CPS: Medium: Making Every Drop Count: Accounting for Spatiotemporal Variability of Water Needs for Proactive Scheduling of Variable Rate Irrigation Systems

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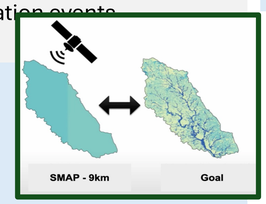
Project Overview

HYDRO is a CPS for precision agriculture. The overarching objective of HYDRO is to develop an end-to-end cyber-physical intelligence system that forecasts space-time crop water needs in a given field and implements variable rate irrigation strategies to optimize crop yield throughout the field.

We instrument the field with a limited number of in-situ soil moisture content sensors; these in situ observations are complemented with remotely sensed data from radars and satellites. The effort includes design of novel AI (Artificial Intelligence) methods based on deep neural networks (DNN) to generate forecasts of water needs. These DNNs operate on multimodal, high-dimensional data to identify soil moisture deficits and variability in different parts of the field. The generated forecasts account for crop, soil type, precipitation events, and the crop growing phase.

The project closes the loop between the sensing environment and actuation within the AI-guided cyber physical system. These projections are leveraged within a game theory-based algorithm to inform precise actuations of the watering arm with prescription plans that control watering rates at the nozzle and zone level. The algorithm is adaptive and responsive to precipitation events, uncertainty in the forecasts, and actuation overheads.



Generating Soil Moisture Maps

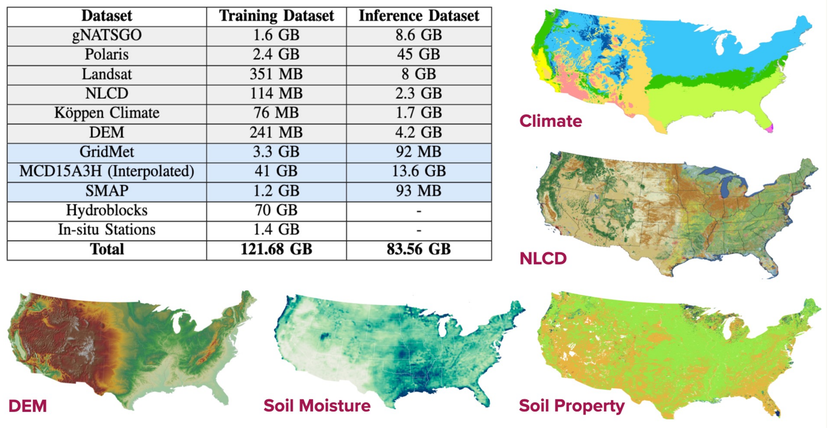
Overview

Generating high-precision soil moisture maps at 30m resolutions for the top 5 cm of soil. We integrate deep neural networks with scientific models, topographical data, and environmental conditions. We leverage in situ sensors and remote sensing (satellites) of soil moisture while infusing the model training process with domain science.

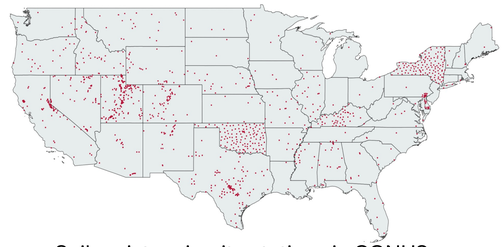
Data Wrangling

In-situ measurements: Time-consuming and sparse spatial coverage. There are only 1500+ stations in CONUS
Remote-sensing satellites (SMAP): Coarse resolution (36km-pixels) every 2-3 days
Scientific models: HydroBlocks
Ancillary datasets: soil properties and weather information

Dataset	Training Dataset	Inference Dataset
gNATSGO	1.6 GB	8.6 GB
Polaris	2.4 GB	45 GB
Landsat	351 MB	8 GB
NLCD	114 MB	2.3 GB
Köppen Climate	76 MB	1.7 GB
DEM	241 MB	4.2 GB
GridMet	3.3 GB	92 MB
MCD15A3H (Interpolated)	41 GB	13.6 GB
SMAP	1.2 GB	93 MB
Hydroblocks	70 GB	-
In-situ Stations	1.4 GB	-
Total	**121.68 GB**	**83.56 GB**



