GeoClaw-ArcGIS Integration for Advanced Modeling of Overland Hydrocarbon Plumes

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Overview

- Background, motivation, and the aims of this work
- Modeling hydrocarbon overland flow with full shallow-water equations
  - GeoClaw
  - Added features and code modifications
- Integration with Microsoft Azure
- Integration with ArcGIS

Demo video

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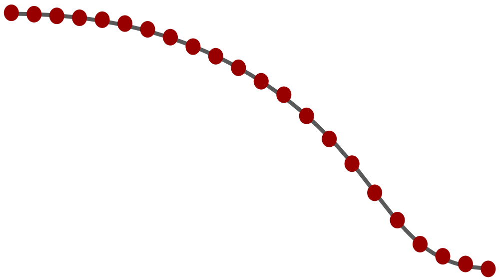
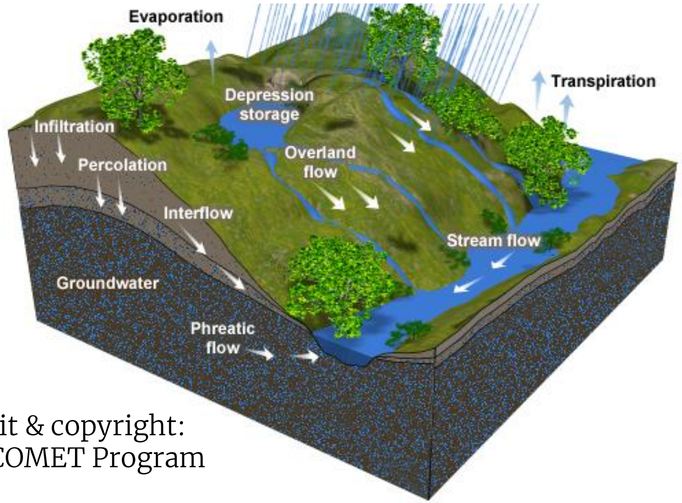
HCA analysis

- Hazardous liquids HCA (high consequence area) analysis
  - To identify “could affect” pipeline segments
  - Required by Title 49 CFR §195.452
  - Time consuming

A large number of simulations



Complicated physics phenomena



Credit & copyright:
the COMET Program

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Flow model: low-fidelity vs. high-fidelity approaches

Low-fidelity models

- 1D open-channel modeling
- 1D gravity flow modeling

Need less computing power
&
Currently popular for HCA analysis

High-fidelity models

- 3D free-surface full Navier-Stokes equations
- 2D shallow-water equations (SWEs)
  - Full SWEs
  - Kinematic approximation
  - Diffusive approximation

Need higher computing power
&
No open-source option specifically for HCA analysis

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This work

Full shallow-water equations solver

- For HCA analysis
- Open source license

Integration with cloud computing for large projects

- Microsoft Azure
- Scalable computing power
- Auto-scaling
- Usage-based charges

Integration with ArcGIS Pro

- Launching cloud simulations from a local machine/laptop

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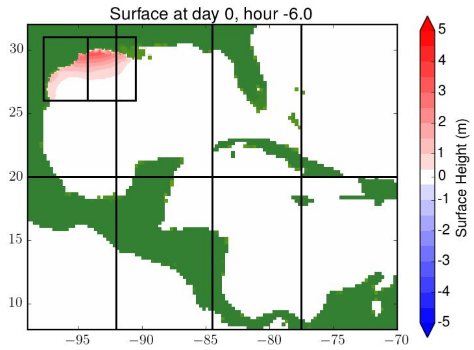
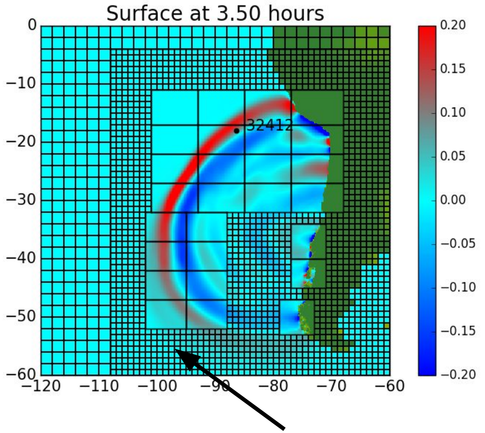
Solver for full shallow-water equations: GeoClaw

- Websites
  - Official: http://www.clawpack.org/geoclaw
  - Source code: https://github.com/clawpack/geoclaw
- Applications
  - Tsunami simulations
  - Storm surge simulations
- Feature
  - BSD-3 open-source license
  - Adaptive mesh refinement
  - Shared-memory parallelization

Storm surge



Tsunami



Adaptive mesh refinement:

- dynamic & non-uniform spatial resolution (raster grid)
- save calculations on areas that do not require high resolution

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Missing from GeoClaw

Done in this work

- Point source inflow (pipeline rupture point)
- Interaction with inland water bodies
- Darcy-Weisbach friction
- Temperature-dependent viscosity
- Evaporation model

Work in progress

- Adhesion
- Infiltration

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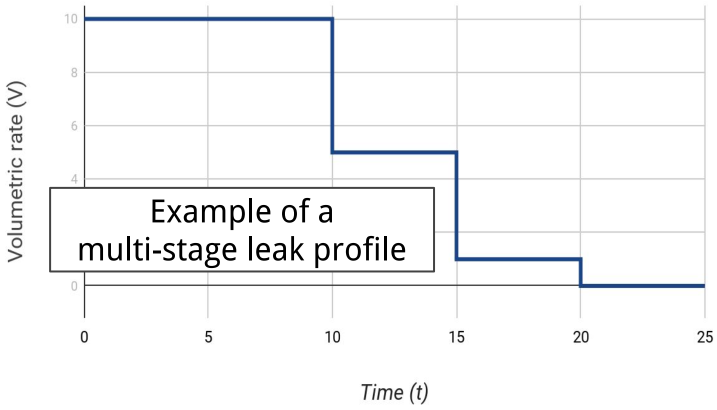
Rupture point & viscosity model

- Point source inflow as rupture point
  - Multi-stage constant rate



- Temperature-dependent viscosity (Lewis-Squires, 1934)
  - Hydrocarbon viscosities highly depend on temperature

$$\mu_a^{-0.2661} = \mu_k^{-0.2661} + \frac{(T_a - T_k)}{233}$$

T_a: desired temperature (℃)

