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An Integrated Simulation and Distribution System for Early Flood Warning

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Abstract—**This research presents an integrated system of computer software, networking and web-based display developed and deployed to allow drainage management authorities immediate access to results from the Weather Research and Forecasting (WRF) Hydrological Extension model, WRF-Hydro. Output data from the model are analyzed by a chain of GIS, database and web publishing tools to forge updated and readily understandable flood warning information. The system design incorporates a flexible configuration such that it can be adopted for basin management anywhere.**

*Keywords**; hydrology, modeling, hydro-graph, WRF-Hydro, flooding, GRASS_GIS, web mapping***

I. INTRODUCTION

Advanced warning of impending flood events could save lives and help mitigate property damage by allowing drainage system administrators time to take precautionary steps. Many hydrological and hydro-meteorological computer models can create flood simulations ahead of the actual event. One such popular modeling software is WRF-Hydro, developed by the National Center for Atmospheric Research (NCAR). However, the output from these models consists of tabular data, not readily understandable by managerial level staff working in drainage management. Even professionals in hydrology and engineering need expert consulting and further manipulation of the model forecasts in order to understand the coming event and draw operative conclusions.

In oder to address this need, we have developed a set of programs and scripts for each of the following stages of the WRF-Hydro simulation: automated running of the model several times a day, including downloading and preprocessing of Global Forecast System (GFS) meteorological data files; special formating of output files; transfer of the files to a web server immediately upon completion of each simulation run; processing of the data on the web server to create flood maps and updated hydro-graphs; and targeted email alerts sent to specific staff members when anticipated flooding exceeds a threshold. These web pages and email alerts allow on-the-spot and easy to comprehend information for drainage personnel.

A. Background

Flash floods in arid regions challenge drainage authority personnel with sudden, unexpected and severe events endangering property and lives. Reference [13] summarizes press reports on flash flood damages in the western Mediterranean. Data on the Centre for Research on the Epidemiology of Disasters (CRED) website (http://www.emdat.be/) indicates damages in tens of millions of dollars across Israel, Jordan and the Palestinian Authority in 2013 alone. In addition, some research [17] points to growing risks due to climate and landuse changes [1] .

In order to address these dangers, a Decision Support System (DSS) needs to be implemented which pushes advanced warning information to drainage management authorities in a timely and easy to comprehend fashion.

However, a DSS will be applicable only if the information available is accurate and focused. Recently work has been done to develop a two-way approach to merging meteorological date with land surface parameters to achieve a fully coupled hydro-meteorological simulation [23]. Among the many climate and hydrology models in use ([16]) for research and forecasting the WRF-Hydro flood simulation model was chosen since it implements the fully coupled two-way approach [4], yielding relatively good correlation with measured flow rates. Reference [18] discusses the importance of WRF-Hydro and how it fits into a data management and distribution system. This research implements a DSS to supply early warning to Israeli drainage authorities by integrating WRF-Hydro with a web based facility for presentation and distribution of the information.

B. Goals

Hydrological forecasts have significant importance for decision-makers in taking preventive measures against extreme flooding events. Traditional flood forecasting systems based on rain gauge readings are insufficient for preparing necessary precautions against potential losses. The design of this modeling and distribution system has contributed to rapid and focused response to flood events in Israel. Visitors to the web interface can view rainfall and runoff predictions up to two days in advance of a storm. Localized alerts are available both on-line and through targeted email messages to drainage management officials. Furthermore, the structure of the system allows for smooth adoption to other regions. We submit that this research lays the groundwork for an early flood warning network applicable in any arid climate.

C. The structure of the WRF-Hydro model

The WRF-Hydro model grew from the increasing need for development of spatially-distributed, physics-based, conservative modeling approaches for a variety of applications such as regional hydro-climatic impacts of climate change and flood forecasting. The fully-coupled hydro-meteorological model attempts to answer these needs by providing a flexible and extensible structure for representing distributed hydrological processes. The initial WRF-Hydro development follows the WRF modeling paradigm of relatively simple extensibility of model physics within the existing WRF modeling framework.

