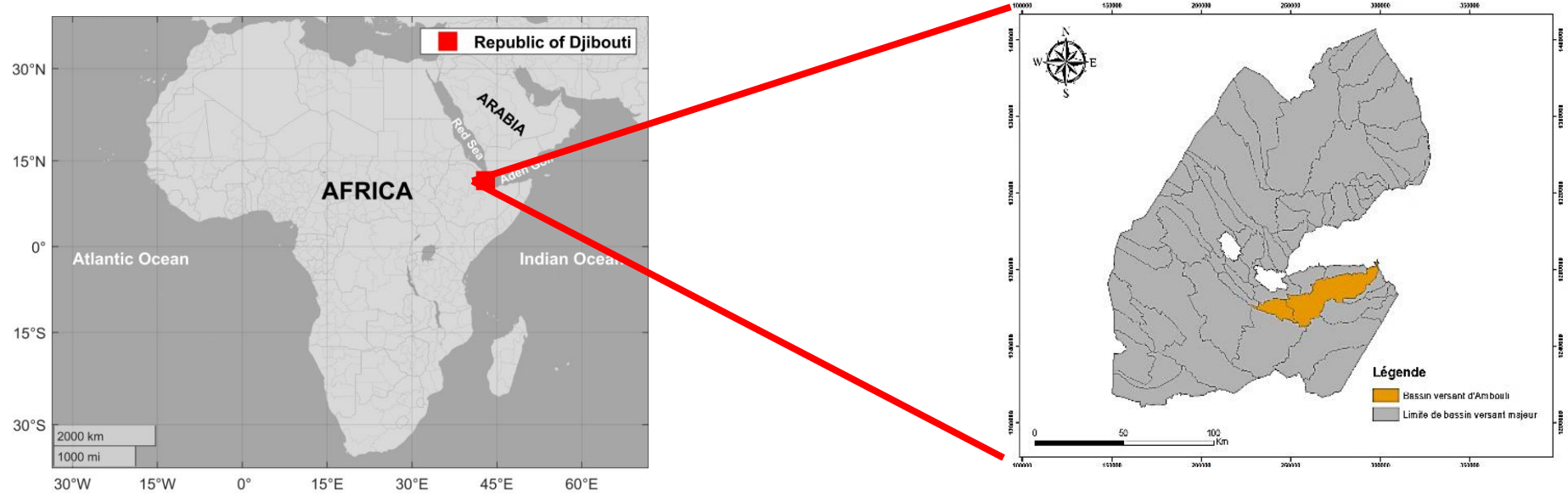
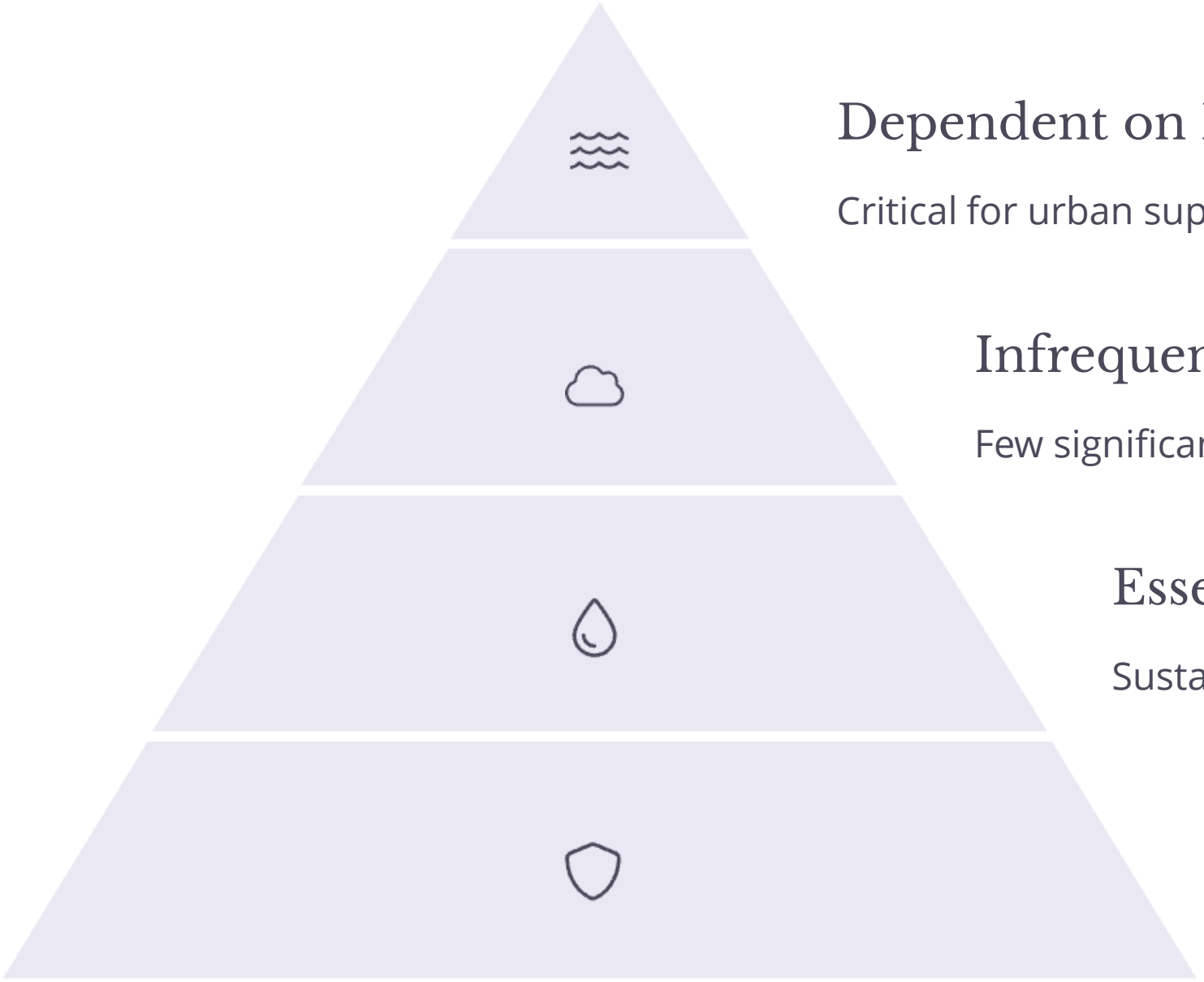
Challenges in Hydrological Modeling in a Data-Limited Catchment: The case of the barrage de l'Amitié, using HEC-HMS and GR4H (Republic of Djibouti).

