

GeoClaw–ArcGIS Integration for Advanced Modeling of Overland Hydrocarbon Plumes

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INTEGRATED
SOLUTIONS

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

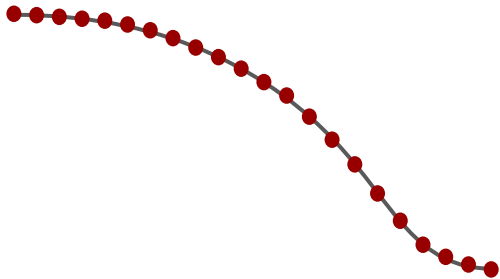
[Demo video](#)



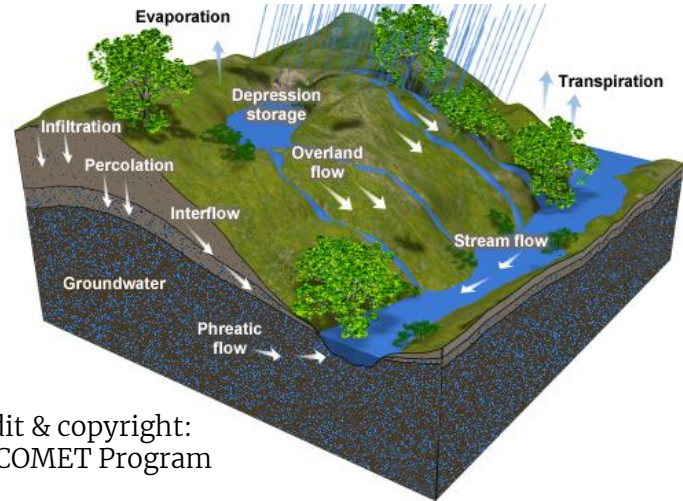
HCA analysis

- 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

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**

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

Solver for full shallow-water equations: GeoClaw

- Websites

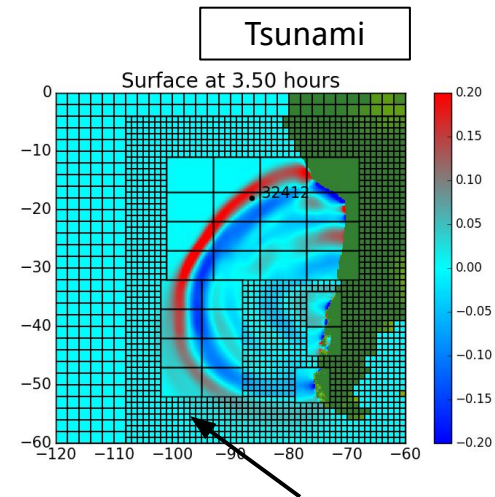
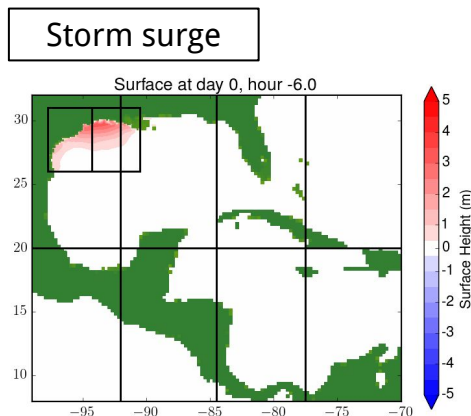
- Official: <http://www.clawpack.org/geoclaw>
- Source code: <https://github.com/clawpack/geoclaw>

- Applications

- Tsunami simulations
- Storm surge simulations

- Feature

- BSD-3 open-source license
- Adaptive mesh refinement
- Shared-memory parallelization



Adaptive mesh refinement:

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

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

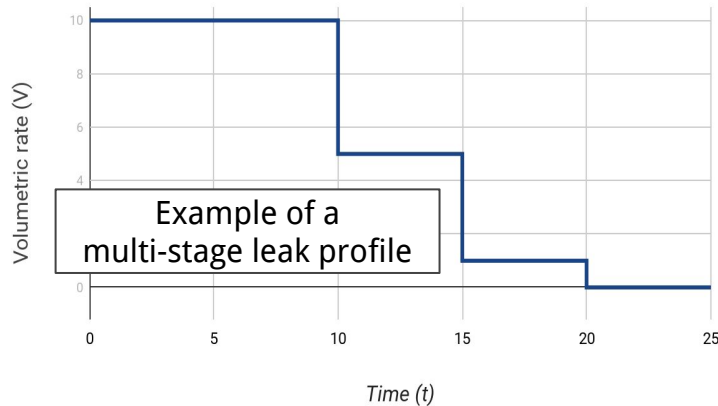
Work in progress

Adhesion

Infiltration

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 (°C)

T_k : reference temperature (°C)

μ_a : dynamic viscosity at the desired temperature (cP)