Two-way interactions between the land surface and the atmosphere present a core challenge in earth system modeling. The chaotic and non-linear response of the atmosphere to land surface perturbations implies that relatively small heterogeneities in land surface states and fluxes have the potential to drive upscale responses in the atmosphere. Improper representation of land surface processes such as the spatial patterns of soil moisture and snow-pack may significantly limit prediction accuracy for many meteorological events.

The WRF meteorological model is a meso-scale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. The system is a fully compressible and Euler non-hydrostatic model. The Yonsei University (YSU) planetary boundary layer (PBL) scheme is used for calculating PBL height in this study. The scheme uses counter-gradient terms to represent fluxes due to non-local gradients, and the entrainment effect is explicitly considered in the scheme. A more detailed description of WRF model can be found in the WRF web-site http://www.wrf-model.org/index.php.

WRF-Hydro is both a stand-alone hydrological model as well as an architecture for coupling of hydrological models with atmospheric models. This coupling is described graphically in the *Model HPC Computer* pane of Figure 1. WRF-Hydro is fully parallelized to enable running in either a cluster or high performance computing (HPC) platform alike. Similar to the original WRF meteorological model it does not attempt to prescribe a particular or singular suite of physics; rather it is designed to be extensible to new hydrological parameterizations.

The following characterize the WRF-Hydro:

- Multi-scale functionality to permit modeling of atmospheric, land surface and hydrological processes on different spatial grids
- Modularized component model coupling interfaces for many typical terrestrial hydrological processes such as surface runoff, channel flow, lake/reservoir flow, sub-surface flow, land-atmosphere exchanges.
- Parallel code development for application on commodity cluster and higher performance computing systems
- Stand-alone capabilities for hydrological prediction and research uncoupled to atmospheric models
- Efficient coupling architecture so that it can be embedded within (or coupled to) other types of Earth system models such as the NCAR Community Earth System Model (CESM) or the NASA Land Information System (LIS)
- Utilization of many standard data formats for efficient job construction and evaluation
- Freely distributed software from the website: http://www.ral.ucar.edu/projects/wrf_hydro

As the lowest boundary of WRF model, WRF-hydro calculates the soil-vegetation-atmosphere interactions. In these processes, while moisture and heat fluxes between atmosphere and land-sea surfaces are determined, 1-dimensional surface and sub-surface water balance calculations are also performed. The physical-based WRF-Hydro model performs these calculations by importing precipitation, humidity, surface radiation, temperature, wind speed and pressure values from WRF atmospheric model outputs. Within the model, multi-layered surface soil structure is represented by 16 different categories of soil types and a three kilometer grid resolution of land-cover data is represented by 24 class types from [1]. In each land cover classification, land type is defined by albedo, surface roughness, soil moisture, vegetation resistance factor, and water vapor deficit parameters.

This model offers two advantages over other hydrological models. The WRF climate predictions and the WRF-Hydro hydrological modeling scale to very wide geographic extents. Furthermore, interfacing with and importing weather forecasts as well as high resolution land surface data are built into the model. One popular alternative model, the Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS), has successfully simulated flood events (for example [19] and [11]), but mostly in a single basin. The HEC-HMS system does have the capability to be deployed in a larger region, but it requires precipitation input from rain gauges or rain radar. In either case the simulation completes only after the flood event, thus precluding use of this model in an advanced warning framework. Other models have been similarly analyzed ([11]) and have shown to reach good correlation with measured runoff, but only given actual past rainfall data, and in smaller homogeneous domains. WRF-Hydro, on the other hand, attains a reasonable match with measured runoff as shown by ref [5] when using weather forecast data from two days in advance of the storm event. This modeling system produces operational predictions for drainage authorities in Israel since the winter of 2013. In this research we highlight the capability of the WRF-Hydro system while simulating flood events two to three days in advance.