Golab Moussa Omar[1, 2*], Jean-Emmanuel Paturel[2], Christian Salles[2], Gil Mahé[2], Mohamed Jalludin[1],
[1]Centre d'Etudes et de Recherches de Djibouti, Institut des Sciences de la Terre, Route de l'aéroport, Djibouti-ville, République de Djibouti
[2]HSM, Univ. Montpellier, CNRS, IRD, IMT Alès, Montpellier, France



Djibouti's Hydrological Context



Dependent on Limited Water Resources

Critical for urban supply and agriculture

Infrequent but Intense Rainfall

Few significant precipitation events yearly

Essential Groundwater Recharge

Sustains Djibouti aquifer for drinking water

Infrastructure Vulnerability

Flash floods cause significant damage

The Barrage de l'Amitié: Purpose and Context

Primary Flood Protection

Effectively shields Djibouti-ville from catastrophic flood events, protecting critical infrastructure and saving lives during seasonal intense rainfall.

Groundwater Recharge

Enhances infiltration in the reservoir area, potentially improving recharge rates for the Djibouti aquifer that supplies drinking water to the population.

Agricultural Support

Provides essential water resources for irrigation, enabling agricultural activities in an otherwise challenging environment with limited consistent water access.

Catchment Characteristics

Located in a 494 km² catchment characterized by arid conditions and subject to only a few intense rainfall events annually.

