Introduction

The creation of CIROH was guided by these four research themes:

1. Expansion and improvement of water resources prediction capabilities
2. Advancement and acceleration of community water resources modeling
3. Innovative hydroinformatics applications
4. Applying social science, economics, and impact modeling to strengthen decision support and build community resilience

CIROH collected abstracts and summaries of the ongoing projects and previously circulated them. Those abstracts and summaries are also on the CIROH web site. For your convenience, the table below lists the major topics of the ongoing CIROH research projects in each research theme. Please visit the CIROH web site or contact Amanda Blair if you need further information related to ongoing projects.

Research Theme	FY22 and FY23 CIROH Project Research Topics
1. Prediction Capabilities	• Prediction system testbed and test battery • Model and forecast evaluation • Inputs/forcings and data assimilation • Land surface model advancements • Integration with unified weather forecasting • Probabilistic modeling / ensembles • Use of hydrologic signatures to suggest dominant processes and suitable model formulations • Performance evaluation of model structures for representation of land surface and forcing spatial variation • Calibration of multi-model mosaics • CONUS scale snow melt modeling & related water management products • Evaluation of quantitative precipitation forecast accuracy • Enhanced streamflow data assimilation • Multi-source hydrologic ensemble augmentation for CHPS-HEFS forecast system • Improved cold regions process models, snow, ice, ice jams • Probabilistic modeling / ensembles in NextGen framework • AI/ML for improved rain/snow determination in mountains • Improved characterization of drought and groundwater driven low-flow conditions • Fire effects on hydrologic behavior • Deep learning ensemble predictions of forcing for hydrological modeling • Benchmarking data assimilation methods/standardized testbed

	• Developing/refining ensemble streamflow forecasts in NextGen and the RFC Hydrologic Ensemble Forecast Service
2. Community Water Model	• Digital Twin infrastructure for the NextGen development • Advances in heterogeneous computing for hydrologic modeling • Hydrologic process representation and unification • Hydrologic model integration and coupling • Optimized guidance for hydrologic model, process, scale selection • AI/ML advancements to hydrologic modeling • Training: National Water Center Summer Institute • Improved collaboration through Hydroshare • Creation of research portal for R2O web applications • Developing and benchmarking data assimilation methods on a standardized testbed • Community accessible NextGen in the cloud • Novel geospatial channel and floodplain morphological attributes representation in hydrofabric • ML-based flexible flood inundation mapping and intercomparson framework • AI-augmented immersive digital twin and visual analytics framework for hydrology • Collaborative development of comprehensive FIM output, models, methods
3. Hydroinformatics	• Flood inundation mapping and modeling • Data management and information sharing • Apps and user interfaces • Novel approaches for user interaction with forecasts • Real-time hydrological information system • Forecast impact and risk assessment analytics • Novel geospatial channel and floodplain morphological attributes representation in hydrofabric • ML-based flexible flood inundation mapping and intercomparson framework • AI-augmented immersive digital twin and visual analytics framework for hydrology • Collaborative development of comprehensive FIM output, models, methods
4. Decision Support and Community Resilience	• Determining risk perceptions and decision analysis • User response to forecast products • Value of forecast information • Extending hydrologic prediction to assess water quality, social impacts, and ecosystem services

	• Improving forecasts in underserved areas • Building community resilience • Scoping water forecasting needs and NOAA product use in Indigenous communities in Northeast Oklahoma • Audience segmentation to improve FIM by engaging and testing with technical users and impacted communities • Optimizing flood warning information sharing • Community crowdsourcing application of water hazards • Enhancing collection and application of hydrologic data in American Samoa

Overview of CIROH FY24 Research Priorities

The objectives and questions guiding CIROH FY24 research addresses needs for three sponsors:

1. NOAA Priorities. Advancing operational forecasting across NOAA, especially in the Office of Water Prediction, National Water Center, River Forecast Centers, and National Ocean Service.
2. USGS Priorities. Improving capability to assess waters of the U.S. for the U.S. Geological Survey (USGS).
3. US Army Corps of Engineers (USACE), Engineer Research and Development Center Priorities. Developing seamless national hydro-terrestrial modeling and data capability for the effective management of the nation's water resources and hazards associated with extreme hydrologic events.

Below are descriptions of the NOAA, USGS, and USACE priorities. Project ideas, when solicited, must address either the NOAA, USGS, or USACE priorities. An idea may address more than one RT and FA.

