HEC-RAS Overview, Recent Developments, and Future Work

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Overview

- HEC-RAS Overview
- RAS Mapper
- 2D Flow Modeling Capabilities/Features
- Example Modeling Applications
- Current/Recent Research and Development Work
- Future Research and Development Work
HEC-RAS – What is it?

HEC River Analysis System:

- 1D/2D hydraulics/hydrodynamics model
- Computes water surface elevations; depths; velocities; flood inundation maps; hazard maps (depth x velocity), etc…
- Sediment Transport/Movable Bed modeling
- Water Quality modeling
HEC-RAS Software Vision

- To research and develop the best possible (powerful and user friendly) river analysis software system for the Corps of Engineers; their partners; and the general hydraulic engineering community.

- Continually improving hydraulic modeling techniques and capabilities in HEC-RAS for the full range of applications.
- Improve the efficiency of performing large hydraulic model development; calibration/verification; alternative analyses; and risk and uncertainty analyses. Which will ultimately reduce the costs of performing such studies.
- Improve the User Interface to make it easy for new to intermediate users to pick up RAS on their own, but not slow down advanced users.
- Create output visualization tools that will improve hydraulic understanding and help to convey the significance of the project performance/model alternatives to the public.
HEC-RAS Project Team

Gary W. Brunner - HEC-RAS Team and Development Lead

Mark Jensen – User Interface, RAS-Mapper, Water Quality

Steve Piper – Computational Engines (Hydraulics and sediment Transport)

Cameron Ackerman – RAS-Mapper, Geo-RAS, GIS specialist

Stanford Gibson – Sediment Transport

Alex Kennedy – Computer Scientist (RAS-Mapper, HDF, GDAL, Graphics)

Alex Sanchez – Computational Engines (2D sediment, 2D Hydrodynamics)

Ben Chacon – RMA Contractor, 2D Solver

Anton Rotter-Sieren – Computer Scientist (RAS-Mapper, Gridded Data)
Who Uses HEC-RAS

- **Who are the Customers:**
  - All Corps District and Division offices
  - Other Federal Agencies (NWS, USGS, NRCS, NRC, FHWA, Bureau of Reclamation, FEMA, TVA, etc…)
    - Adopted by NWS for real time forecasting
  - State and Local governments
  - Private Industry
  - Environmental Organizations (Nature Conservancy, etc…)
  - Universities (professors and students)
  - Engineers from many other countries (government and private engineers)

- **HEC-RAS 5.0.3 has been downloaded over 100,000 times from over 200 countries.**
Type and Scale of Applications

- Types of Studies
  - Initial screening and reconnaissance studies
  - Detailed investigations and alternative evaluations
  - Design studies
  - Real-time forecasting
  - Risk and uncertainty analyses
  - Dam and Levee Safety

- Spatial Scale of Application
  - Very small urban areas with small drainage systems
  - Moderate-size river systems with natural and constructed channels
  - Large-scale river systems (Ohio, Columbia, Mississippi)

- Time Scale of Applications
  - Peak flow profiles
  - Single event simulations
  - Long term simulations (period of record analyses)
HEC-RAS Mapper

- HEC-RAS Mapper is completely new for version 5.0

- Goals:
  - Terrain and other supporting data layers
  - Model Development and Layout
  - Visualization of results
  - Improve the efficiency of hydraulic modeling
  - Utilize and focus modelers skill using HEC-RAS
  - Reduce the dependency of GIS skills
HEC-RAS Mapper

Data Layers Window

Display Window

Status Window
HEC-RAS Mapper Terrain

- Single or multiple terrain model support
- Flexible tile arrangements
- Different data resolutions per tile ok!
- No intended terrain file size limitations
TIN Stitches

- Covers transitions across datasets
- Fills in holes in terrain data
Land Cover Data

- Support use of Land Cover data for estimating Manning’s $n$ values
  - Raster and Shapefile polygon datasets
- NLCD 2011
- USGS LULC
- Additional Resources-
2D Area Manning’s n Regions
Manning’s n by Land Cover
HEC-RAS Mapper Results Mapping

- **Dynamic Mapping - Animation**
  - On-the-fly mapping – you don’t have to wait for inundation map to be processed!