T_k: reference temperature (℃)

μ_a: dynamic viscosity at the desired temperature (cP)

μ_k: dynamic viscosity at the reference temperature (cP)

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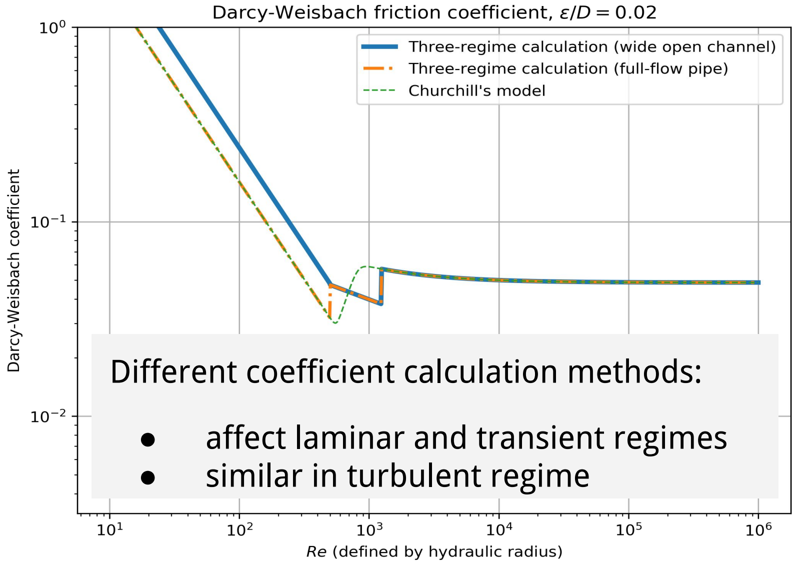
Darcy–Weisbach friction model

- Only require fluid viscosity and surface roughness
  - No extra experiments needed
  - Vegetation on the ground

Add to the right-hand-sides of the momentum equation

$$\begin{bmatrix} S_{fx} \\ S_{fy} \end{bmatrix} = \frac{f_{DW}}{8gh^3}\sqrt{(hu)^2+(hv)^2}\begin{bmatrix} hu \\ hv \end{bmatrix}$$



Different coefficient calculation methods:

- affect laminar and transient regimes
- similar in turbulent regime

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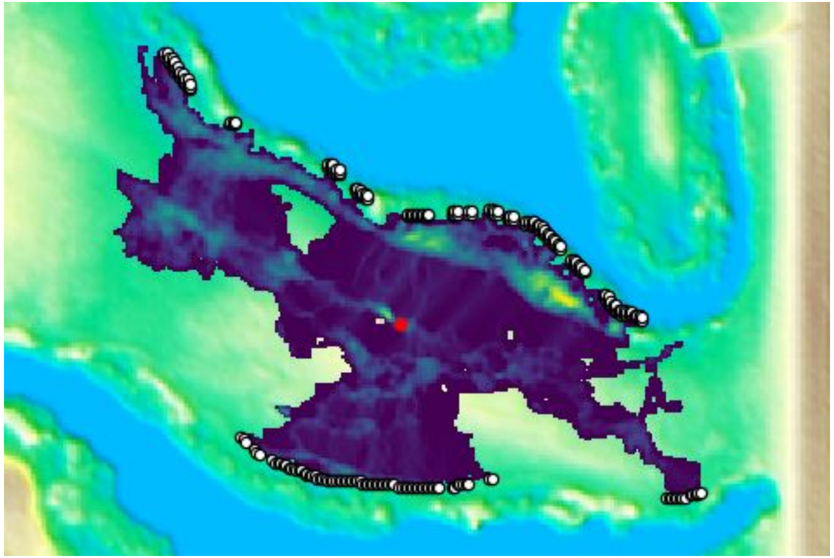
Intersection with In-land hydrological features

- Capture information required by hydrographic transport simulator



	x	y	time	w/o evap	w/ evap
	A	B	C	D	E
6	-12460297	4985236.9	1559.1	3.79E+00	3.62E+00
7	-12460297	4985237.9	1592.9	1.15E-01	1.08E-01
8	-12460296	4985234.9	1517.4	2.42E-01	2.27E-01
9	-12460296	4985235.9	1517.4	3.92E+00	3.73E+00
10	-12460296	4985236.9	1559.1	3.79E+00	3.62E+00
11	-12460296	4985237.9	1592.9	1.15E-01	1.08E-01
12	-12460295	4985232.9	1462.6	1.26E+01	1.20E+01
13	-12460295	4985233.9	1462.6	1.27E+01	1.21E+01
14	-12460295	4985234.9	1517.4	3.46E-01	3.25E-01
15	-12460295	4985235.9	1517.4	2.43E-01	2.27E-01
16	-12460295	4985236.9	1808.2	2.78E-04	2.58E-04
17	-12460294	4985231.9	1463.9	1.02E+01	9.76E+00
18	-12460294	4985232.9	1462.6	2.28E+01	2.18E+01
19	-12460294	4985233.9	1462.6	1.27E+01	1.21E+01
20	-12460294	4985234.9	1517.4	1.04E-01	9.85E-02
21	-12460293	4985230.9	1537.5	8.60E-03	7.98E-03

Example of the output data regarding hydrocarbon-waterbody intersection

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Evaporation models

- Account for the primary product loss in hydrocarbon plume

Fingas' model for non-volatile fluids (1996)

1. *Natural logarithm:* $\%_{Evap} = (C_1 + C_2 T)\ln(t)$
2. *Square root model:* $\%_{Evap} = (C_1 + C_2)\sqrt{t}$

$\%_{Evap}$: percentage of evaporated against initial spill volume

C_1 & C_2: coefficient obtained from experiments

T: ambient temperature (℃)

t: elapsed time (minutes)

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Workflow features

- Automatically download topography and hydrologic features
  - 3DEP server & NHD servers (US data only)
  - ESRI World Elevation server (require ESRI credential)
- NetCDF raster output
  - CF-1.7 convention
  - Multidimensional dataset
- Docker image available
  - Useful for Windows machines