NOAA Research Priorities

NOAA research priorities align with the CIROH research themes outlined on page 1 and in the original CIROH proposal. Further, NOAA has identified a few focal areas in each research theme and provided **sample** priority research questions. CIROH encourages project ideas addressing research needs to the below focal areas, CIROH research themes outlined on page 1, and those proposed in the original CIROH proposal.

Research Theme 1: Expansion and Improvement of Water Prediction Capabilities

NOAA-RT1-FA1. Hydrologic Modeling

- Do generalized methods exist to formulate and evaluate parsimonious, novel, BMI streamflow prediction models driven by NOAA estimated and forecast forcings in the NextGen framework?
- Can differentiable ML approaches solve the ungauged basin problem?

NOAA-RT1-FA2. Hydrologic Model Ensembles

- Can the NextGen Framework running ensembles of different hydrologic models help quantify forecast uncertainty?
- How can we better leverage the full suite of available meteorological models (global, regional, high-res, deterministic and ensemble) to produce more accurate probabilistic hydrologic forecasts?
- What is the useful lead time for forecast informed reservoir operations using hydrological models with different structures driven by available NOAA forcing ensembles?

NOAA-RT1-FA3. Data Assimilation

- Can assimilating streamflow, soil moisture, groundwater, snow cover, and other observations allow meaningful updating of internal states for a variety of model formulations?
- Will ML effectively and consistently remove biases from model forcings?

NOAA-RT1-FA4. Cold Regions Processes

- How can the NextGen Framework simulate river ice cover formation, breakup and decay? (e.g., process modules, machine learning)

NOAA-RT1-FA5. Groundwater

- Can streamflow recession observations inform model selection to simulate groundwater contributions to streamflow at different scales?

NOAA-RT1-FA6. Reservoir Simulation

- Is there a generalizable open-source reservoir simulation code available for use in the NextGen framework that allows optimization of reservoir operations and meet multiple stakeholder needs using probabilistic streamflow forecasts?

Research Theme 2: Advancement and Acceleration of Community Water Resources Modeling

NOAA-RT2-FA1. NextGen Modeling Concepts

- How can we improve the efficiency of the Basic Model Interface (BMI) model coupling standard developed by the Community Surface Dynamics Modeling System (CSDMS) for implicit coupling of two or more numerical models?
- What information is needed to implement a perceptual model checker for the NextGen Framework that evaluates formulation completeness, internal consistency, and enforces conservation laws?
- Can models running in the NextGen Framework be stopped and restarted using the existing BMI 2.0 standards? If not, what extensions are required?

NOAA-RT2-FA2. NextGen Community Framework Development

- What community advantages arise from coupling the Nextgen Framework with other modeling frameworks (e.g., NOAA Unified Forecasting System)?

- What is the research to operations process? (e.g., How to determine that a new hydrological model formulation or module provides a performance advancement and is ready for NWS operational forecasting?).

NOAA-RT2-FA3. NextGen Applications

- What objective calibration measures are most appropriate for predicting floods, droughts, etc.?
- How can open-source technologies, standards, and software development best practices accelerate R20 and O2R for common operating infographics, picture tools, and dashboards leveraged by operational water prediction forecasters?
- How can the community leverage development of NextGen Framework training/educational modules using virtualization and/or cloud implementations to speed the discovery process?

Research Theme 3: Innovating Hydroinformatics Applications

NOAA-RT3-FA1. 3D Channels

- What properties does a flexible, extensible data model for topo-bathymetric data (e.g. channel cross-sections, bathy rasters, banklines, hydraulic geometry) need to support flood inundation modeling across a wide range of scales using techniques varying from hydraulics to HAND?
- How should topobathy data compiled from disparate data sources, collection methods and estimation techniques be organized to support continental scale hydraulic routing and inundation mapping?
- What means of estimating bathymetry exist? Do LiDAR point clouds before the hydro-flattening process create value for flood inundation mapping purposes?

NOAA-RT3-FA2. LiDAR Processing

- Can feature detection algorithms identify small scale and curvilinear topographic features that strongly influence flood extent from LiDAR data?
- How do we further the science on the processing of (filtering, gridding, etc) LiDAR point clouds and what novel means of resampling and mosaicking can be developed to coarsen DEM's while preserving the most important features (flow divides, bathymetry, anthropogenic features, etc.) for hydraulic modeling and inundation extent and depth prediction?