Data Limitations: The Monitoring Challenge

Limited Monitoring Infrastructure

Single hydrometric station located approximately 7 kilometers upstream from the dam

Measurement Threshold Issues

Station unable to measure flows below one meter height

Data Gaps in Flow Records

Smaller and moderate runoff events go unrecorded

High Model Uncertainty

Incomplete data creates significant modeling challenges

Modeling Approach: HEC-HMS vs. GR4H

HEC-HMS

Event-based modeling approach utilizing:

- Curve Number (CN) loss method
- Clark's Unit Hydrograph for runoff transformation
- Focused on peak flow simulation
- Suitable for flood forecasting

Relies heavily on accurate initial conditions for each event

GR4H

Conceptual approach featuring:

- Reservoir-based structure
- Captures both surface and subsurface flows
- Better representation of continuous processes
- Four parameters requiring calibration

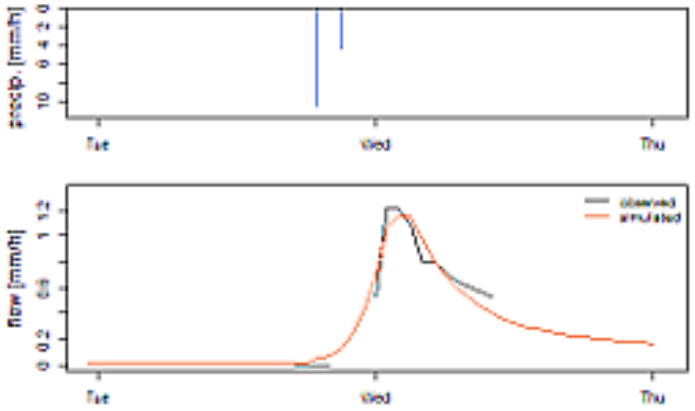
More effective at modeling soil moisture dynamics between events

Our study employed these two distinct modeling approaches to address the data limitations. We used five rainfall-runoff events for both calibration and validation, implementing a cross-validation procedure to test parameter transferability between events - a critical test of model robustness in data-scarce environments.