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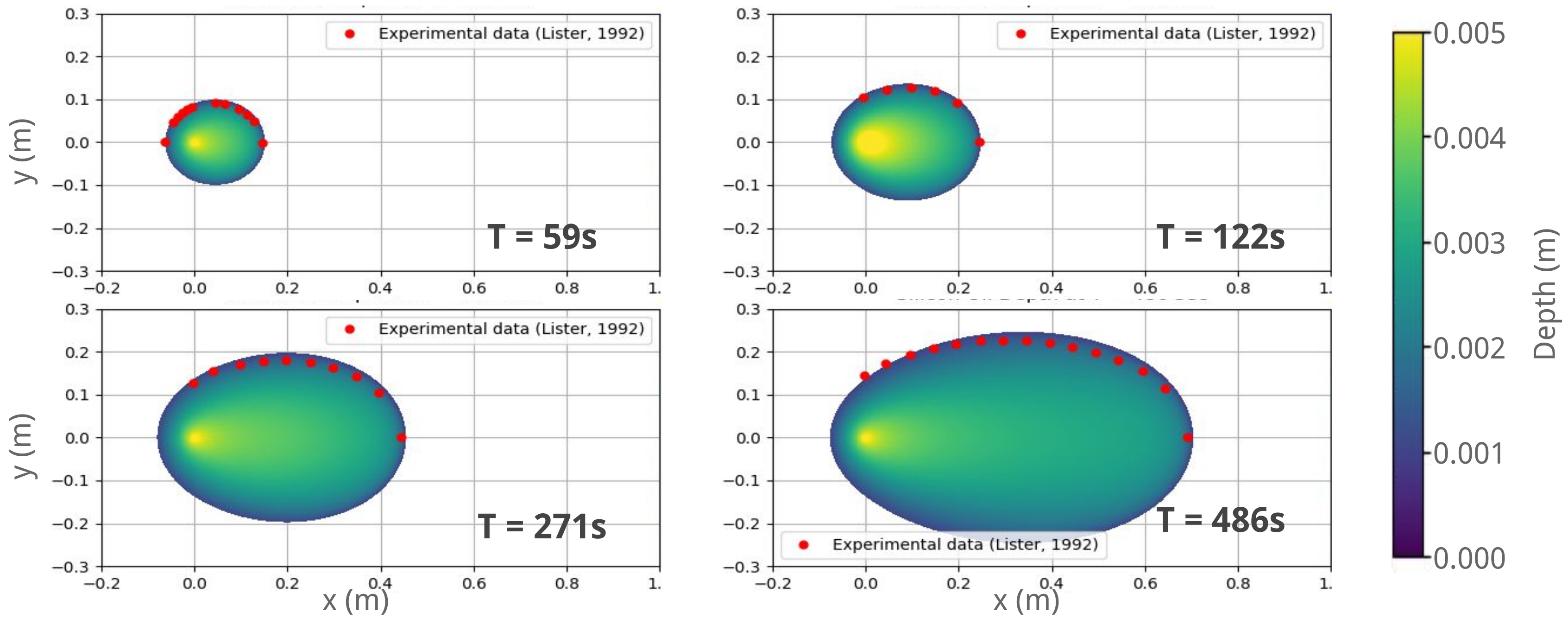
Validation: silicone oil, inclined glass plate

- Angle: 2.5°; Rate: 1.48e^{-6} m^3/sec; Surface roughness: 0; No evaporation



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Viscosity effect: horizontal plate spill

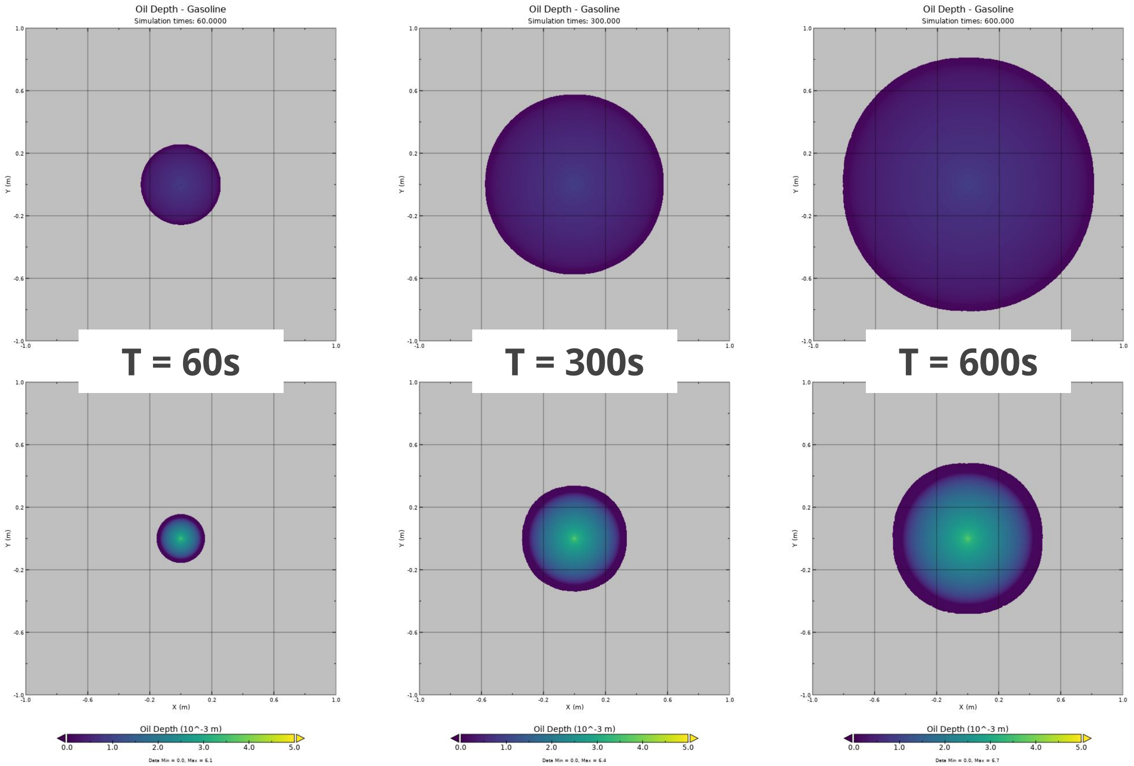
Gasoline:

- μ_a: 0.6512 cP @ 15°C
- API gravity: 45°

- Rate: 1.48e^{-6} m^3/sec
- Roughness: 0
- No evaporation

Maya crude:

- μ_a: 332 cP @ 15°C
- API gravity: 21.5°



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Common settings of the demos