NOAA-RT3-FA3. HAND FIM

- What is the most effective methodology for simultaneously optimizing interacting variables, roughness and bathymetry, to maximize the skill of HAND based FIM?

NOAA-RT3-FA4. Flood Inundation Modeling

- Under what conditions is two-dimensional hydraulic modeling required to accurately predict flood inundation?

NOAA-RT3-FA5. Dams, Levees and Waterbodies

- What is the most effective means of accounting for reservoir flooding with the NWM and HAND based FIM?
- What is the availability of data, models and tools to build a continental scale system allowing operational forecasters to quickly predict inundation extent and depth for dam and levee overtopping or break scenarios?

NOAA-RT3-FA6. Probabilistic FIM

- How do we account for various sources of uncertainties to advance beyond deterministic flood inundation maps (extents and depths) to probabilistic forecast inundation maps?
- What techniques allow determination of forecast uncertainty based on the temporal evolution of forcing model predictions?

NOAA-RT3-FA7. Machine Learning Informed FIM

- How can machine learning technology enhance HAND based synthetic rating curves and inundation mapping solutions?
- To what extent and at what spatial scale can machine learning technology predict inundation extent and depth from National Water Model forecasts?
- How can machine learning methods function as surrogate models (meta-models, emulators) to 1-dimensional (1D), 2D, or quasi-2D hydrodynamic models to deliver rapid inundation extents and depths (Liu, 2022)?
- How can physics informed deep learning methods leverage automatic differentiation to optimize the 1D/2D Saint Venant Equations and provide advantages over traditional numerical solvers (Raissi et al., 2019)?
- How can deep learning models trained as surrogate models or solvers generalize in a transfer learning paradigm across different yet still similar sets of problems (different regions, parameter values, boundary conditions etc.)?

NOAA-RT3-FA8. Advance Quality and Access of Key Datasets of Interest to the Water Enterprise

- How can the following key datasets be improved to benefit hydrologic prediction?
    - Bridge mounted stage-only river observations
    - Remotely sensed water surface observations (e.g. SWOT)
    - Water Prediction Hydrofabric Data
    - Operational National Water Model (NWM) Forecasts
    - National Water Model Retrospective Simulations
    - Analysis of Record for Calibration (AORC) Dataset
    - Hydrologic Ensemble Forecast System (HEFS) Forecasts

NOAA-RT3-FA9. Dissemination and Visualization Research

- How can cloud native technologies and geospatial data dissemination standards support the sharing of large quantities of water prediction data following FAIR (findable,

accessible, interoperable and reproducible) guidelines, enhance emergency response, and promote open science?

Research Theme 4: Application of social, economic, and behavioral science to water resource products and services

NOAA-RT4-FA1. Communication and Visualization

- How can CIROH effectively survey and regularly interact with NOAA-NWS RFCs to identify and document local knowledge for use in NextGen, and transfer that knowledge into projects?
- What non-traditional visualizations enhance the communication and utilization of FIM data? (e.g., NOAA Sea Level Rise Viewer – https://coast.noaa.gov/slr/)
- How can the NWS best communicate probabilistic forecasts, including FIM services, to support risk-informed decision making?

NOAA-RT4-FA2. Communities and End-users

- How can we best incorporate guidance from ungauged rivers produced by the NWM into an early flood warning system?
- What are the barriers for use of FIM to inform underserved and socially vulnerable populations, and what are the most effective means to provide FIM services to underserved communities?
- How do end users perceive the applicability and ease of use/understanding of NWM and FIM services?

USGS Research Priorities

USGS research priorities align with the CIROH research themes outlined on page 1 and in the original CIROH proposal. USGS has specific requests outlined here.

Research Theme 1: Expansion and Improvement of Water Prediction Capabilities

The USGS Water Resources Mission Area (WMA) is developing the National Water Census (NWC), which will provide on-line model results for water quantity, quality, and use components of the Nation's surface and ground water, in a supply and demand context. When fully realized, the NWC will provide information on past conditions over multiple decades, updated information on current or near-current conditions, and forecasts of future conditions in the short and long term. While the timeline and components delivered differ from the mission of the NWS, there is potential for overlapping research needs in Research Theme 1.