- **Stored Maps** – Depth Grid written to a file.

![Screenshot of HEC-RAS Mapper Results Mapping interface](image)
Dynamic Mapping
Adding a New Results Map Layer

- Depth, Elevation, Flow, Velocity, Shear Stress
- Inundation Boundary
- Arrival Time, Duration, Percent Time Inundated, Recession, (at a certain depth)
- Hazards (depth*velocity and depth*V^2)
Creating Static (Stored) Maps

- Tools – Manage Results Maps
Querying HEC-RAS Results
Profile Lines – Water Surface
Profile Lines - Flow Time Series
Time of Arrival
HEC-RAS Mapper – Background Imagery
HEC-RAS Two Dimensional Flow Modeling Capabilities/Advantages

1. The ability to perform 1D, 2D only, or Combined 1D and 2D modeling
2. The 2D equation solver uses an Implicit Finite Volume algorithm.
3. Can solve either 2D Diffusion Wave or 2D Full Saint Venant Eqns.
4. The 1D and 2D solution algorithms are tightly coupled on a time step by time step basis (or even iteration by iteration).
5. The software was designed to use Unstructured or Structured Computational Meshes. The outer boundary of the computational mesh is defined with a multi-point polygon.
6. The underlying terrain and the computational mesh are pre-processed in order to develop detailed Hydraulic Property Tables for the Cells and the Cell Faces.
7. Mapping of the combined 1D/2D inundation area, and animations of the flooding can be done right inside of RAS, using RAS-Mapper.
8. The 2D flow computations take advantage of Multi-processors.
9. 64 Bit and 32 Bit Computational Engines.
2D Hydraulics

- **Mass Conservation** (Continuity)

- **Full Momentum Equation** (Shallow Water Eqns.)
  - Gravity and Friction
  - Hydrostatic pressure
  - Acceleration (local and convective)
  - Turbulence Modeling - Eddy viscosity (optional)
  - Coriolis term (optional)

- **Diffusion Wave Equation**
  - Gravity and Friction
  - Hydrostatic pressure
Unstructured/Flexible Computational Mesh

- Irregular polygon outer boundary
- **Unstructured** (irregular) or **structured** (squares, rectangles), or **mixed** computational mesh
- **Computational cells can vary in shape or size.** Cells can have up to 8 sides
- Cells must be **Convex**
- HEC-RAS can handle **orthogonal** and **non-orthogonal** grids, but orthogonality simplifies formulation and reduces compute time.
Example Flexible Computational Mesh
Break Lines for Channel Banks
Cell and Face Pre-Processing

- The 2D Mesh pre-processor computes a detailed elevation-volume relationship for each cell.
- Each face of a computational cell is pre-processed into detailed hydraulic property tables (elevation versus, wetted perimeter, area, roughness, etc...).
- Computational cells can be partially wet.
- This allows the user to use larger computational cells, without losing too much of the details of the underlying terrain.
- The net effect is that larger cells means less computations, which means much faster run times.
- Additionally, HEC-RAS will produce more detailed results for a given cell size than other models that use a single elevation for each cell and face.
Computational Mesh with Detailed Sub-grid Terrain Data - Continued
Computational Cells are Pre-Processed

Elevation vs. Volume
Computational Faces are Pre-Processed

Elevation vs. Area, Wetted Perimeter, and n
Benefits of using the detailed sub-terrain for the cell and face hydraulic properties
Separate 2D Flow Area(s) with External Boundary Conditions

- User can have a model that exists entirely as a single 2D Flow Area
  - Requires at least one external boundary condition applied to the 2D area (generally at least 2 would be used)
  - Can use multiple boundary conditions and types
    - Flow Hydrograph
    - Stage Hydrograph
    - Rating Curve
    - Normal Depth – Manning’s Equation
    - Precipitation