- Inflow rate:
  - 0 min ~ 30 min: 0.5 m^3/sec
  - 30 min ~ 210 min: 0.1 m^3/sec
  - 0 m^3/sec afterward
- Total volume released: 1980 m^3
- Surface roughness: 0.1 m
- Ambient temperature: 25 ℃
- Simulation time: 0 ~ 8 hr

Gasoline:

- μ_a: 0.6512 cP @ 15℃
- API gravity: 45°
- $\%_{Evap} = (13.2 + 0.21T) ln(t)$

Maya crude:

- μ_a: 332 cP @ 15℃
- API gravity: 21.5°
- $\%_{Evap} = (1.38 + 0.045T) ln(t)$

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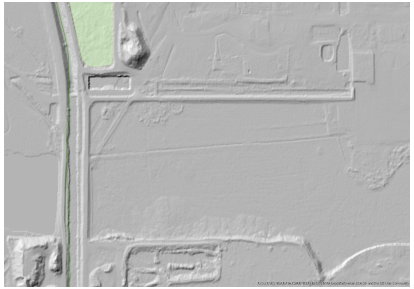
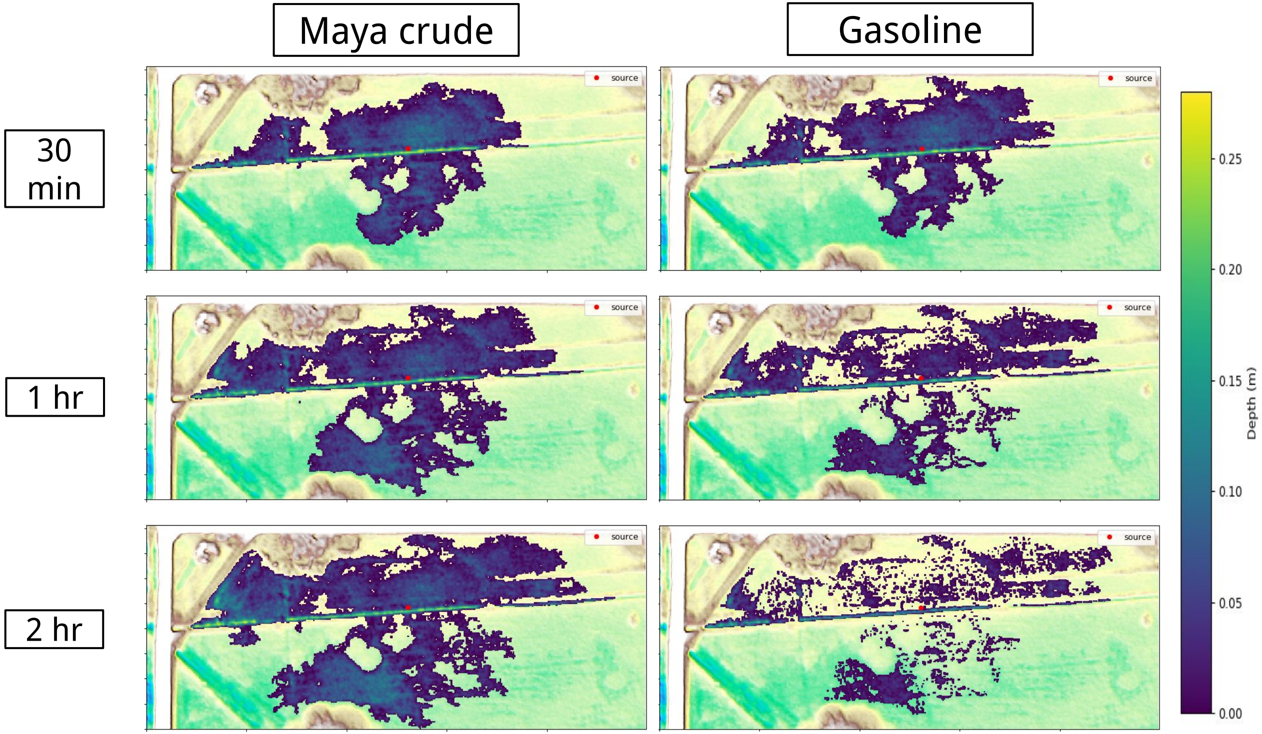
Demo: flat area





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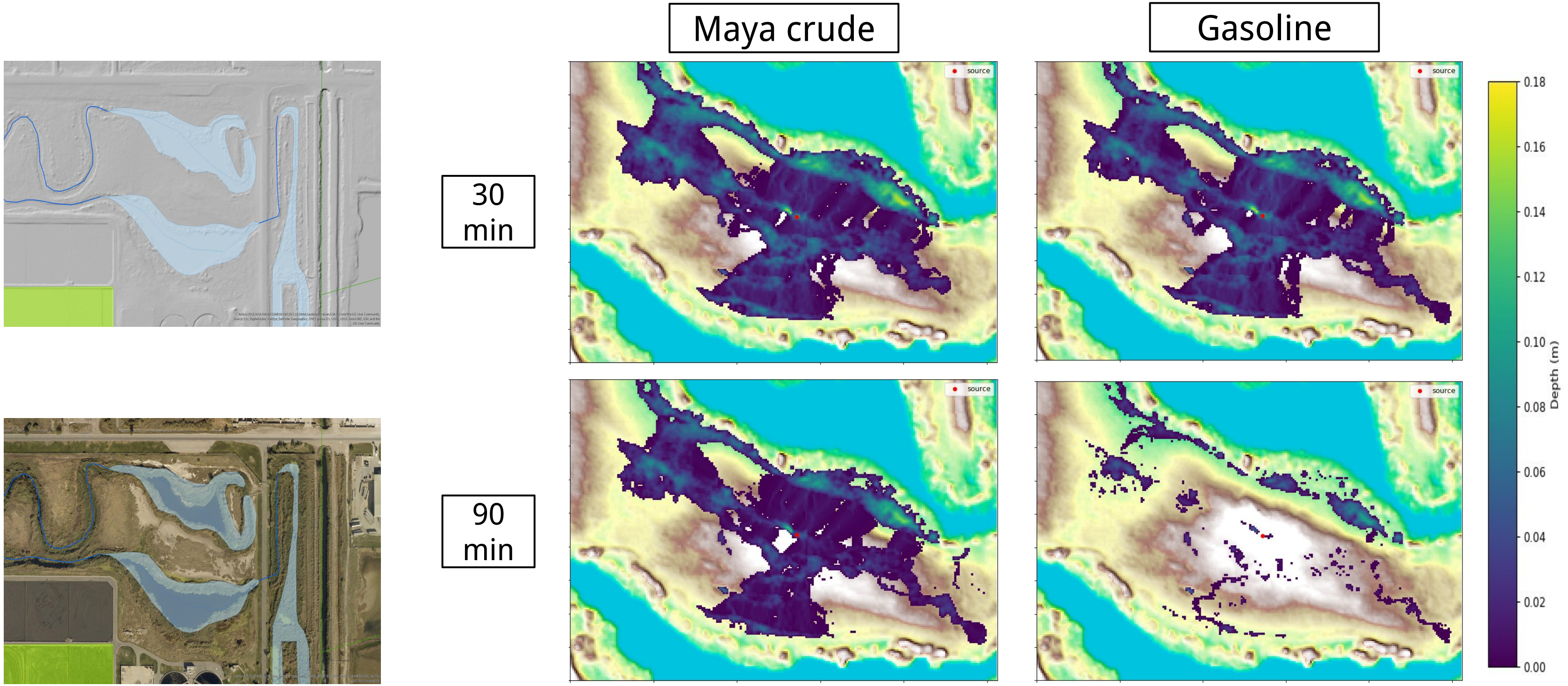
Demo: with inland water bodies