The Water Observing Systems Portfolio (WOSP) encompasses Programs that aim to carry out the WMA's objectives to collect, manage, and disseminate consistently high-quality and reliable water information in real-time and over the long-term. The primarily overarching priorities of the WOSP are the following:

1. Strategically integrate, enhance, and expand the temporal and spatial collection of water-quantity, -quality, and -use data using robust, innovative technologies to deliver readily accessible "fit-for-purpose" information with various levels of quantified uncertainty.
2. Modernize the way in which we transmit, process, store, quality-assure, and deliver hydrologic data - with the specific goals of:
    a. Reducing monitoring costs and improving continuous records processing; and
    b. Develop innovative, intuitive web-based internal and external data analysis and visualization tools/services to better understand the status and trends of the Nation's water resources.

The following research focal areas provide an overview (organized by the individual science programs of the WOSP) of the research topics that are of specific interest to advance the objective and overarching priorities for the WMA-WOSP.

<u>USGS-RT1-FA1. Next Generation Water Observing System (NGWOS) Program</u>

The NGWOS program designs and implements water observation networks in targeted basins across the Nation by the USGS to provide high-fidelity, real-time data on water quantity, quality, and use necessary to support National modern water resource availability prediction and decision support systems with lower uncertainties, and rapid and informed hazards response. The NGWOS program is also the research arm of the WOSP tasked with developing new and innovative techniques, methods, and instrumentation using Technology Readiness Levels and Product Maturity Levels as frameworks for eventual migration into our National monitoring networks. Research priorities for NGWOS include:

- Develop an OSSE "factory" - conduct Observing System Simulation Experiments (OSSEs) using Regional or National models to help guide our monitoring investments

- Establishing Electrical Engineering students at the HIF and develop curriculum around sensor innovation/design, power systems, telemetry /IoT technologies and autonomous vehicles.
- Developing Smart Gaging Network approaches and technologies targeting deployment at the national, regional, or local scales and could include the following:
    - Technologies that support the seamless data collection, integration and delivery of data from mobile assets (drifters, autonomous underwater vehicles, rapid deployment gages) with our fixed site networks;
    - Technologies for increased spatial and temporal coverage through improved integration of IoT sensors at or near USGS fixed sites which may include mesh networks and custom 5G networks;
    - Systems designed using MQTT data, command/control, and integrated edge-computing capabilities;
    - Technologies that increase edge computing capabilities on dataloggers at the gages or within a network of gages that may include artificial intelligence / machine learning (AI/ML);
    - Improved infrastructure for the rapid integration of new sensors and/or platforms.
- Remote sensing research or associated curriculum, including Uncrewed Aircraft Systems, and advancements in image processing and edge computing for imagery
    - Methods and Techniques for assimilation and fusion of satellite data to combine multi-sensor sources and increase spatial and temporal coverage based on periodic satellite overpasses;
    - Machine Learning methods for rapid processing of high-rate satellite data into hydrologic variables;
    - Calibration and validation of wide-area satellite observations with USGS fixed site or UAS monitoring;
    - Design and test Internet of Things (IoT) sensors and edge computing resources which collect imagery and/or video
    - AWS or other cloud platform data handling and analysis, including custom coding
    - Online display and dissemination of geospatial and satellite raster data
    - Radar data analysis for monitoring of hydrologic variables
- Specific priority areas of instrumentation R&D:
    - IoT Telemetry
    - Camera-Based Monitoring
    - Surface velocity methods
    - Power systems
    - HABs and PFAS sensors
    - Low-cost Autonomous Underwater Vehicles
    - Rapid deployment gages
    - Water use monitoring
    - Soil moisture sensors
    - Urban Hydrology

USGS-RT1-FA2. National Hydrologic Monitoring (NHM) Program

Through the National Hydrologic Monitoring (NHM) program, the USGS WMA operates, modernizes and strategically expands its streamflow, groundwater and water-quality monitoring enterprise to provide impartial, timely, rigorous, and relevant data for short- and long-term water decisions by stakeholders across the United States. Research priorities for NHM include:

- Research and testing of various observational data uncertainty analysis approaches
- R&D into display of data uncertainty on USGS monitoring location pages
- Research associated with automated water data records processing algorithms

The Water Resources Availability Portfolio (WRAP) is a portfolio focused on research, model development, and assessment of integrated water availability for human and ecological uses both regionally and nationally, directly in response to the SECURE Water Act of 2009. The following three focal areas provide an overview (organized by the individual science programs of the WRAP) of the research topics that are of specific interest to advance the objective and overarching priorities mentioned above.