- Multiple 2D Flow Areas can be linked together with Hydraulic structures
Cherry Creek Dam Break Example

- Clear Creek
- Sand Creek
- S. Platte River
- Cherry Creek
- Emergency Spillway
Cherry Creek Example Animation
Connecting a 2D Flow Area to 1D Hydraulic Elements

- Laterally to 1D river reaches using a **Lateral Structure** (lateral structures can now be georeferenced).
- Directly to the downstream end or upstream end of a river reach with the last or first XS of the reach.
- Directly to another 2D Flow Area or Storage Area using the **SA/2D Area Connection** (hydraulic Structure).
- Multiple 2D Flow Areas in a single model
Hooking up a 2D Flow Area to a 1D River Reach with Lateral Structures
Lateral Structure editor
Sacramento River System Model
Natomas, California
Directly connecting an Upstream River Reach to a Downstream 2D Flow Area
Directly connecting an Upstream 2D Flow Area to a Downstream River Reach
Connecting a 2D Flow Area to a Storage Area using a Hydraulic Structure
SA/2D Hydraulic Connection
Montecello Dam Breach Example
Montecello Dam Breach Example
Montecelio Dam Breach Example
Connecting a 2D Flow Area to another 2D Flow Area using a Hydraulic Structure
Multiple 2D Flow Areas in the one Model
Hydraulic Structures inside a of a 2D Area
Hydraulic Structure Computation Options
External 2D Flow Area Boundary Conditions

- Flow Hydrograph
- Stage Hydrograph
- Normal Depth
- Rating Curve
- Precipitation
Running the Combined 1D/2D Unsteady-flow Model

Plan: SA to 2D Area Conn - 2D Levee Structure
Short ID: 2D Levee Struc

Geometry File: SA to 2D Flow Area
Unsteady Flow File: 1972 Flood Event - 2D Levee Structure

Programs to Run:
- Geometry Preprocessor
- Unsteady Flow Simulation
- Post Processor
- Floodplan Mapping

Simulation Time Window:
Starting Date: 01JAN1999
Ending Date: 04JAN1999
Starting Time: 1200
Ending Time: 1700

Plan Description:
This is an example of how to modify the 2D Mesh and add an internal hydraulic structure in order to model a levee. Additionally, the internal hydraulic structure was used to analyze levee overtopping and breaching.

Computation Settings:
- Computation Interval: 20 Second
- Mapping Output Interval: 5 Minute
- Hydrograph Output Interval: 1 Minute
- Detailed Output Interval: 1 Hour
- DSS Output Filename: C:\HEC Data\HEC-RAS\Automated Test Datasets\2D Unsteady

Storage Area Connection with breach data. 1 set to breach.

debug parameters
Example Applications

- Detailed Urban Flooding – Grid Resolution Tests
- Bridge Hydraulics
- Detailed Structure with Piers
- New Orleans Gated Outfall design
Detailed River and Urban Floodplain 10 ft cells – with break lines

- Equation set = Diffusion Wave
- Grid Size = 10 ft X 10 ft
- Time step = 2.0 seconds
- No. Cells = 231490
- Event Duration = 2 days 9 hours
- Run Time = 12 hours 26 minutes

- Buildings left in the terrain on purpose.
Detailed River and Urban Floodplain
50 ft cells– with break lines

- Equation set = Diffusion Wave
- Grid Size = 50 ft X 50 ft
- Break lines at high ground along channel Banks, gravel pits, etc…
- Time step = 4.0 seconds
- No. Cells = 15050
- Event Duration = 2 days 9 hours
- Run Time = 19 minutes, 51 seconds
- Buildings left in the terrain
Detailed River and Urban Floodplain Animation
Upstream of Weir

Water Surface Elevation (ft)
Upstream of Split

Water Surface Elevation (ft)

- 10 ft Grid
- 50 ft Grid
Downstream of Bend

Water Surface Elevation (ft)