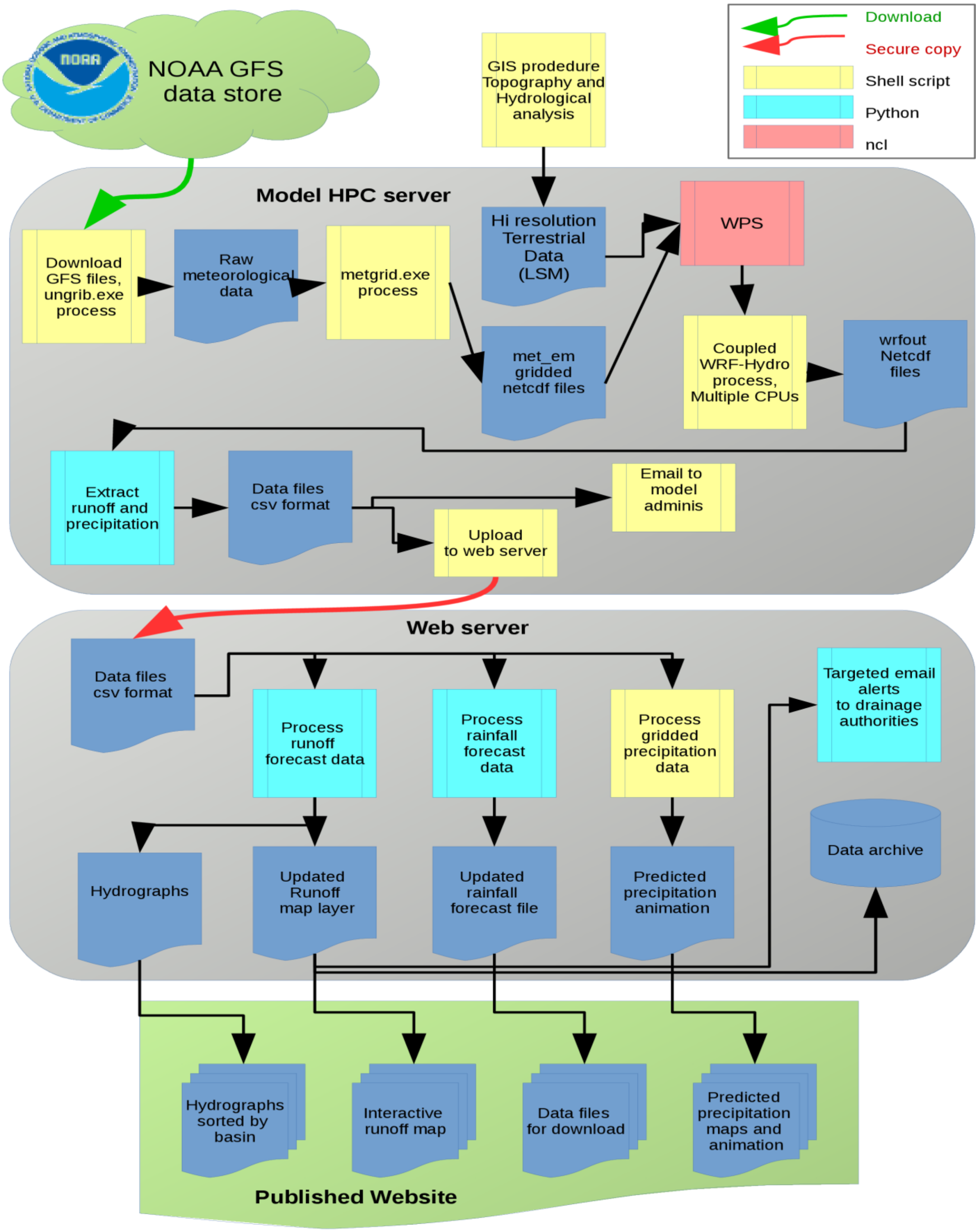

Figure 1: Flow diagram of integrated WRF-Hydro model and distribution system. The top pane depicts processes running the on HPC server, The middle pane are programs that start automatically when new discharge data is uploaded to the web server. The lower pane represents the actual web pages

D. The web interface

In considering the stated goal of this project, supplying timely flood warnings to drainage management officials, the obvious presentation platform is a website. The site design offers a rich set of operative information both to the public and to drainage officials, and with interfaces in English, Hebrew and Arabic. Runoff data is available in two graphical formats: as hydro-graphs for each drainage outlet location, with a map of all outlets showing maximum predicted flow rate at each location graphically. The predicted flow rates are transformed for each drainage outlet into flow probabilities (rate of return in hydrology terms). Thus a small basin that drains into a town where even a low flow rate could potentially cause significant damage, will show in red indicating an alert, even though the total flow is small. Along with the flow rates, predicted accumulated rainfall is presented as an animated map spanning the time period of the simulation. In addition, logged in users can access and download the actual data files for further analysis.