Research Theme 2: Advancement and Acceleration of Community Water Resources Modeling

USGS-RT2-FA1. Integrated Water Prediction

The USGS Integrated Water Prediction (IWP) science program focuses on the development of advanced models for forecasting (daily, monthly, annually, and decadal) multiple water quality and quantity attributes including water budgets and components of the water cycle.
It is also developing the cyberinfrastructure and workflows required to implement national and local-scale models to be used by water resource managers over the decades ahead. There are many opportunities for collaboration with USGS, NWS, and CIROH in terms of hydroinformatics, operational prediction, and improved terrestrial models, additional USGS research priorities focus on:

- Impact of hydroclimate forcings on water availability futures through a variety of interpretive approaches, across a spread of plausible scenarios, at a national scale.
- Development and implementation of processes for co-designing data networks and modeling efforts that links data across national, regional, watershed, and local scales using model-informed design of data collection strategies to guide the collection of new data sets that can improve model testing and calibration.
- Evaluate techniques and methods to simulate the effects of water use (pumping, diversions, irrigation, reservoir ops) on water budgets and flow dynamics using USGS Water Use Program products.

USGS-RT2-FA2. USGS Integrated Water Availability Assessments (IWAAs)

IWAAs will provide nationally consistent assessments of water available for human and ecological needs in the United States and identify factors that limit water availability or could lead to conflict. The designs of the IWAAs are to provide information for meeting the goals of the National Water Census as established through the SECURE Water Act. Specific research needs associated with improved assessment capacity in IWAAs include:

- Focused research and analysis to create a more holistic view of water availability in the US through incorporation of coastal water availability assessment capacity
- Assessment of groundwater quantity and quality in three dimensions at a national scale using innovative methods such as data mining and machine learning
- Research aimed at improving our understanding of how reservoir operations impact the transport of dissolved solids through the system and how this impact changes over space and time

USGS-RT2-FA3. Water Use

USGS is the only federal agency with a requirement to report water use nationally. Historically this has been done via a county level compilation of use by 8 categories every 5 years. Beginning in 2018, the USGS has shifted water use reporting methods from this historical compilation approach to development of models to estimate and predict withdrawal and consumptive uses. Initially this will be done for the thermoelectric, irrigation, and public supply categories, which make up 90% of uses nationally. Upcoming model development will focus on the remaining five categories of use (livestock, mining, aquaculture, domestic self-supplied, and industrial) with the goal of having them completed in FY25, research priorities for water use include support of model development for these categories, including:

- Remote sensing and data science approaches for developing models to estimate livestock, aquaculture, mining, and identification of indoor vs outdoor residential use. These categories are minor categories nationally but locally and regionally impactful. Identification of spectral differences related to on-site technologies or techniques for the different categories is of interest.

USGS-RT2-FA4. Developing Numerically Robust Terrestrial Models

As the USGS looks to address requirements outlined in the SECURE Water Act, advancing our hydro-terrestrial modeling capacity through development of a new integrated framework will be critical. The new framework must allow for the integration of quantity, quality, and use for water resource assessment (current conditions) and prediction (short and long-term). The framework must also be able to incorporate the new types of data being collected through the USGS Next Generation Water Observing System in the Delaware, Upper Colorado, Illinois and Willamette River Basins to improve modeled process representation.

Research Theme 3: Innovating Hydroinformatics Applications

Research Theme 3 is an area where there is already some collaboration with NWS and USGS and there should be plenty of opportunities to build off or leverage this research theme to advance USGS goals more broadly, especially in terms of advanced tools and technologies, services, and compute resources. The USGS could benefit from the application of data fusion to obtain more accurate or complete water datasets at varying scales. Two data types of interest are bathymetry and river corridor geometry and characteristics, leveraging USGS datasets in addition to other datasets available from governmental or academic institutions. Another beneficial area of hydroinformatics research would involve application of the IoT concept of a "digital twin" as related to stream gages and other environmental monitoring locations of

interest. This area of research has the potential to make improvements in the operation and systems understanding of such monitoring locations.