- 10 ft Grid
- 50 ft Grid

Date and Time:
- 4/17/2014 0:00
- 4/17/2014 12:00
- 4/18/2014 0:00
- 4/18/2014 12:00
- 4/19/2014 0:00
- 4/19/2014 12:00
- 4/20/2014 0:00
Downstream Outflow (cfs)
Detailed Bridge Modeling

- Equation set = Full Momentum
- Eddie Viscosity Coefficient = 1.0
- Grid Size = 2x2 ft up to 8x8 ft
- Time step = 0.1 seconds
- No. Cells = 218748
- Event Duration = 30 min. Steady Flow
- Run Time = 1 Hour 25 min
Detailed Bridge Modeling
Detailed Bridge Animation
Detailed 2D Flow Area Model of Proposed Structure with Piers in Floodplain
3D View of Proposed Structure Piers
Proposed Structure with Piers - Continued

- Equations = Full Saint Venant
- Grid Size = 2 ft X 2 ft
- Time step = 0.25 second
- No. Cells = 454,603
- Event Duration = 24 hours
- Run Time = 6 hours 64 minutes
Pier/Mesh Details
Proposed Structure with Piers - Animation
Velocity Tracking and Colored Grids
Water Surface Elevation with Contours
17th St. Pump Station with Gate Openings

- Equation set = Full Momentum
- Grid Size = 1x1 ft up to 4x4 ft cells
- Time step = 0.1 seconds
- Eddie Viscosity Coefficient = 1.0
- No. Cells = 104197
- Event Duration = 30 minutes
- Run Time = 50 minute 46 seconds
Boundary Conditions

Upstream Flow Hydrograph:
0 to 12500 cfs over 5 minutes

Downstream Boundaries:
Stage Hydrograph = -1.0 feet

Initial Conditions:
Flat water surface at -1.0 feet

11 Gate Openings

Downstream Stage Hydrograph

Pump Station

Upstream Flow Hydrograph
Mesh Details – Gate Openings
WSE HEC-RAS 2D and Fluent 3D
Velocity HEC-RAS 2D and Fluent 3D
Velocity Plotting RAS 2D and Fluent 3D
# Flow and Velocity Comparison

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<th>3</th>
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<td>1110</td>
<td>1102</td>
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</table>
Velocity Animation
Current/Recent Activities

- Improved hydraulic structure modeling algorithms for structures placed inside of a 2D flow area
- 1D Finite Volume solution algorithm
- Terrain Development/Modification Tools for Alternative Analyses
- HEC-RAS Mapper Model Development/Editing Tools
  - 1D/2D model development/editing; 2D mesh editing/refinement tools
- Verification and Validation Testing/Document
- Internal Boundary Condition Lines
- Variable Time Step Computations
- Improved Parallelization/Faster Computations
- Iterative Matrix Solvers
- Wind Forces (1D and 2D)
- Spatial Precipitation/Infiltration
- Turbulence Modeling
- Pump Stations inside of 2D Flow Areas
- DSS-7
Improved Hydraulic Structure Modeling Algorithms
Improved Hydraulic Structures
Spatial Connections
1D Finite Volume Solution Algorithm

- The current 1D Finite Difference scheme has trouble in the following situations:
  - Can’t handle starting or going dry in a XS
  - Low flow model stability issues with irregular XS data
  - Extremely rapidly rising hydrographs can be challenging
  - Mixed flow regime (i.e. flow transitions)
  - Stream junctions do not transfer momentum directly

- The new 1D Finite Volume algorithm has the following positive attributes:
  - Can start with channels completely dry, or they can go dry during a simulation (wetting/drying)
  - Very stable for low flow modeling
  - Can handle extremely rapidly rising hydrographs without going unstable
  - Handles subcritical to supercritical flow, and hydraulic jumps better
  - Junction analysis is performed as a single 2D cell when connecting 1D reaches (continuity and momentum is conserved through the junction)
Partial Cells
Left floodplain, Main channel, Right floodplain