Model Performance: Calibration and Validation

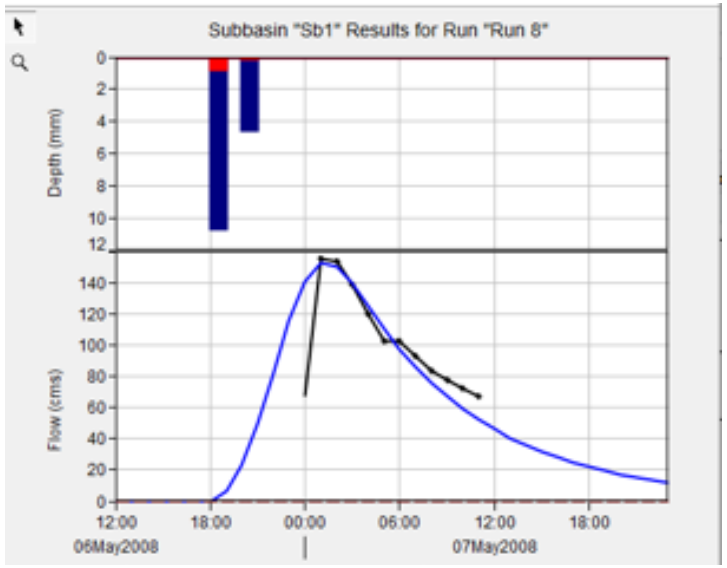
Calibration

GR4H : 6-7/05/2008



Nash = 0.94

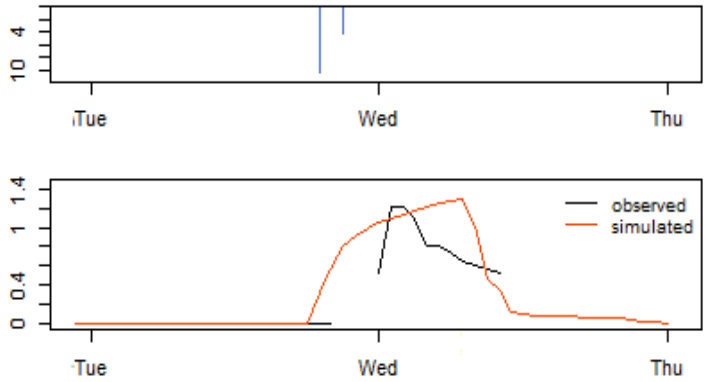
HEC-HMS : 6-7/05/2008



Nash = 0.97

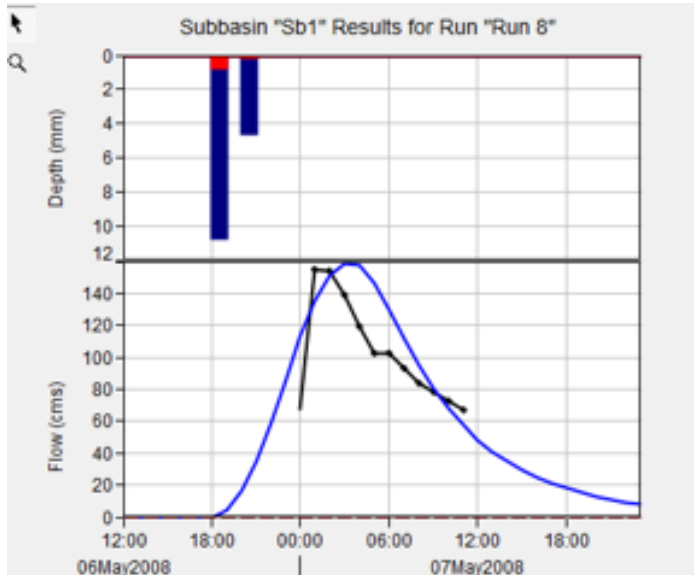
Validation

GR4H : 1-6/11/2008



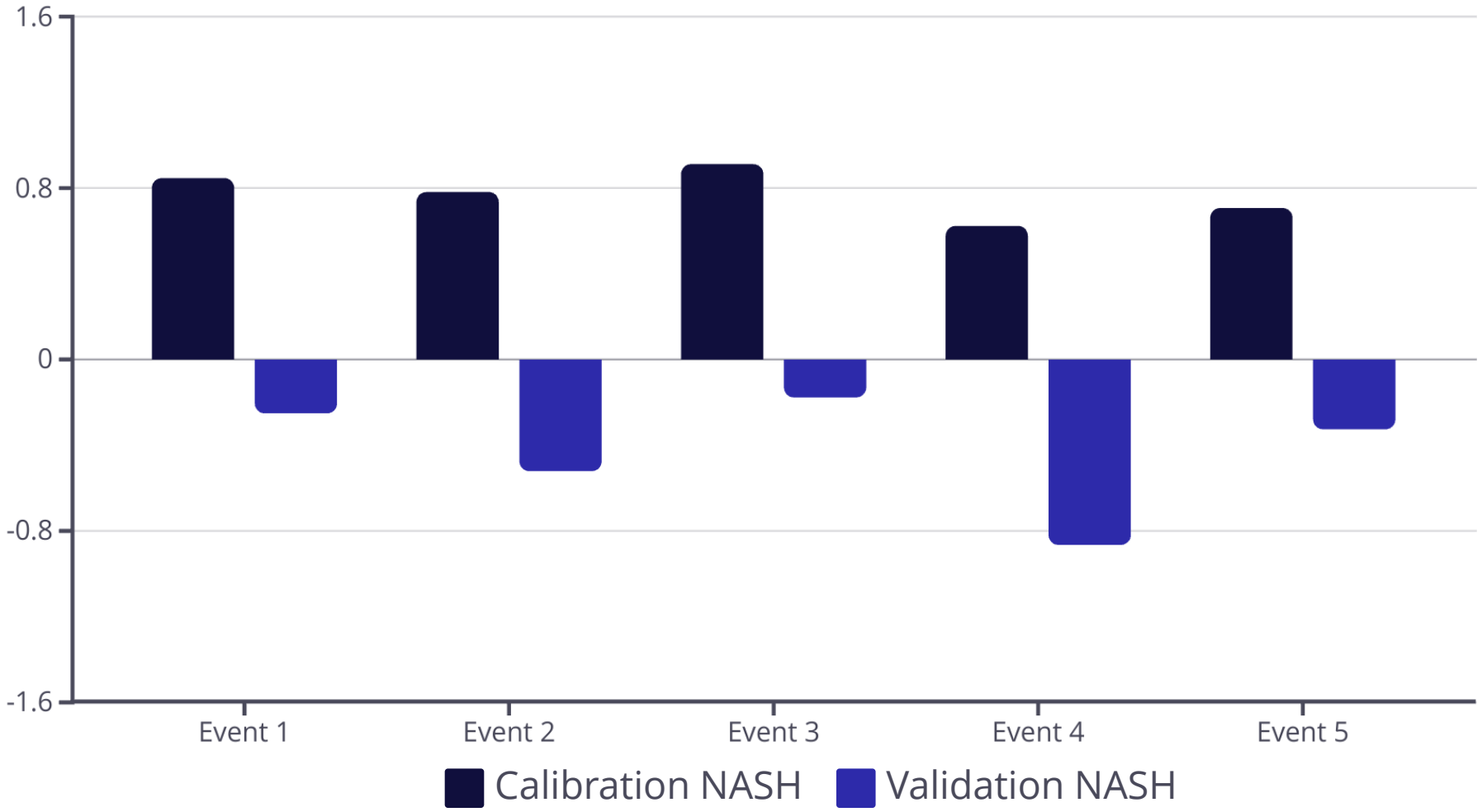
Nash = 0.2

HEC-HMS : 15-16/04/2010



Nash = 0.75

HEC-HMS Performance Results



HEC-HMS showed strong calibration performance but poor validation.

Parameter sets did not transfer well between events.

GR4H Performance Results

Event Type	Calibration NASH	Validation NASH	Key Challenge
Single-peak	0.76-0.88	-0.11 to 0.42	Generally good performance
Multi-peak	0.58-0.69	-0.95 to -0.27	Poor reproduction of complex patterns
Low intensity	0.34-0.61	-1.23 to -0.45	Inadequate representation of minor flows

- ***GR4H performed well in calibration but struggled with complex hydrograph patterns and parameter transferability.***

Cross-Validation: Testing Parameter Transferability

Calibrate Model Parameters

Optimize parameters for Event A

Transfer Parameters

Apply Event A parameters to Event B

Rotate Through Events

Test all event combinations

Validate Performance

Assess NASH coefficient for Event B

Cross-validation provides a more rigorous test of model robustness than standard validation, especially crucial in data-limited environments. By transferring calibrated parameters from one event to another, we can assess whether the models truly capture the underlying physical processes or merely fit individual events.

Unfortunately, both models struggled during cross-validation, often yielding negative NASH values. This indicates that parameter sets optimized for specific events failed to transfer effectively to others, highlighting the challenges of hydrological modeling in this arid, data-poor catchment.

Key Findings and Limitations

Model Performance Variability