USGS-RT3-FA1. National Water Information System Modernization Program

The current version of Water Information System (NWIS) is inflexible, suffers from extensive technological debt and is at increased risk of system failure because of aging infrastructure. There is a need for a modernized NWIS to support a robust, authoritative enterprise water information system to advance the Water Mission Area priorities and meet the needs of USGS and WMA stakeholders. The focus of the NWIS Modernization program is to provide the necessary improvements to NWIS. Research priorities associated with NWIS Modernization include:

- Research around automated records processing algorithms
- Advancements in image processing and edge computing for imagery
    - Design and test IoT sensors and edge computing resources which collect imagery and/or video
    - Design and test of novel Unoccupied/Uncrewed (UAS) platform, sensor packages, and techniques which utilize remote sensing data in new ways
    - Design a machine learning "gamification" project to build-well labeled and/or segmented imagery data sets using USGS monitoring station imagery data utilizing public involvement in data production (through playing the game)
    - Test citizen science contributed imagery research to determine if it is feasible to include an publicly supplied “scientific imagery” resource as valid hydrologic data
- Software development capacity (anything from full-stack development to simple scripting)
- Hydroinformatics
    - Advancing standards for water data models (e.g., WaterML, Hydrologic Features) and the way in which they are applied in modern software (standard exchange methods or service patterns)
    - Research to advance IoT for water monitoring

USGS-RT3-FA2. Data Cyberinfrastructure and Information Delivery (DCID) Program

The DCID program ensures that water data and other hydrologic information are seamlessly delivered, and that state-of-the-art tools are used to develop hydrologic information and visualization products to meet the ever-evolving needs of our users and cooperators to make informed water resource decisions. Research priorities associated with the DCID Program include:

- Advancing water data visualization techniques

Research Theme 4: Application of social, economic, and behavioral science to water resource products and services

Research priorities outlined in RT2 as part of the WRAP portfolio includes opportunities and needs for research related to RT4.

USGS-RT4-FA1. Socioeconomics

USGS has traditionally focused water availability reporting on hydrologic quantity or quality drivers only. This has left out a large and changing component of water availability – human drivers of use and management. For USGS, being able to represent what decisions are made and how those decisions impact availability is critical for accurate representation and prediction of water availability moving forward. Research priorities for socioeconomics include:

- Collection of water policy or water managing institutions at multiple scales for quantitative modeling purposes.
    - There is a need to understand contextual factors that also determine issues of water availability such as access.
    - This work will provide information of influences of water availability to inform and incorporate within USGS modeling efforts.
    - Qualitative to Quantitative metrics for modeling (fuzzy metrics):
        - Existing treaties for water sources within the US (State level agreements)
        - Policy and water rights turning into quantitative metrics for modeling purposes into IWAAs

USACE Research Priorities

USACE research priorities align with the CIROH research themes outlined on page 1 and in the original CIROH proposal. Further, USACE has identified areas in each research theme and provided a sample of priority research questions.

US inland and coastal damage has increased from $5B to $50B/year over the past 40 years and fatalities have increased tenfold. The goal of Comprehensive Water Risk Management (CWRM), one of the critical USACE strategic focus areas, is to provide advanced quantitative, actionable flood risk information to support operations, contingency response, planning, design, as well as operation and management (O&M). Furthermore, USACE mission space includes performing humanitarian assistance, undertaking Multi-Domain Operations (MDO) involving the water domain by providing stream network and coastal conditions, and the determination of water management strategies.

The following research focal areas provide an overview of the research topics that are of specific interest to advance the objective and overarching priorities of CWRM and other programs for the USACE and the ERDC:

Research Theme 1: Expansion and Improvement of Water Prediction Capabilities

USACE-RT1-FA1. Integrated Global Hydro-terrestrial Modeling Framework

Predictions of hydrologic conditions in the field are important to strategic military operations and necessary for proper planning of military exercises and the deployment of troops. Warfighters require a highly specialized understanding of the terrain that is both globally aware and locally precise. Funded by the U.S. Air Force and NASA, a multi-agency hydrology integrated product team was formed to develop Global Hydro Intelligence (GHI). Even though extensive hydro-modeling tools already exist, several technical challenges need to be addressed:

- Various legacy models and physics packages have their own formats and data structures tailored for specific applications.
- The data used to parameterize the models are typically curated by multiple agencies and stored behind institutional firewalls limiting access
- The disjointed nature of the modeling systems and data structures makes it difficult to adequately address water issues holistically over large geographic extents
- Uncertainty quantification and enhancements to physics of modeling components
- Standardizing datasets and model input/output to enable interoperability, creating common development environments and computational testbeds
- Harmonizing the evaluation of new and existing code, sharing data transformation and modeling workflows to facilitate repeatability and reproducibility of hydro-terrestrial modeling across scales
- Due to the lack of available global streamflow observations a multi-model ensemble for global hydrologic prediction could be a key technology enabler to assess accuracy and improve model parameters through traditional hydrologic model calibration studies
- Assimilation of remotely sensed data into model predictions