- Separate cells for main channel, left floodplain and right floodplain.
- Current Finite Difference uses only two flow areas: channel & floodplain
- Notation: Partial cells indexed by $i$
  - $u_{ji} =$ channel or overbanks velocities at $j$
  - $A_{ji} =$ channel or overbanks partial areas for cross-section $j$
  - $A_j = \sum_i A_{ji}$ cross-section total area
- Cross-section partial conveyance $K_{ji} = \left(A_{ji} R_{ji}^{2/3}\right) / (n_{ji}/k)$
- Cross-section total conveyance $K_j = \sum_i K_{ji}$
Junctions

Data Requirements:
1. Elevation - Volume Curve
2. XS/Face Properties
3. Angles with respect to controlling cross section
4. Junction Reach Lengths
Natural River Mapping Animation - Dry to Wet to Dry
Terrain Modification Tools for Alternative Analyses

- Improved capabilities for making huge terrain models
  - Oroville Dam Issues—over 50G of data with over 3700 LIDAR files, USGS 10m DEM’s, and channel cross section data from existing studies.

- Improved channel modification/cutting tools
  - Used in Oroville project
Oroville Dam Spillway Issues
HEC-RAS Mapper Model Development/Editing Tools

- Create and edit 1D and 2D model elements
- Easy to use tools
- Data extraction
- 2D mesh development
  - New Breakline tools
  - Mesh Refinement Regions tool
Edit Geometry
Editing Toolbar

- Add New Feature
- Select/Edit Feature
- Undo/Redo
- Plot Elevations
Tools

- **Copy, Paste** and **Delete** Feature options are available.
- **Reverse Feature** will reverse the order of the points in a line feature.
- **Merge Feature** will combine the selected features. For line features, this tool is very robust, but for polygon features, the polygons must overlap.
- **Clip - Preserve** - clip against overlapping polygons, preserving the selected feature. (Polygons must intersect.)
- **Clip - Discard** - clip against overlapping polygons, discarding the overlapping portion of the selected feature. (Polygons must intersect.)
- **Buffer Polygon** - enlarge or shrink the selected feature by the buffer value.
- **Filter** - filter the points on a feature given a user tolerance.
- **View/Edit Points** will bring up a dialog with all of the points in the feature. You can then modify the points in the table.
Model Construct

- Automatic calculation of hydraulic parameters and data extraction during model development
Create/Edit Model Features

- Mouse hover indicates action
  - Green point indicates: Creation, Move, Insert, Delete
Breaklines

- Locate and Enforce Breaklines
Breaklines
Error plotting

- Identify and inform user of model deficiencies.
  - Cross Section don’t cross river line or cross more than once
  - Cross Sections intersect each other
  - Missing Bank Stations

- General feature layer
Profile Plot

- Plot updates interactively
Mesh Generation Refinement Tool
Mesh Generation Refinement Tool
Verification and Validation Testing/Document

- Analytical Test cases
- Lab Test cases
- Field test case
- Released with version 5.0.4
Internal Boundary Condition Lines for 2D Areas
Internal Boundary Condition Lines for 2D Areas
Variable Time Step Capabilities

HEC-RAS Unsteady Computation Options and Tolerances

1. Fixed Time Step (Basic method)
   - 10 Second

2. Adjust Time Step Based on Courant
   - Maximum Courant: 1
   - Minimum Courant: 0.45
   - Number of steps below Minimum before doubling: 4
   - Maximum number of doubling base time step: 2
   - Maximum number of halving base time step: 0

3. Courant Methodology
   - Courant (Velocity * dt / Length)
   - Residence Time (flow out * dt / Volume)

4. Adjust Time Step Based on Time Series of Divisors

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Improved Parallelization/Faster Computations

- The HEC-RAS computational engine has been further parallelized.
- In previous versions the 2D matrix solver was parallelized, but everything else was not.
- We have further parallelized the code to include matrix setup, matrix coefficient computations, hydraulic computations between time steps, etc…
- This has dramatically sped up the code and will result in reduced run times for all data sets.
### Improved Parallelization/Faster Computations