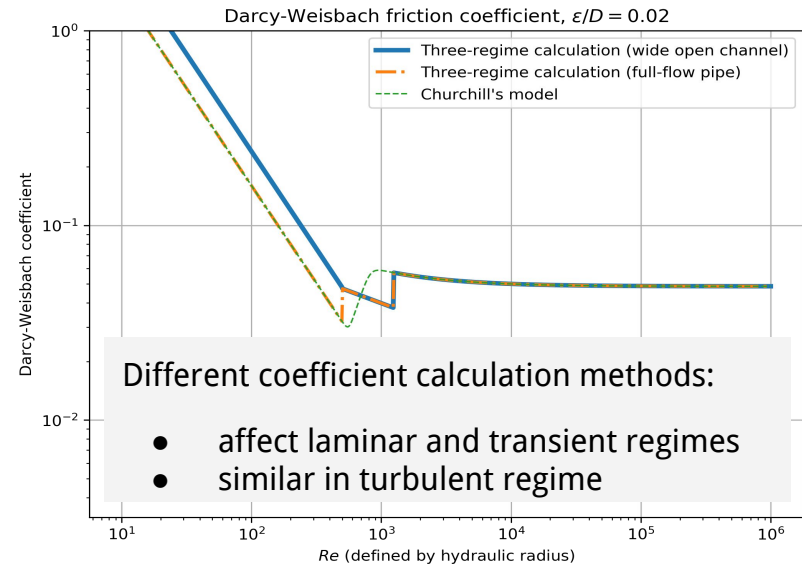
μ_k : dynamic viscosity at the reference temperature (cP)

Darcy-Weisbach friction model

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

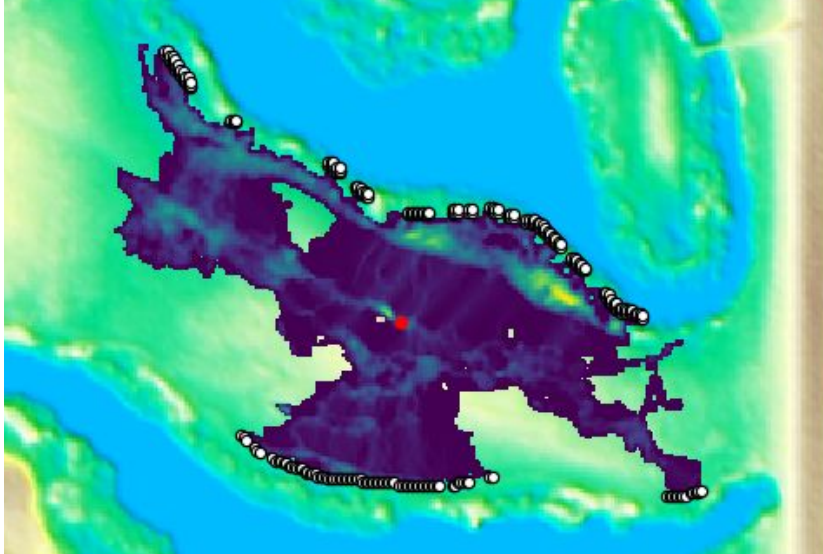
Add to the right-hand-sides of the momentum equation

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



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

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 (°C)

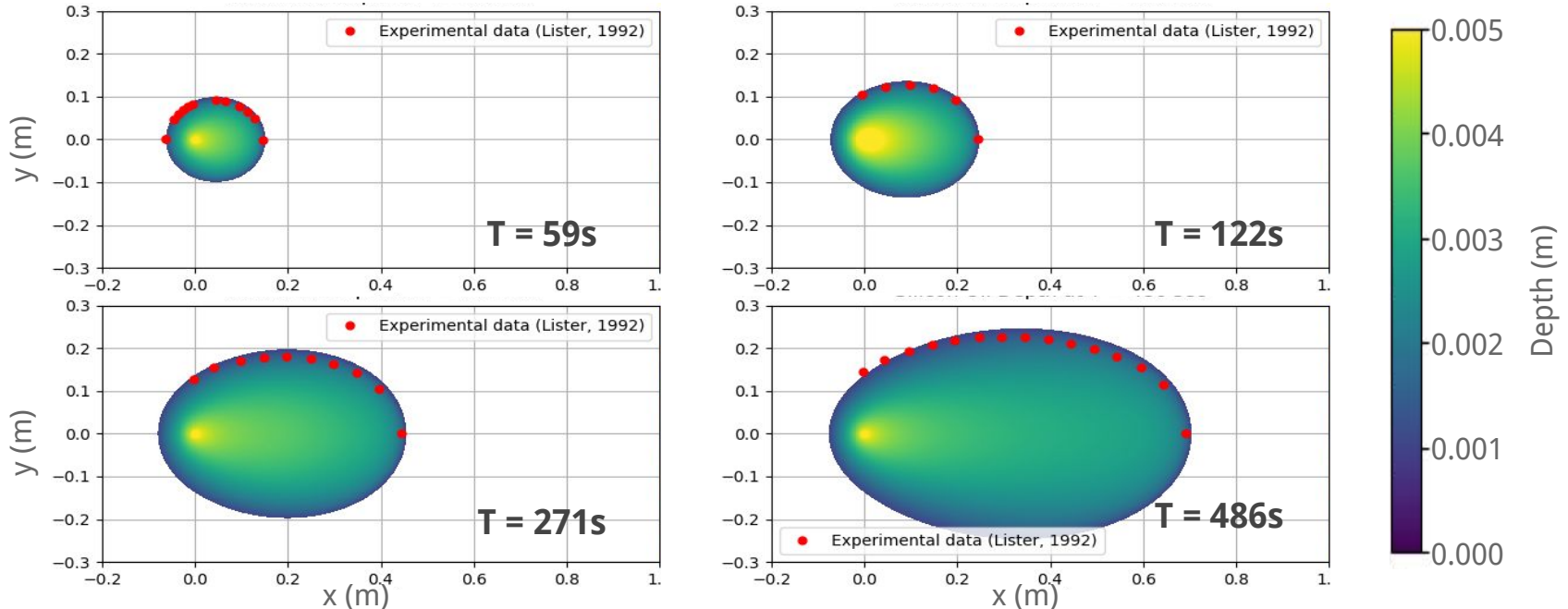
t : elapsed time (minutes)