II. METHODOLOGY

The integrated system presented here runs on two separate but interconnected computing platforms. The model itself is installed and configured on a powerful HPC machine, while the web interface and database backend reside on a separate Internet accessible computer. Nearly all stages of the simulation and distribution system are implemented using open source software. This choice insures that the system is available to other flood management programs at low cost. We avoid the problems of vendor lock-in associated with proprietary software, and thus facilitate adoption of the system by other drainage control administrations. Figure 1 describes graphically the process flow and resulting outputs.

A. The preprocessing component

Before actually running the model, several preparatory steps are performed. The bash shell scripts which contain these steps read a collection of model variables from a configuration file including start time, length of the simulation, a unique output directory, which GFS data to download, topography and soil parameters etc. Simulation runs are scheduled twice daily and timed to match the availability of the raw GFS climate data. A series of processes begins to download the needed meteorological data, pre-process those data files, and place the input data into the unique download location. The tables of parameters for the WRF-Hydro model itself, known as namelist files, are also created dynamically at this stage.

The model operates in three geographical “domains”. Each domain is nested within the previous, and each has a higher resolution than the previous. The domain structure is described in chapter 3 of [21]}. Thus the raw data files, downloaded from GFS contain meteorological data at a resolution of 50 km per pixel. After downscaling, domain 1 is defined to cover a large area: 140 x 140 cells at 27 km resolution. Domain 2 is further downscaled to 9 km grid cells and covers 189 x 187 cells. Finally the domain 3 definition of the research area contains 120 x 222 cells at a 3 km grid. This local 3 km inner domain is then overlaid with a 100 meter resolution grid of land surface data for the hydro model. After grid disaggregation and overlapping, each 3 km x 3 km WRF grid cell consists of 900 higher resolution cells of 100 x 100 meters each, used for the final routing grids.

At the next routing stage the 100 m resolution grid of geographical (topography, longitude, latitude) and hydrologic (flow direction, channel grid, stream order, basin mask, forecast points) parameters are generated individually and then concatenated into a single NetCDF file for input into the WRF-Hydro model. Thus, on completion of pre-processing, the output directory contains all necessary input files in NetCDF format for the WRF-Hydro model, as well as links to the WRF software executable files installed on the server, to be deployed in the next stage.

B. The WRF-Hydro component

With the required input files in place, another set of bash scripts calls the WRF software executables. This stage is started under the control of MPICH, the Message Passing Interface, which allows multiple instances of the WRF model to run in parallel ([10] and [15]). The MPICH control software allocates wrf processes for subsequent hours of the model analysis period among the HPC computer's CPU cores. This essential capability insures timely completion of the simulation.

The actual WRF-Hydro model software includes several algorithms that couple meteorological forecasts and hydrological land surface data layers ([7] and [12]). These complex algorithms require quite a long computation time. However, in light of the goal to push accurate and understandable results in advance of impending floods, we require that the model finish in a short time. With the large number or processing cores and RAM memory in the HPC hardware employed in this research, several tens of the executable wrf.exe processes are started in parallel, thus allowing completion of a long forecast within a few hours.

Each of the individual wrf.exe processes deals with one of the input files, for one of the domains. With the routing information from the input files prepared in the preprocessing stage, surface runoff is calculated for each time slice in the forecast period. The results, saved also in netCDF format, contain a collection of meteorological and runoff forecast variables throughout each of the domains. Again one output NetCDF file for each forecast hour is created for the whole timespan covered by the model. In this project we chose a forecast period of up to 84 hours. Therefore, on completion of all the parallelized wrf.exe processes, 84 output data files are ready for post-processing

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C. The post-processing component

After all of the wrf.exe processes finish, all discharge data are then available in the netCDF output files. However these data need to be extracted and formatted in order to be accessible for laymen and drainage management authorities. This final stage on the HPC server reads runoff variables from the NetCDF files for each time slice in the domain 3 data, and collects a text file of predicted runoff for a list of 170 preset discharge locations. The resulting text file, readable by any standard spreadsheet software, is uploaded to a web accessible location on a separate server, and also emailed to selected research colleagues. Furthermore, the WRF-Hydro output data also contains precipitation predictions. These data are also reformatted to a simple comma-separated-values (CSV) text file and also uploaded to a web accessible location. Refer to the *Model HPC Server* and *Web Server* panes in Figure 1 for a detailed flow diagram of the above chain of data transfers.