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Matrix Solvers

- Sparse matrix solver used for hydrodynamics, water quality, and sediment transport
- Current approach: **Direct** solver PARDISO
- Ongoing work: **Iterative** (approximate) solvers
- Direct solvers are very robust but can be relatively slow compared to iterative solvers especially when the solution procedure already requires iterations for convergence
- Developing high-level sparse matrix solver library with extremely simple interface
Solvers and Preconditioners

- **Solvers**
  - Gauss-Seidel with and without Successive-Over-Relaxation
  - Preconditioned Flexible Generalized Minimal Residual solver (PFGMRES)
  - Preconditioned Conjugate Gradient (PCG) Method

- **Preconditioners**
  - Jacobi
  - (Symmetric) Successive-Over-Relation ((S)SOR)
  - Incomplete Lower Upper Factorization with zero infilling (ILU0)
  - Incomplete Lower Upper Factorization with Threshold for infilling (ILUT)
Framework and Testing

- All solvers and preconditioners wrapped within a single generic solver and implemented within the 2D flow and sediment framework
  - Makes adding or changing the methods really easy
  - Setup to solve matrix multiple times with updates to Right-Hand-Side (useful for water quality and sediment transport)

- Test Cases:
  - Laboratory test case of channel constriction and expansion with a mobile bed
  - Upper North Bosque River Watershed
Solver Performance Results

- Channel constriction and expansion
  - Water level correction equation

- Upper North Bosque River Watershed
  - Water level correction equation
Turbulence

- Current approach:
  - Parabolic Model: Simple one equation model which takes into account only bottom shear and water depth. Model is isotropic meaning the eddy viscosity is the same in all directions.

- Ongoing work:
  - Modified Subgrid Model: One equation model, which takes into account bottom, surface, and horizontal shear, water depth, and grid size. Also anisotropic.
  - Could potentially add more complex turbulence models such as K-eps in the future
Wind

- Ongoing work (TVA and NWS)
- Only for SWE model
- Wind data from stations/gages or grids
- Spatial mapping done by RAS Mapper.
- Temporal calculations done by computational engine
- Key Features: Eulerian or Lagrangian reference frame, various wind drag coefficient formulations, wind sheltering, and wind height corrections
Precipitation/Infiltration

- Ongoing work
- Applicable to DWE and SWE models
- Precipitation data from gages or grids
- Infiltration methods: SCS Curve Number, Deficit-Constant, Green-Ampt with Recovery/Redistribution
- Also includes evapotranspiration, canopy and surface depression storage
Future Research and Development Work

- Additional Computational Speed Improvements
  - Iterative Solvers; Code Profiling/improvements; Graphics Card Computations; SIMD (Single Instruction Multiple Data); MPI parallelization
- Turbulence Modeling: Modified subgrid; K-\( \varepsilon \) turbulence model, etc.
- Eulerian advection scheme (currently using Lagrangian advection)
- Secondary Flow Corrections (quasi 3D term)
- Enhancements to Mesh Generation/Editing Tools
- Integrate 1D finite Volume solution with the 2D finite volume solution so they can be solved in the same matrix (fully coupled)
- Improved Initial Conditions capabilities for 2D Flow Areas
- Terrain Modification tools using points; lines and polygons, as well as predefined shapes: circles, rectangles, etc. to modify the terrain data.
- 2D Bridge Hydraulics:
  - Integrate Current 1D Bridge hydraulics inside of a 2D Flow Area
  - True completely 2D Bridge Hydraulics (open channel flow, pressure flow, overtopping)
Future Research and Development Work

- FEMA Floodways within 2D Flow Areas
- 3D Graphics/Animations of Terrain and water depth or velocity
- Integration of the HEC-RAS “Rules” within 2D Areas/Structures
- Vertically varying Manning’s roughness
- Integration of Observed data locations/data in RAS Mapper
- Raster Calculator for RAS Mapper
- Uncertainty Analysis – further enhance our uncertainty analysis for RAS standalone
- Cloud Computing for RAS standalone