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

Validation: silicone oil, inclined glass plate

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



Viscosity effect: horizontal plate spill

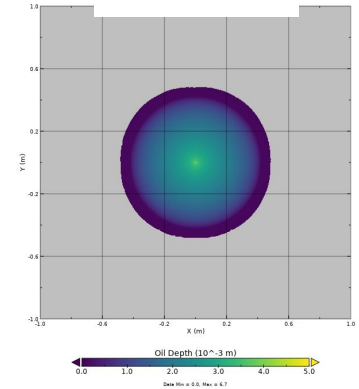
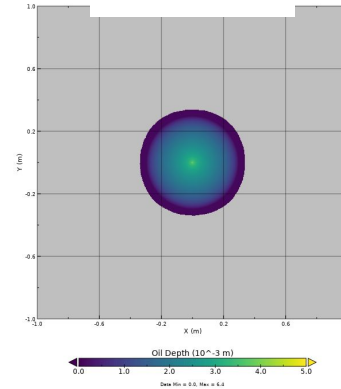
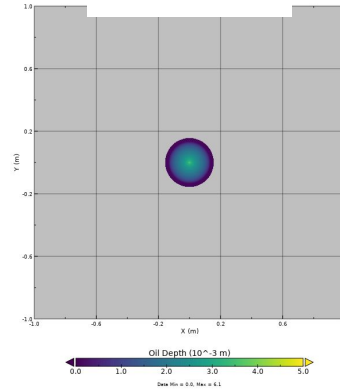
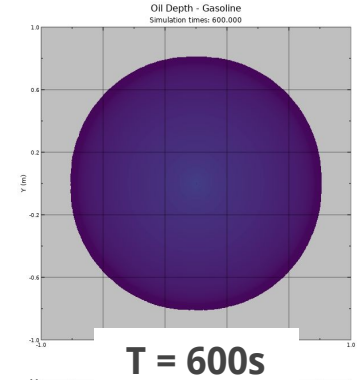
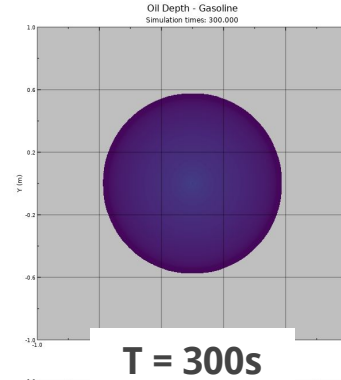
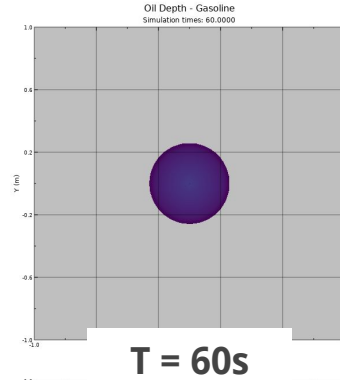
Gasoline:

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

- Rate: $1.48 \times 10^{-6} \text{ m}^3/\text{sec}$
- Roughness: 0
- No evaporation

Maya crude:

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



Common settings of the demos

- Inflow rate:
 - 0 min ~ 30 min: 0.5 m³/sec
 - 30 min ~ 210 min: 0.1 m³/sec
 - 0 m³/sec afterward
- Total volume released: 1980 m³
- Surface roughness: 0.1 m
- Ambient temperature: 25 °C
- Simulation time: 0 ~ 8 hr

Gasoline:

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

Maya crude:

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

Demo: flat area



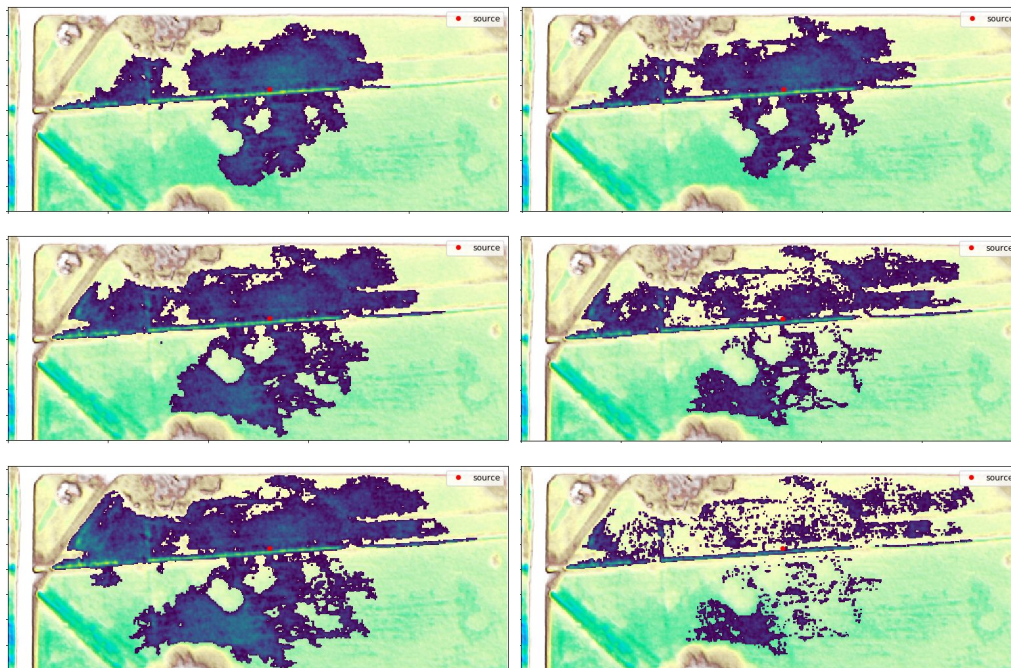
30
min

1 hr

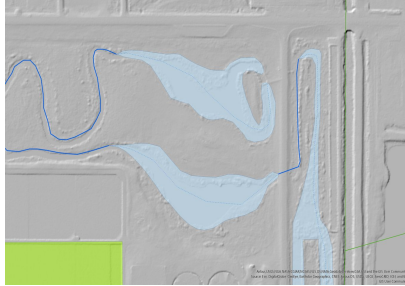
2 hr

Maya crude

Gasoline



Demo: with inland water bodies

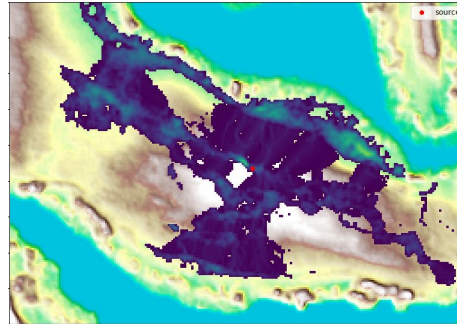
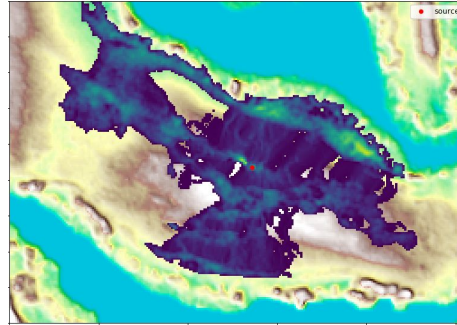


30
min

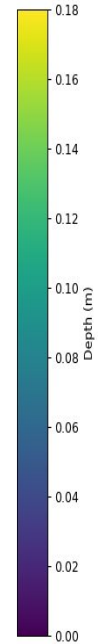
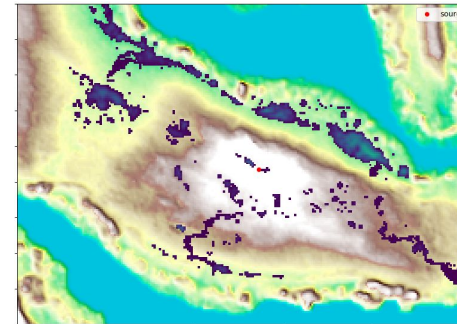
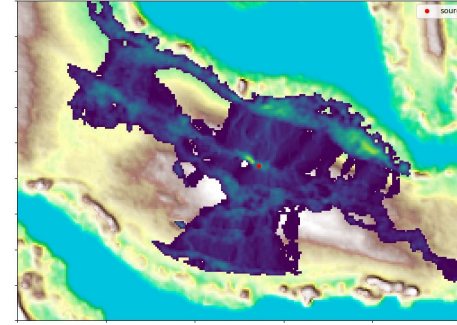