USACE-RT1-FA2. Forecast Informed Reservoir Operations (FIRO)

Forecast-Informed Reservoir Operations (FIRO) investigates the use of advanced observation and prediction technologies to allow water managers to safely and effectively retain or release water from reservoirs based on longer-term forecasts, particularly of atmospheric rivers, to simultaneously improve water availability, enhance flood risk reduction, and achieve additional ecosystem benefits. Key areas of research and development needs related to FIRO include:

- Forecast skill assessment and improvement for multiple types of flooding storms
- Developing FIRO screening process to the nationwide portfolio of USACE dams
- Adaptation of the screening process as necessary

Research Theme 2: Advancement and Acceleration of Community Water Resources Modeling

USACE-RT2-FA1. Coastal and Inland Compound Flooding

Coastal areas all around the world are at an increased risk of flooding due to rising sea levels, climate change and associated precipitation changes. Recent hurricanes, Sandy, Harvey, Florence, and others, have shown that when storm surges are combined with precipitation and riverine flows, that flooding can be substantially exacerbated. Compound flood (CF) events impact the mission space of several agencies including the USACE, USGS, NOAA, USBR, etc. Therefore, the requirements for CF modeling must involve USACE's partner agencies. Prioritized tasks to address CF events are as follow:

- Model linkage techniques and locations of information hand-off in the transition zones, between the hydrologic, hydraulic, estuarine and coastal numerical models.
- Methods for probabilistic understanding of compound hazards
- Models that incorporate all facets of compound flooding including groundwater and drainage networks
- For active and future USACE coastal FRM projects, identify conditions and use scenarios under which different levels of considerations for CF analysis are required (e.g. event hindcasts and forecasts, planning, design and operations, hazard and risk analysis);
- Research existing literature and establish a state-of-the-art understanding of existing knowledge, guidance and tools and associated gaps in regards to CF implementations, both within USACE and externally within the community (e.g. numerical models and coupling strategies, probabilistic analysis tools and applications, in-situ and synthetic data and availability);
- Coordinate with USACE districts and other federal, state and local agencies to leverage ongoing initiatives (e.g. FEMA, NOAA, USGS, USNRC, and Louisiana Watershed Initiative) and minimize duplication/conflict of effort towards formulating a unified USACE perspective and guidance.
- Development of water hazard system (WHS). USACE-Coastal Hydraulics Laboratory (CHL) developed a probabilistic coastal hazard assessment (PCHA) known as the coastal hazards system (CHS). CHS leverages USACE regional coastal studies; historical measurements and high-fidelity climate, surge, and wave modeling results, creating a national storm database. An Inland Hazard System (IHS) is needed to support both USACE and NWS for riverine flood events, including linkage to the coast. Recent hurricane events such as Harvey (2017) and Florence (2018) necessitate the coupling of

coastal and inland operational systems. Therefore, the USACE needs a hazards system that incorporates both the CHS and the HIS into a WHS.

USACE-RT2-FA2. Innovation in Sediment Management

One of the USACE R&D priories is to mitigate and adapt to climate change. Currently, USACE partners with 77 organizations in 10 countries to develop international guidelines for natural and nature-based (NNBF) infrastructure. Estimation of watershed sediment at the continental scale is an important step to better understand the overall sediment behavior in a waterway. Distributed hydrologic and sediment models (such as HEC-HMS, GSSHA, SWAT, etc.) require large amounts of data for sophisticated calibration processes. Furthermore, uncertainty in model parameters and computational demands pose challenges for modeling continental-scale river networks. The future R&D goal through the Engineering with Nature (EWN) program is to convert 70% of dredged sediment to beneficial use versus 30% today. USACE strategic targets for sediment management are listed below:

- **Sustainable Sediment Operations**
  - Strategic sediment placement
  - Recover disposal site and reservoir capacity
  - Treat/sequester contaminated sediments
- **Innovative Construction and Operations Technologies**
  - Advanced sediment handling and site management
  - Low-cost construction
  - Sediment at the intersection of water and soil
- **Engineering with Nature®**
  - Advanced real-time and forecasting models for life-cycle dynamics
  - Document engineering guidance, multi-benefits of sustainable management
  - Research to understand river and estuarine sediment dynamics
- **NextGen Dredging**
  - Sensors for on-site and remote monitoring of dredging processes
  - National physical modeling facility to test new construction methods with NNBF solutions
  - Optimize dredging and placement operations
  - Reservoir flushing methods and models