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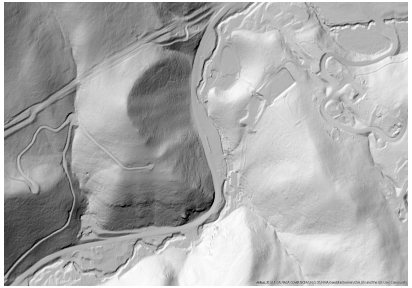
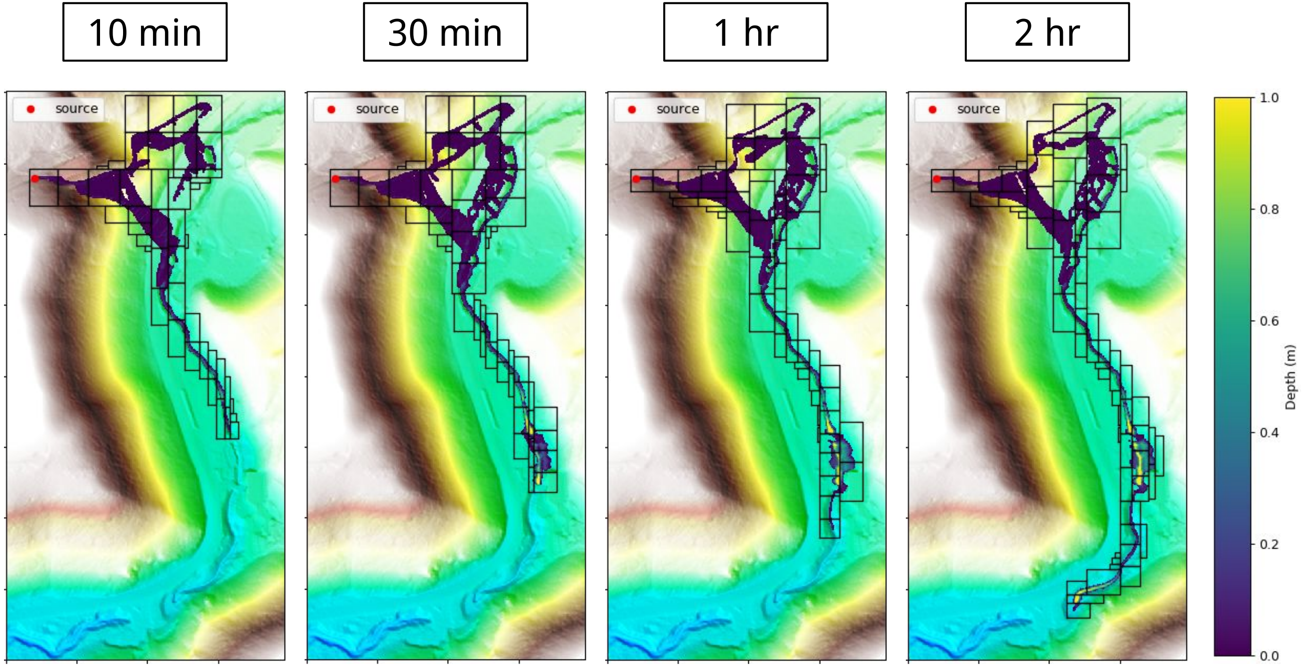
Demo: hill area (Maya crude)





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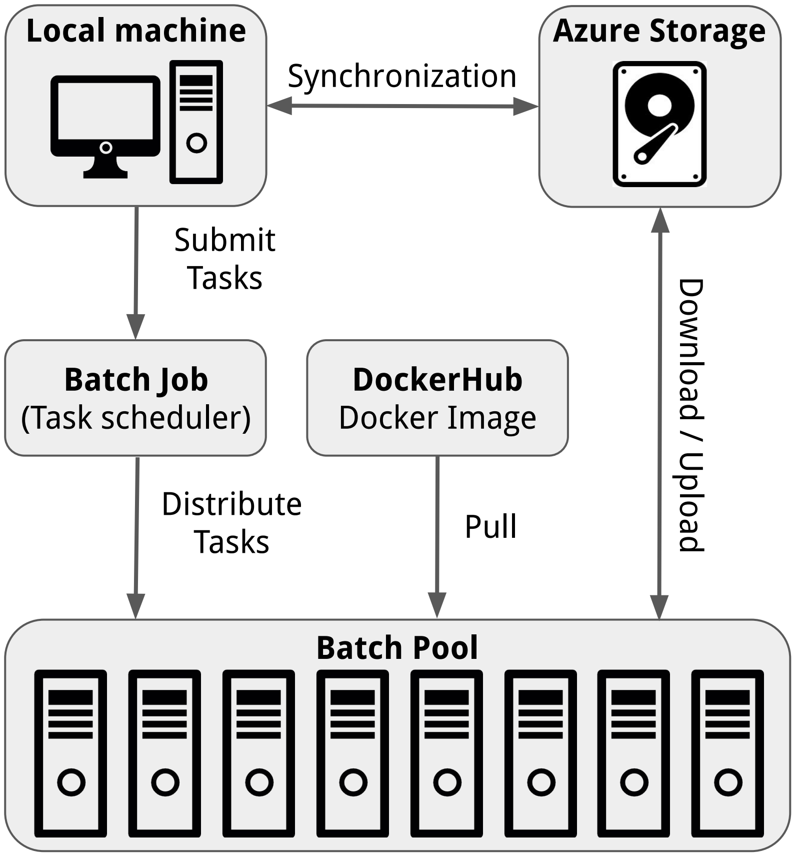
Microsoft Azure

