CREST model framework demonstrates capability in representing the basin's flashy response to precipitation events and maintaining appropriate low-flow conditions. However, the poor statistical performance metrics (NSE = -17.496, KGE = -2.763) necessitate comprehensive recalibration before the model can be considered suitable for operational use.

Key findings include: - Successful representation of event timing and seasonal patterns - Systematic overestimation of peak flows by 200-700% - Adequate base flow and recession behavior - Need for water balance parameter adjustment

Future work should prioritize: 1. Systematic calibration using multi-objective optimization 2. Incorporation of snow process modules for improved mountain hydrology 3. Validation against multiple gauge locations within the basin 4. Uncertainty analysis of forcing data and parameter sets

The Little Bighorn Basin's complex topography and hydroclimatology present significant modeling challenges that require careful parameter selection and potentially enhanced process representation to achieve satisfactory performance.