Communication between the HPC machine and the web server is through secure copy, an encrypted protocol which allows secure transfer of files between computers. By using pairs of Public Key Infrastructure (PKI) encryption keys, copying of the flow and precipitation data files can be automated, and no manual intervention is needed.

D. The Web component

The website utilizes Asynchronous Javascript and XML (AJAX) as well as a spatial database backend. In view of the need for rapid action to an impending flood event, a responsive web interface was required, so AJAX technology was chosen. The server hosting the website also runs UMN Mapserver [20] to deliver the various map layers as Open Geospatial Consortium (OGC) compliant services. UMN mapserver compares favorably in speed with the alternative open source web mapping platform, Geoserver, ([8]) but without requiring the overhead of Java. This combination of UMN Mapserver, AJAX, with php scripts to access the database backend is also used by ref [6] in a web-based GIS for monitoring air quality in Cyprus. Precipitation data and runoff data are published on the web site as static images, and dynamic maps using the OpenLayers javascript library. Both of these applications are open source, thus maintaining the policy of wide availability and low cost to other projects.

A python program runs on the web server at each upload of new data from the HPC server. This program immediately recognizes that new flow data are available thus insuring that the website is always displaying the fresh model output. The python script processes that data as follows. First, the runoff for each of the drainage points is collected for the whole