USACE-RT2-FA3. High Resolution, High Fidelity and Basin Scale Next Generation Modeling

This focus area is intended to improve USACE mission delivery in flood risk management (FRM) and navigation (NAV) through seamless modeling of large-scale waterway hazards. The results of this work will improve decision making skill, accuracy, and efficiency regarding hazards during extreme events. This effort supports USACE priorities to tackle climate change, support resilient communities, revolutionize and accelerate decision making, and protect and defend the arctic, Army priorities of upgrading the Nation's waterways and ports. This focus area aims to improve the following:

- Modernize civil works FRM and NAV programs to better serve the needs of disadvantaged communities

- Invest in science/R&D to deliver enduring water-resources solutions; and White House priorities of Innovation for Equity, National Security and Economic Resilience, and STEM Engagement
- Increase FRM and NAV resilience through better predictions of sedimentation, water depth, and flow, e.g., reducing unforeseen navigation disruptions during high/low river flows
- AI/ML Tools for large scale hydrology and hydraulics
- Next-Gen continental Scale hydraulic and hydrologic models
- Numerical methods to accelerate continental scale physics models
- Methods and techniques for managed aquifer recharge
- Web/Cloud hosted decision support databases
- Robust water hazards system (coastal and inland hazards system)
- Research to understand local scale hydrology
- Methods and techniques to incorporate social and economic justice into decision making
- Real-time data streams

USACE-RT2-FA4. Big Data Analytics and Artificial Intelligence

- **Sensor Integration and Big Data Discovery**
  - Automated data collection, harvesting and mining from sensors and digital systems
- **Model Integration Framework**
  - Integrated framework to run multi-physics models across multidisciplinary areas
  - Automated approaches for digital twinning for enhanced performance forecasting
- **Tradespace Analytics and Design**
  - Understand trade-offs between functionality and cost for decision-making.
  - AI-infused tools to simplify user-interface; automated dashboards
  - Advanced capabilities to emulate and evaluate threat and adversarial attacks on the Nation's critical infrastructure and associated networks
- **Rapid High-Fidelity Decision Support**
  - Reduced order modeling to accelerate time for real-time analysis and decisions
  - AI algorithms for automated forecasting

Research Theme 3: Innovating Hydroinformatics Applications

USACE-RT3-FA1. Climate Change and Hydrology Analysis

Due to climate change and climate variability, the temporal variability and spatial distribution of water availability has been dramatically changing. The magnitude and frequency of extreme events are of critical importance in the evaluation of coastal and river systems to inform flood risk reduction under current and future conditions. Mitigate and adapt to climate change is one of the top 10 USACE R&D priorities and touches all six USACE Civil Works R&D strategic focus areas: Sustainable Species Management, NextGen Water Resources Infrastructure, Innovation

in Sediment Management, CWRM, Innovative Applications of Big Data, Crisis Mitigation Response and Recovery. Some of the R&D topics related this focus area are listed below:

- Evaluate and update flood inundation maps with consideration of climate change at the national scale
- Evaluate the effect that the non-stationary conditions due to climate change will have on the Earth
- Seasonal to decadal prediction and projection of climate forcings and water responses
- Snow-pack water estimation
- Methods to forecast spring melt and seasonal floods
- Operational models for FRM and CSRM forecasts
- Climate assessment and vulnerability of USACE levee system and other FRM features
- Social vulnerability and economical assessment of climate change
- Operational models for low water forecast
- Development of holistic, multi-scale frameworks for sustainable and national water systems that enable climate change resilience through more efficient resource use

Research Theme 4: Application of Social, Economic, and Behavioral Science to Water Resource Products and Services

Research priorities outlined in RT1, RT2, and RT3 includes opportunities and needs for research related to RT4.

<u>USACE-RT4-FA1. Incorporation of Social Justice and Economic Equality Considerations into Flood Risk Management</u>

Flood risk management project authorization is based in part on cost benefit ratio relating the cost of construction, operation and maintenance of the FRM project to the levels of economic benefits afforded by the project in damages prevented or reduced. Identification and standardization of methods and procedures for incorporation of community level valuation from social and historical importance of assets into the decision-making processes for FRM projects is needed.