Datasets used for Hydro SM Model

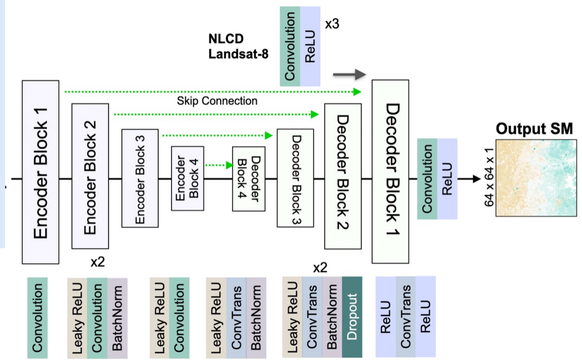


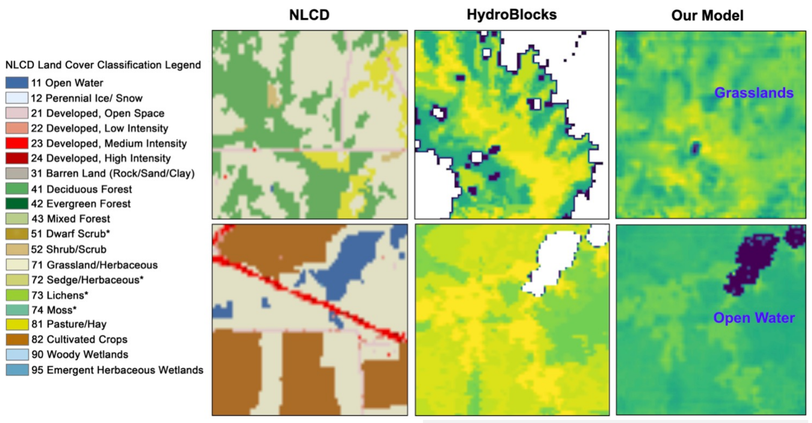
Soil moisture in-situ stations in CONUS

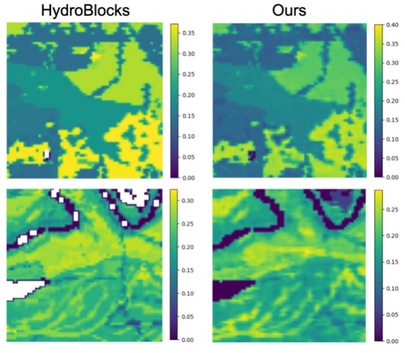
- Reconcile diverse data sources with varied value ranges, spatial resolutions, and temporal frequencies
- Harmonize datasets to a spatial resolution (30m) and temporal frequency (daily)
- Split tiles into 64x64 pixel images

Physics-Guided Loss Function

- Reconcile errors per pixel (Mean-absolute Errors)
- Spatial agreement of soil moisture over smaller patches (Fractional-skill score)







Sample SM maps at 30m Res.

At a 2x2 window size, our model outperforms SMAP satellite data product by 86.9% and the HydroBlocks scientific model output by 55.8%
At a 12x12 window size, out model is within 1% error range of the soil moisture values reported by in-situ measurement stations.

Emerging behavior of Network

Our models can regenerate missing pixels effectively. The model is able to accurately predict soil moisture variations based on the land cover type

Experiment Sites

Field experiments will be conducted during 2025 and 2026 on a 4.8 ha field located at the Agricultural Research Development & Education Center (ARDEC), Fort Collins, CO, USA (40°39'57.4" N, 104°59'53. 1" W). This site corresponds to the south portion of a field under a pivot irrigation system. The soil type is a Kim loam, classified as fine-loamy, mixed, active, mesic Ustic-Torriorthents (Soil Survey Staff, 2000). Based on corresponding soil samples, the texture was classified as sandy clay loam. The slope of the field is 0.9% in a single plane gradient. The field has been under conventional tillage continuous maize cropping system for the past 10 years.

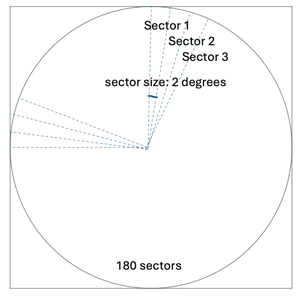
Neutron probes for sensing soil moisture

5 in-situ soil moisture sensors with historical data

Measuring root zone SM hourly 5cm,10cm, 25cm, 50cm, and 100 cm

HydroSim – A Simulator for Variable Rate Irrigation Systems

- Creating virtual sectors and zones
- Applying watering prescriptions (direction; degree; watering depth)
- Bookkeeping and changing prescriptions
- Visualizing soil moisture and crop growth



(a) Sector based VIR field (b) Zone based VIR field

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