- geoclaw-azure-launcher
  - Source code: https://github.com/barbagroup/geoclaw-azure-launcher
  - Python module `helpers.azuretools`
- Required Azure services
  - Azure Batch account
  - Azure Storage account



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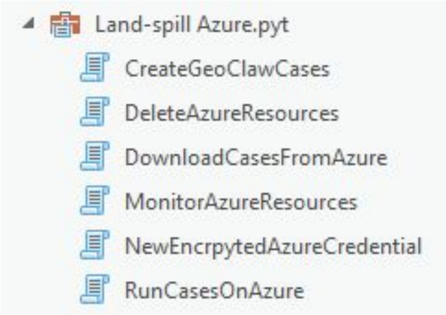
Interface through ArcGIS Toolbox

- geoclaw-azure-launcher
  - Source code: https://github.com/barbagroup/geoclaw-azure-launcher
  - ArcGIS Toolbox `Land-spill Azure.pyt`
  - 6 tools
    - 1 tool to create GeoClaw inputs
    - 4 tools to communicate with Azure
    - 1 utility to create credential file



Check the demo video!

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ArcGIS Python toolbox workflow

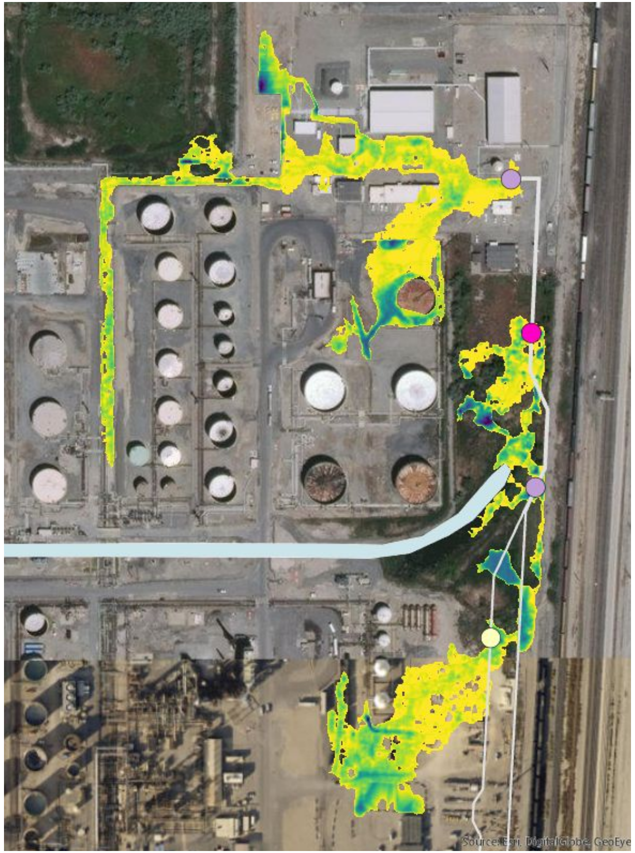
Main workflow

- CreateGeoClawCases → RunCasesOnAzure
- RunCasesOnAzure → MonitorAzureResources
- MonitorAzureResources → DownloadCasesFromAzure
- → **Import NetCDF files**

Other tools

- DeleteAzureResources
- NewEncryptedAzureCredential

Check the demo video!



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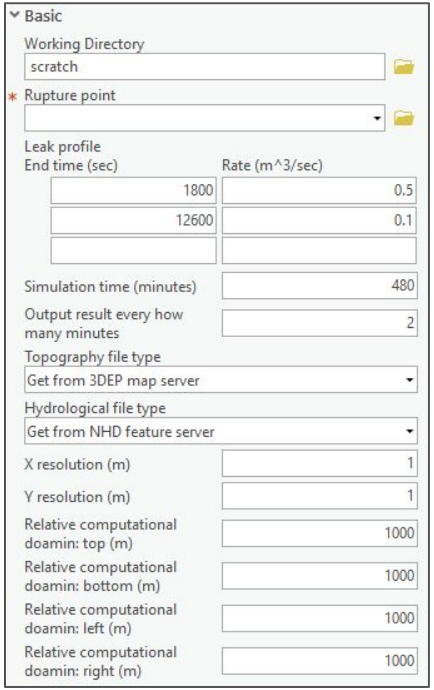
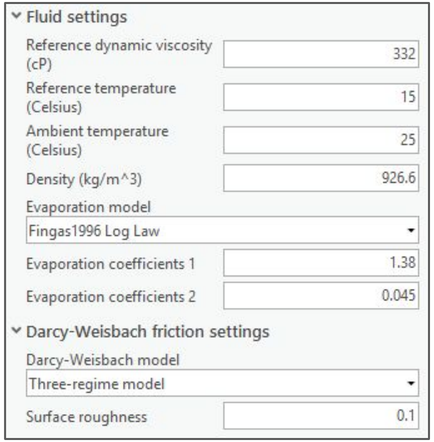
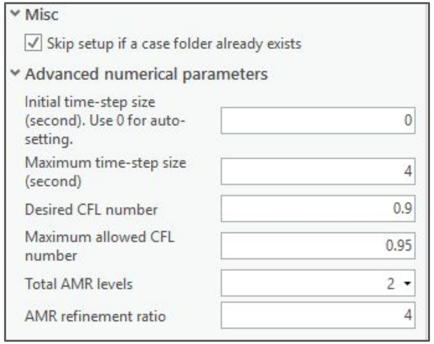
Tool: `CreateGeoClawCases`

- Create GeoClaw cases for selected rupture points
  - Rupture points
  - Leak profile
  - Physical properties
  - Model parameters
  - Computational parameters
  - Topography and inland water bodies