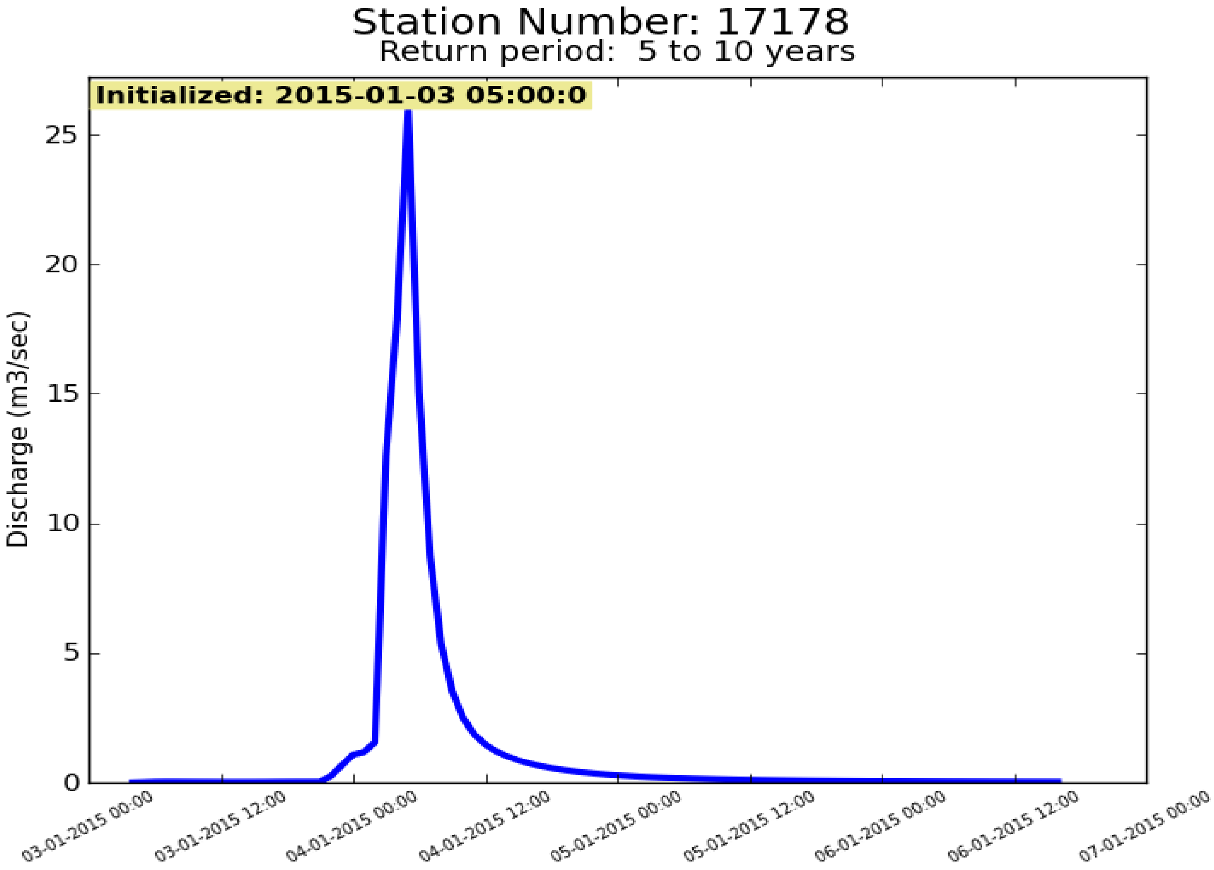


Figure 2: Sample hydro-graph. On completion of each model run, when discharge data is uploaded to the web server, a process is triggered to produce 170 hydro-graph images, such as the above, for each of the 170 drainage outlets around the country

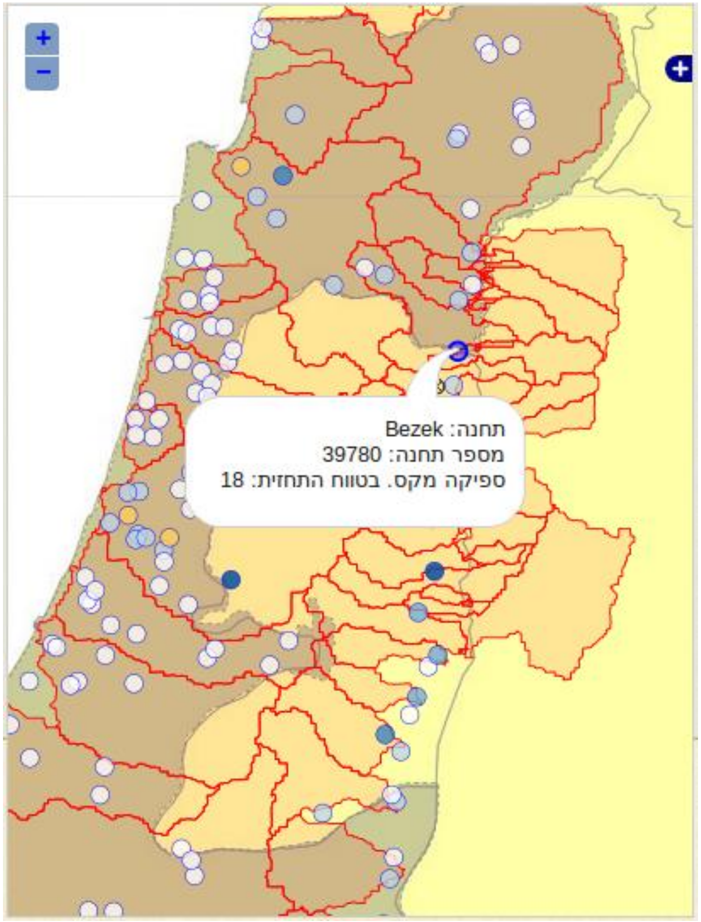
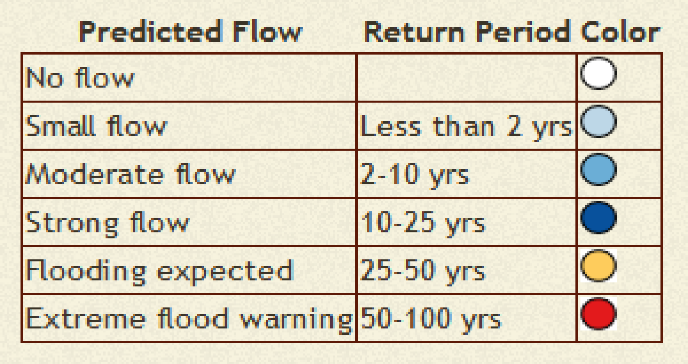


Figure 3: Sample runoff map. Each drainage outlet (hydro-station) is represented by a color coded circle showing the return period of the predicted discharge rate.

period of the prediction, and a hydro-graph image file (Figure 2) is created for each drainage point. Next, the maximum flow rate over the forecast time period for each drainage point is determined, and the probability (return period) for that point is calculated and uploaded to the database. These resulting probabilities for each drainage point are used in a database query to display the severity of flow levels at each outlet point (see Figure 4). A sample flow level map image appears in Figure 3. Thus the python script recreates both the hydro-graphs and flow level map displays twice a day, where all new hydro-graphs and flow data cover a forecast period up to two or three days into the future.