90
min

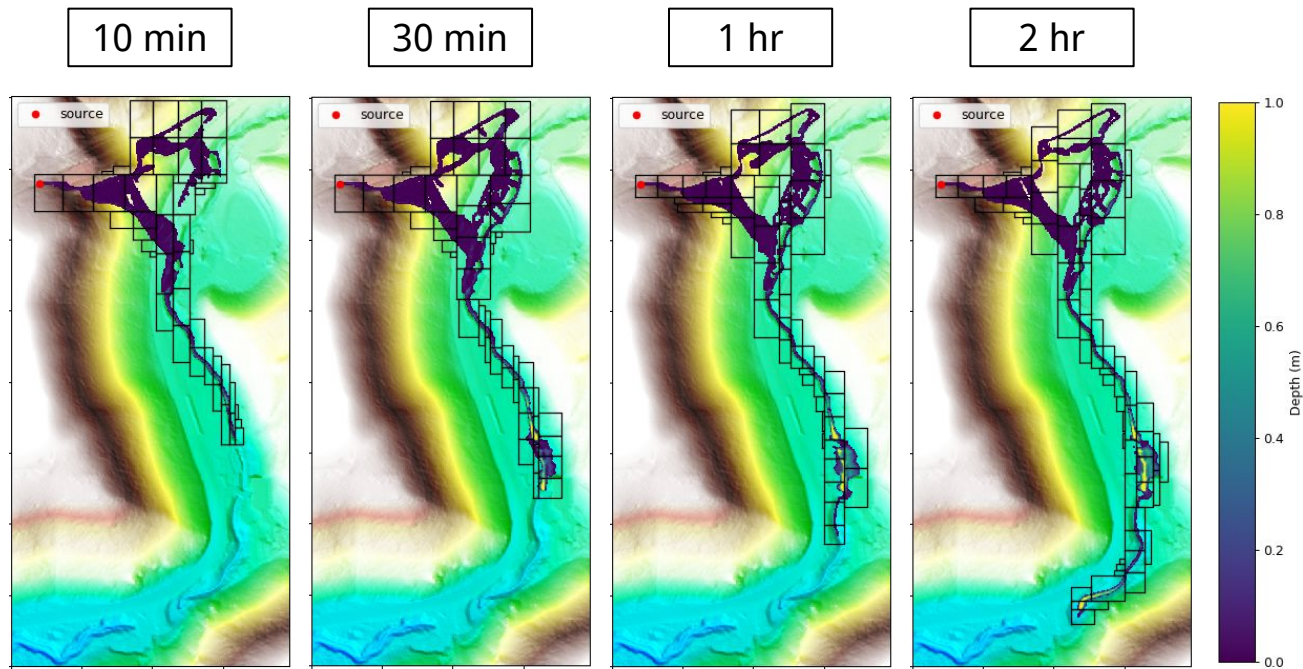
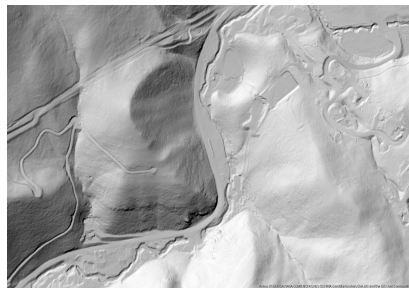
Maya crude



Gasoline

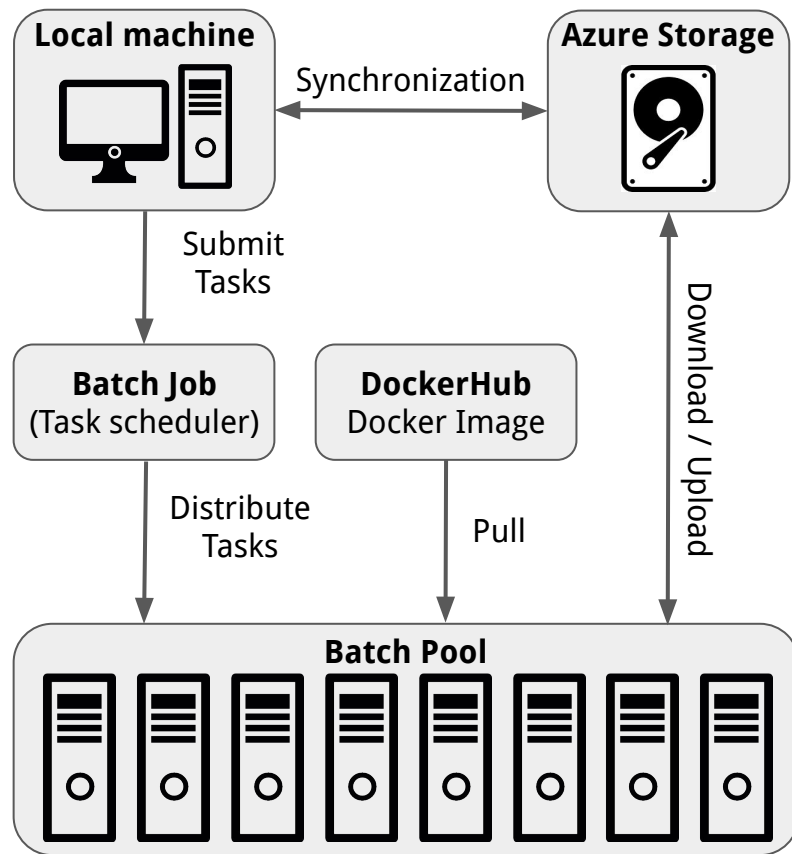


Demo: hill area (Maya crude)