HEC-HMS exhibited strong calibration results but poor validation, suggesting over-parameterization and sensitivity to initial conditions. GR4H showed more balanced performance but struggled with multi-peak events, indicating limitations in representing complex rainfall-runoff dynamics.

Data Insufficiency

The inability to measure flows below one meter creates critical gaps in hydrological understanding. These smaller events, while not causing floods, are vital for groundwater recharge and irrigation potential assessment. Extended periods without observations hinder proper model conditioning.

Parameter Transferability Issues

The negative NASH values during cross-validation reveal fundamental challenges in developing reliable hydrological models for this region. The high temporal variability of catchment conditions in arid environments likely contributes to poor parameter transferability between events.

These findings underscore the significant challenges of hydrological modeling in data-limited arid catchments, particularly when attempting to develop models that are robust across varying conditions.

Recommendations for Improved Monitoring and Modeling

Enhanced Monitoring Network

- Install additional hydrometric stations throughout the catchment
- Implement equipment capable of measuring low flows (below 1m)
- Deploy automated rainfall gauges for better spatial coverage
- Consider remote sensing supplements for rainfall estimation

Improved Model Structures

- Develop arid-specific model components
- Incorporate transmission losses in channel routing
- Better represent soil moisture dynamics between sparse events
- Explore ensemble modeling approaches for uncertainty quantification

Enhanced Infiltration Assessment

- Conduct detailed infiltration studies in the reservoir area
- Monitor groundwater levels to quantify recharge benefits
- Develop specific modules for groundwater-surface water interactions
- Assess irrigation potential based on improved water availability estimates