In the next stage of the python program the precipitation data are scanned and transferred to an automated GRASS GIS [9] script in order to produce the precipitation animation. Finally, the flow probabilities table is queried for instances of low return rate (indicating a significant flood) and targeted email messages are sent out to managers of the specific basins that are at risk. This script completes within a few minutes after new flow data are uploaded from the HPC server, thus the website is updated shortly after the model run completes.



Predicted Flow	Return Period	Color
No flow		○
Small flow	Less than 2 yrs	🔵
Moderate flow	2-10 yrs	🔵
Strong flow	10-25 yrs	🔵
Flooding expected	25-50 yrs	🟠
Extreme flood warning	50-100 yrs	🔴

Figure 4: Legend for the drainage outlet map. Color coded markers indicate severity and return period for each drain point.

The web interface publishes prediction information for Drainage Authority personnel and the public in several easy to comprehend formats. The hydro-graphs for each drainage point, at the outlets of basins, are selected by geographic location (the Drainage Authority) and the name of the hydrometric station at that drainage outlet point. Users of the site can also view hydro-graphs from the past week. The maximum flow rates are displayed in a map frame, with flow levels appearing color coded (The legend appears in Figure 4) by severity level. Using this map site users can see at a glance and zoom in to the critical locations. A second map animation is displayed showing the predicted progress of accumulated precipitation (one such image in Figure 5) over the period of the simulation. Finally, authenticated users can select and download both discharge and precipitation data files for all recent simulation runs.

E. The database component

All the data displayed on the web interface, both spatial and tabular, are stored in an open source PostgreSQL database. All queries against the database are done by a set of server-side php programs. By merging AJAX with server-side php scripts for data extraction, we gain a responsive site with constantly updated data. The PostGIS extension to PostgreSQL enables storage and querying of spatial data tables in addition to alpha-numeric data, thus serving as the database backend. An online comparison of the most popular spatial databases ref [3] rates PostGIS as a full-featured, efficient and reliable tool for spatial data management. Reference [22] have also chosen to use PostgreSQL with PostGIS in their GIS-based management and publication framework for handling large amounts of data from hydrodynamic modeling. Furthermore, ref [2] implement a web based system for monitoring landcover changes in a bird conservation project using much of the same toolset outlined above: PostgreSQL, UMN Mapserver, javascript and php to access the data tables.

The database implemented in this research contains spatial tables of the drainage outlet locations, and other boundary and hydrology layers displayed on the web map pages. The Mapserver software draws from these data layers in order to publish the map layers. In addition, the database