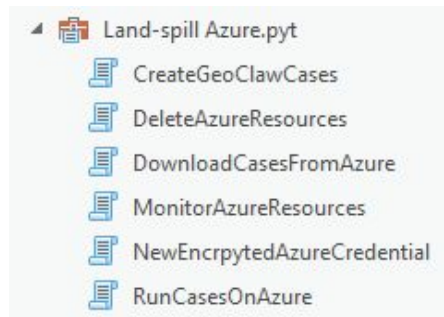
Microsoft Azure

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



Interface through ArcGIS Toolbox

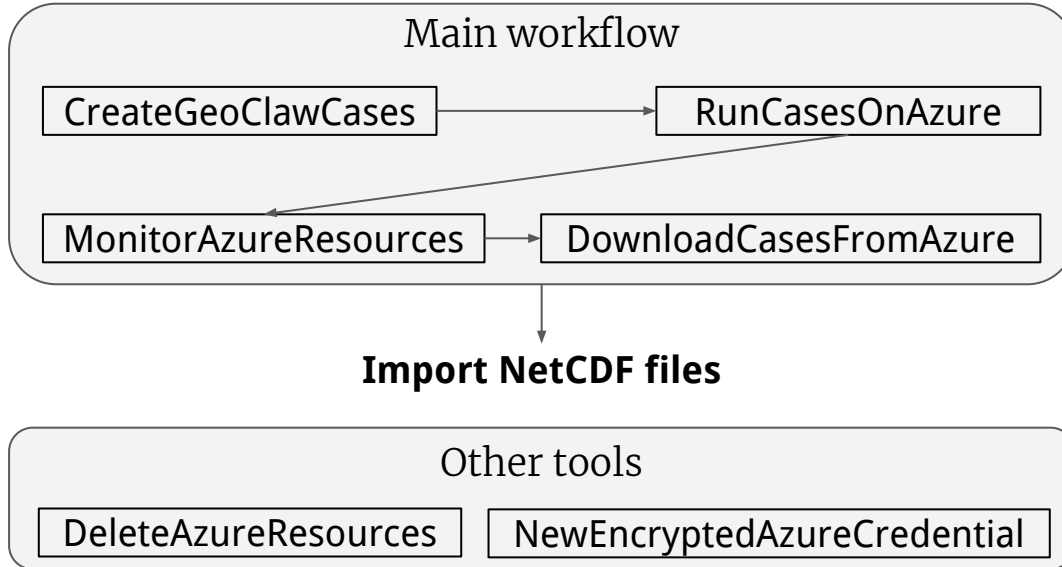
- geoclaw-azure-launcher
 - Source code: <https://github.com/barbagroup/geoclaw-azure-launcher>
 - ArcGIS Toolbox **Land-spill Azure.pyt**
 - 6 tools
 - 1 tool to create GeoClaw inputs
 - 4 tools to communicate with Azure
 - 1 utility to create credential file



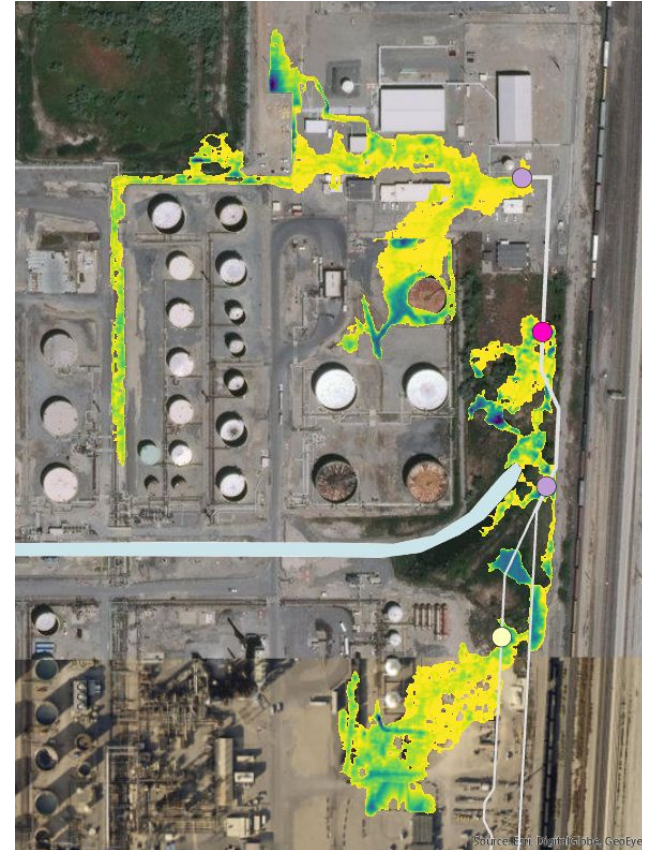
[Check the
demo video!](#)



ArcGIS Python toolbox workflow



[Check the demo video!](#)