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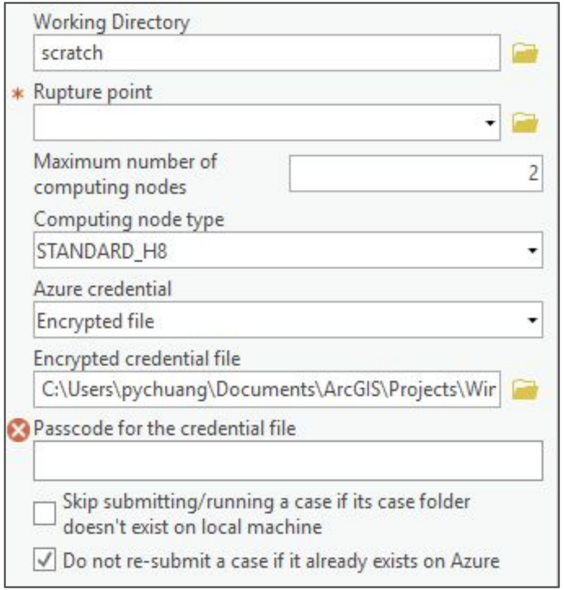
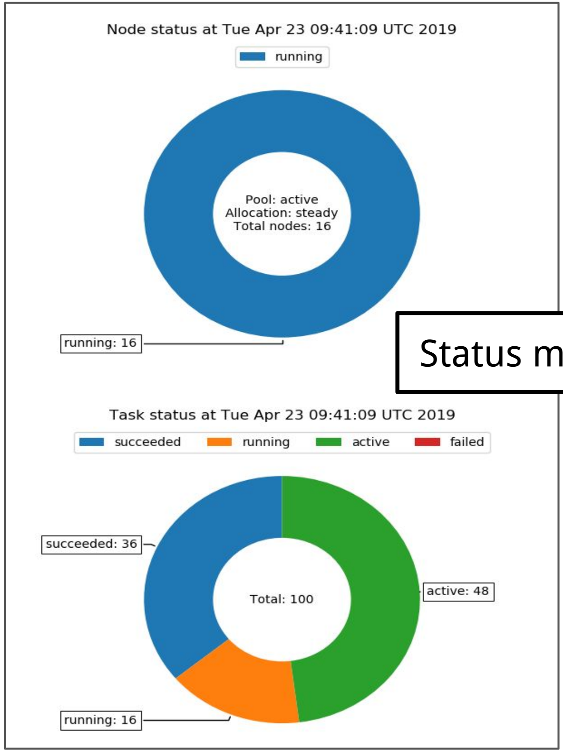
Tool: `RunCasesOnAzure` & `MonitorAzureResources`

GUI for creating Azure resources
and submitting simulations





Status monitor

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Conclusion

- High-fidelity simulator that provides more accurate predictions of pipeline segments affecting an HCA
    - **Model components**: 2D full shallow-water equations, rupture point inflow, Darcy-Weisbach friction, temperature-dependent viscosity, evaporation, hydrocarbon plume/water bodies contact
    - **Simulator features**: automatic downloading from 3DEP and NHD; adaptive mesh refinement; shared-memory parallelization
- Scalable computing performance through Microsoft Azure cloud
- ArcGIS Pro toolbox

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Q & A

- Acknowledgement
  - Tom Bell, G2 Integrated Solution
  - Kyle Mandli, Columbia University

- Source code URLs:
  - https://github.com/barbagroup/geoclaw
  - https://github.com/barbagroup/geoclaw-landspill-cases
  - https://github.com/barbagroup/geoclaw-azure-launcher
- Docker image on DockerHub
  - barbagroup/landspill

Demo video

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INTEGRATED SOLUTIONS

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Extra slides

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Darcy–Weisbach friction model

- Add to the right-hand-sides of the momentum equation

$$\begin{bmatrix} S_{fx} \\ S_{fy} \end{bmatrix} = \frac{f_{DW}}{8gh^3}\sqrt{(hu)^2+(hv)^2}\begin{bmatrix} hu \\ hv \end{bmatrix}$$

Three regime model

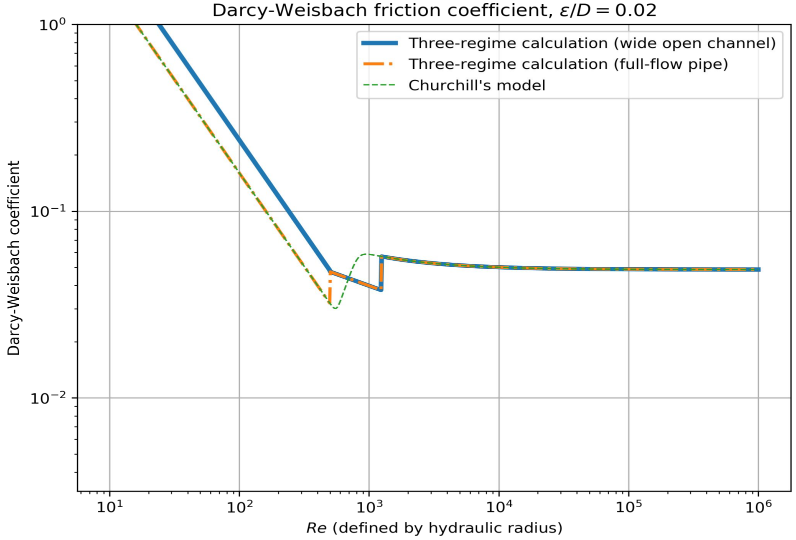
$$\begin{cases} Laminar\ (Re<500):\ \dfrac{24}{Re}\left(or\ \dfrac{16}{Re}\ for\ wide-open\ channel\right) \\ Transient\ (500<Re<1250):\ \dfrac{0.224}{Re^{0.25}} \\ Full\ turbulent\ (Re>1250):\ \dfrac{0.25}{\log_{10}^2\left(\sigma/14.8h+1.648Re^{0.9}\right)} \end{cases}$$

Churchill's model

$$A=\left[2.457\ln\left(\frac{1}{(1.75/Re)^{0.9}+0.0675\sigma}\right)\right]^{16}$$

$$B=\left(\frac{9382.5}{Re}\right)^{16}$$

$$f_{DW}=8\times\left[\left(\frac{2}{Re}\right)^{12}+\frac{1}{(A+B)^{3/2}}\right]^{1/12}$$