Tool: CreateGeoClawCases

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

▼ Basic

Working Directory
scratch

* Rupture point

Leak profile

End time (sec)	Rate (m ³ /sec)
1800	0.5
12600	0.1

Simulation time (minutes) 480

Output result every how many minutes 2

Topography file type
Get from 3DEP map server

Hydrological file type
Get from NHD feature server

X resolution (m) 1

Y resolution (m) 1

Relative computational domain: top (m) 1000

Relative computational domain: bottom (m) 1000

Relative computational domain: left (m) 1000

Relative computational domain: right (m) 1000

▼ Fluid settings

Reference dynamic viscosity (cP) 332

Reference temperature (Celsius) 15

Ambient temperature (Celsius) 25

Density (kg/m³) 926.6

Evaporation model
Fingas1996 Log Law

Evaporation coefficients 1 1.38

Evaporation coefficients 2 0.045

▼ Darcy-Weisbach friction settings

Darcy-Weisbach model
Three-regime model

Surface roughness 0.1

▼ Misc

☒ Skip setup if a case folder already exists

▼ Advanced numerical parameters

Initial time-step size (second). Use 0 for auto-setting. 0

Maximum time-step size (second) 4

Desired CFL number 0.9

Maximum allowed CFL number 0.95

Total AMR levels 2

AMR refinement ratio 4

Tool: RunCasesOnAzure & MonitorAzureResources

GUI for creating Azure resources
and submitting simulations

Working Directory
scratch

* Rupture point
[dropdown]

Maximum number of computing nodes
2

Computing node type
STANDARD_H8

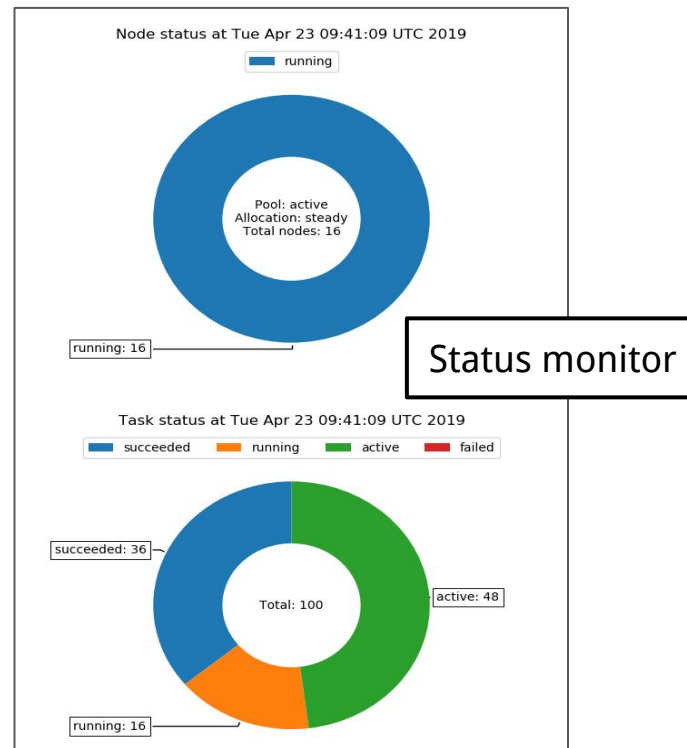
Azure credential
Encrypted file

Encrypted credential file
C:\Users\pychuang\Documents\ArcGIS\Projects\Wir

Passcode for the credential file
[input field]

☐ Skip submitting/running a case if its case folder doesn't exist on local machine

☒ Do not re-submit a case if it already exists on Azure



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

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



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Extra slides

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

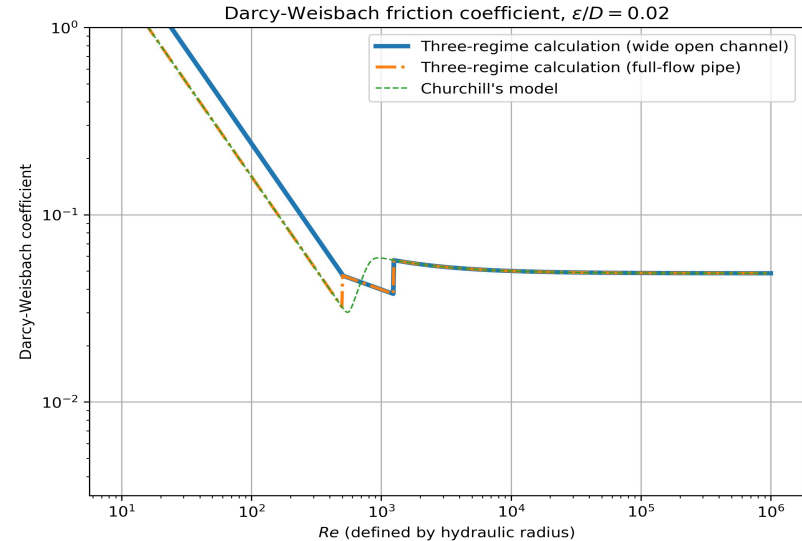
$$\begin{cases} \text{Laminar (} Re < 500 \text{)} : \frac{24}{Re} \left(\text{or } \frac{16}{Re} f \text{ or wide - open channel} \right) \\ \text{Transient (} 500 < Re < 1250 \text{)} : \frac{0.224}{Re^{0.25}} \\ \text{Full turbulent (} Re > 1250 \text{)} : \frac{0.25}{\log_{10}^2(\sigma/14.8h + 1.648Re^{0.9})}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