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Evaporation models

- Evaporation
  - Fingas' observation: **contact area does not affect the evaporation rates of most hydrocarbon fluids when "*the depths are shallow*".**
  - Solution: treat volume on the ground and in the pipeline as a continuum
    - Initial volume: total volume that will be released to the domain
    - For each time step, both the volumes in the pipeline and on the ground undergo evaporation with percentage $\%_{Evap}$
    - Release rate is fixed => shorten the release period

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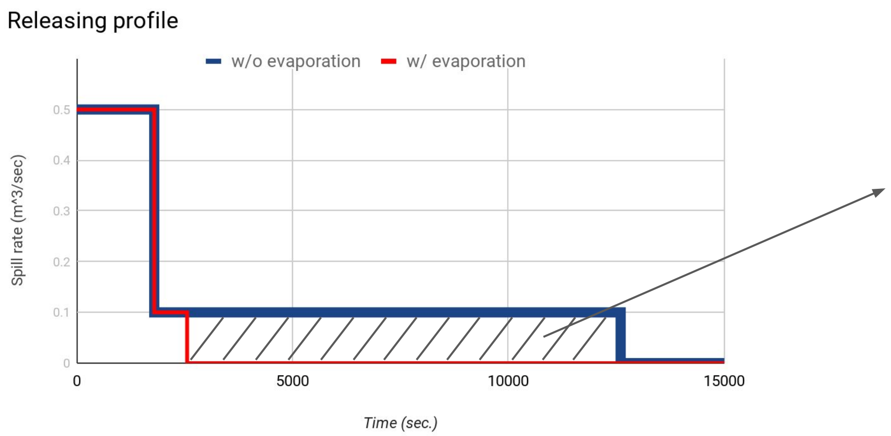
Evaporation models

- Evaporation issues:
  - Oil has flown into water bodies also undergoes the same evaporation mechanism
  - High evaporation-rate fluids evaporate inside pipelines



- About 50% of the volume evaporates directly from inside the pipeline.
- i.e., 50% of the volume never participates in overland flow.

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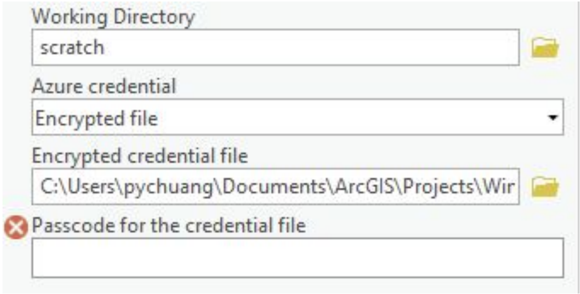
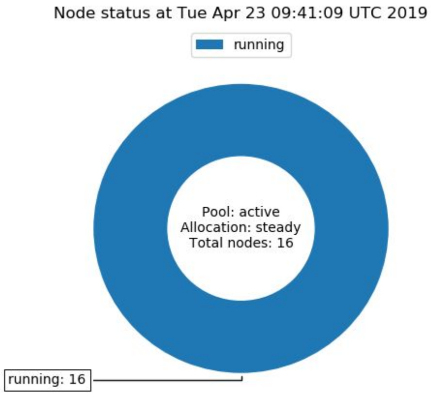
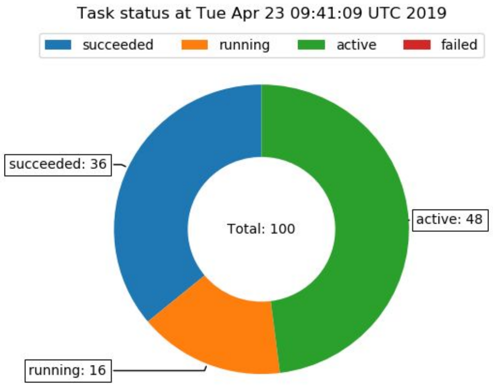
Tool: `MonitorAzureResources`

- Pop up a graphical monitor for the custer and tasks







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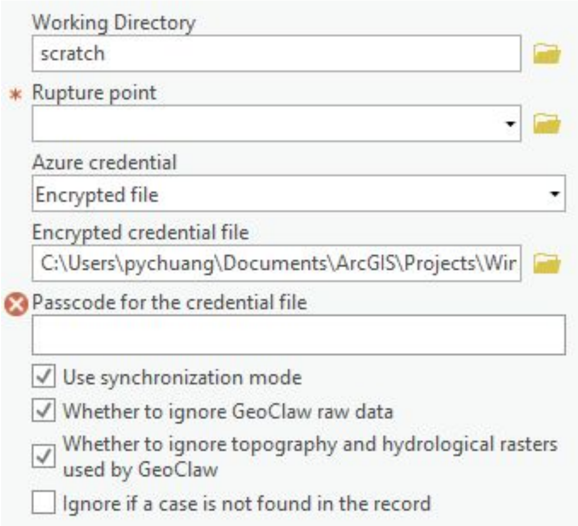
Tool: `DownloadData` & `DeleteAzureResources`

- DownloadData
    - Synchronization mode



- Delete cloud resources

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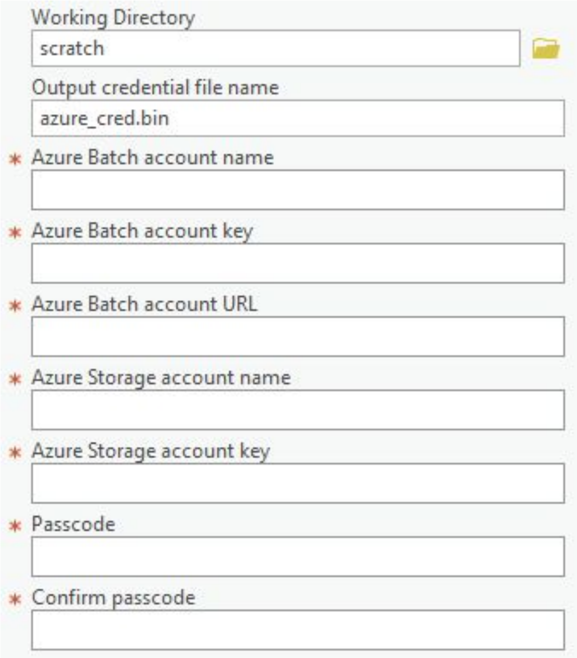
Tool: `NewEncryptedAzureCredential`

- Create an encrypted Azure credential file
  - Batch account name, key, and url
  - Storage account name and key
- Users don’t have to copy & paste credential info every time



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