Churchill's model

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

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

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



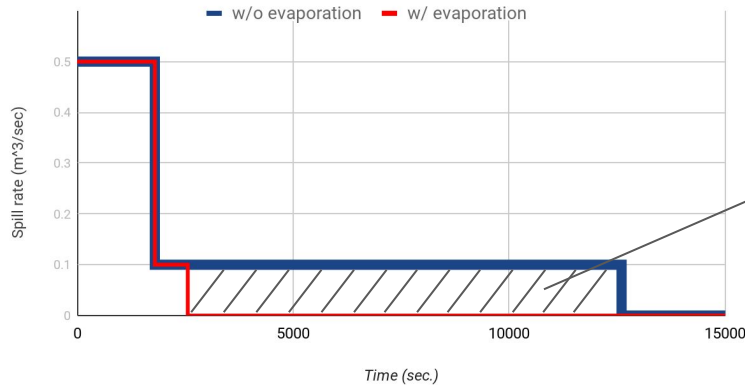
Evaporation models

- 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

Evaporation models

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

Releasing profile



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

Tool: MonitorAzureResources

- Pop up a graphical monitor for the cluster and tasks

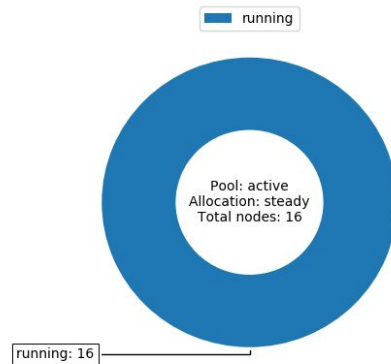
Working Directory
scratch

Azure credential
Encrypted file

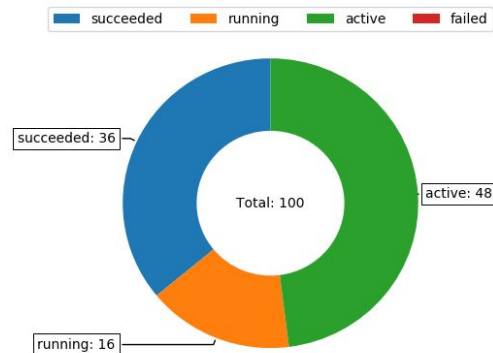
Encrypted credential file
C:\Users\pychuang\Documents\ArcGIS\Projects\Wir

Passcode for the credential file

Node status at Tue Apr 23 09:41:09 UTC 2019



Task status at Tue Apr 23 09:41:09 UTC 2019



Tool: DownloadData & DeleteAzureResources

- DownloadData
 - Synchronization mode
- Delete cloud resources

Working Directory
scratch

* Rupture point
[dropdown]

Azure credential
Encrypted file

Encrypted credential file
C:\Users\pychuang\Documents\ArcGIS\Projects\Wir

✗ Passcode for the credential file
[text box]

☒ Use synchronization mode
☒ Whether to ignore GeoClaw raw data
☒ Whether to ignore topography and hydrological rasters used by GeoClaw
☐ Ignore if a case is not found in the record

Working Directory
scratch

☒ Delete pool (cluster)
☒ Delete job (task scheduler)
☐ Delete storage container

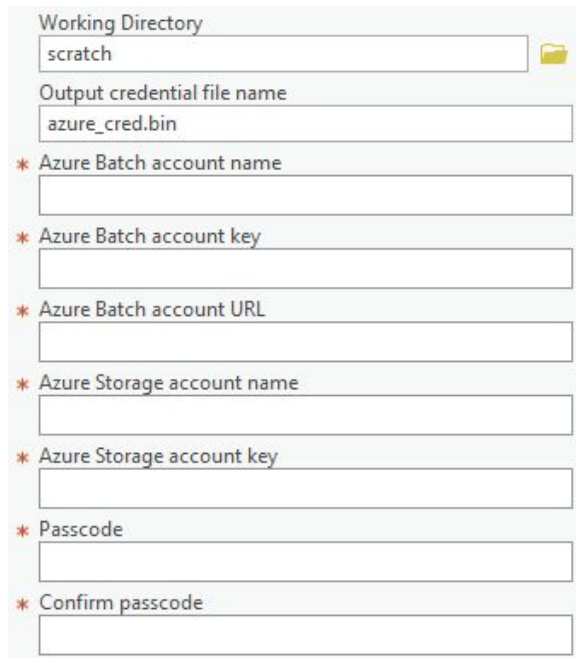
Azure credential
Encrypted file

Encrypted credential file
C:\Users\pychuang\Documents\ArcGIS\Projects\Wir

✗ Passcode for the credential file
[text box]

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



The screenshot displays the user interface of the 'NewEncryptedAzureCredential' tool. It features a light gray background with white input fields. The fields are organized as follows:

- Working Directory:** A text field containing 'scratch' with a folder icon to its right.
- Output credential file name:** A text field containing 'azure_cred.bin'.
- * Azure Batch account name:** A text field with a red asterisk icon to its left.
- * Azure Batch account key:** A text field with a red asterisk icon to its left.
- * Azure Batch account URL:** A text field with a red asterisk icon to its left.
- * Azure Storage account name:** A text field with a red asterisk icon to its left.
- * Azure Storage account key:** A text field with a red asterisk icon to its left.
- * Passcode:** A text field with a red asterisk icon to its left.
- * Confirm passcode:** A text field with a red asterisk icon to its left.