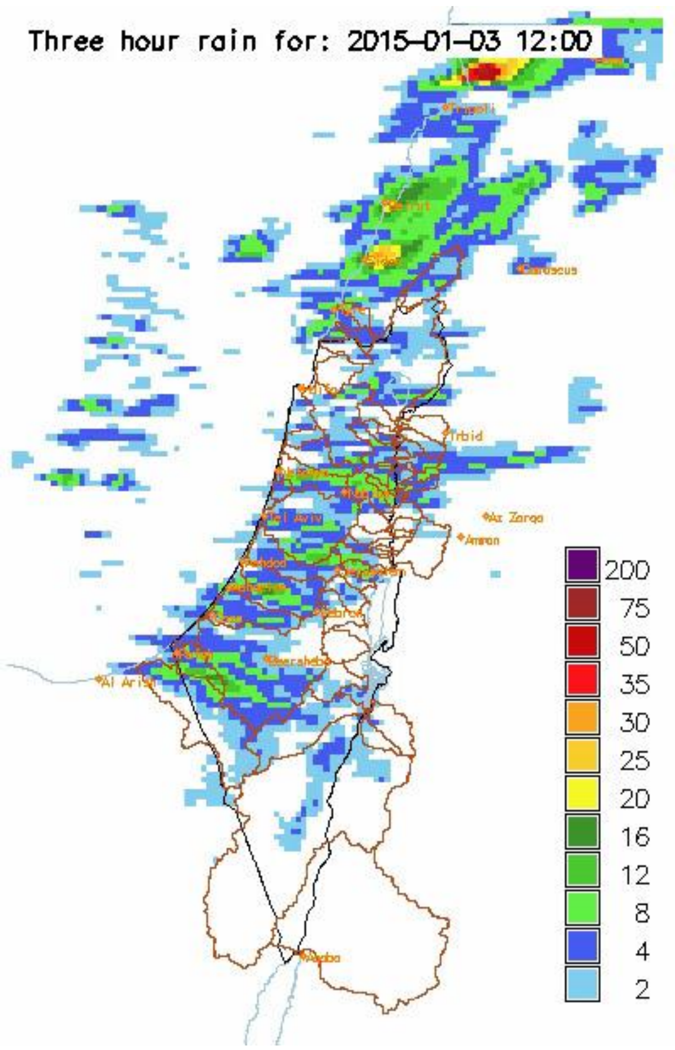


Figure 5: Sample Accumulated Precipitation Map. In addition to the runoff predictions, weather forecasts are also extracted from the WRF-Hydro data files and converted to map images for display on the website

holds updated flow data for all of the drainage outlet points. A database table of basins and contact information for basin management officials is used to pinpoint who needs to be notified during an alert. With this data schema we implement the targeted email alerts explained below.

F. *The alert component*

Targeted alerts are delivered to selected personnel through two mechanisms. First, on completion of each simulation run, as part of post processing an email message is composed automatically and sent to the model administrators. This message contains a summary of the simulation parameters, and the raw discharge and precipitation data files are attached to the message.

Additionally, once the data files are uploaded and consumed on the web server, the computer routine scans the predicted discharge rates to determine where the flow will exceed a preset threshold. Then for each of the Drainage Authorities, those flow locations within that Drainage Authority's area of responsibility and with discharge above the threshold are isolated. Those locations, maximum discharge rates, and hours are collated into an email message and sent to the staff of that particular Drainage Authority. Thus each member of each Drainage Authority receives a message with alert information pertinent to him and his colleagues. The staff are not overwhelmed with irrelevant alerts, rather they get only those warnings that are specific to their region, and only when the discharge rate will reach a level requiring action.

III. DISCUSSION AND CONCLUSIONS

The need for accurate and comprehensible flood prediction information spawned this research to integrate the well known WRF-Hydro model with an easily accessible interface.

A. *Choice of the WRF-Hydro model*

The WRF-Hydro model was chosen for several reasons. Implementation of the fully coupled (two-way) interaction between land surface data and meteorological data results in more precise predictions. The model operates in a downsized domain, again promising higher resolution results. Furthermore, the topographic, hydrological and land surface data can be an order of magnitude higher resolution than the meteorological data. In the current project, the domain 3 parameters were designed to create a downsized grid of 3 km. pixels, while the land surface data layers were prepared at a resolution of 100 meters. The ability of WRF-Hydro to merge high resolution topography and hydrology layers, and thus to achieve better localized results, was a strong consideration in choosing this model.

Finally, the WRF input data also offers the added value of relatively accurate weather forecasts, specifically precipitation, for the time span of each model run. Resulting flow and precipitation data, after post-processing, are uploaded to the web server for assimilation into the website.

B. *Web interface*

The procedure on the web server then creates image files and maps for presentation. The complexities of collating flow data for each drainage point, and calculating the severity levels are handled without the need for user intervention. Visitors to the site, including drainage management staff, can view maps of the flow rates and probability levels as well as maps of predicted precipitation. Hydro-graphs, sorted by drainage basin, are available and updated twice daily. Additionally, those drainage management staff who need access to the tables of data can, after entering credentials, download the raw data.

By running the model on an HPC computing platform, runoff forecasts are available for more than 48 hours in advance of impending flood events. Email alerts are issued, as explained, only to staff of those basins where a flood might occur, and only when the severity exceeds a certain threshold. Coordinating the model simulation runs with publishing of simplified images and maps on the web, and targeted alerts puts into the hands of drainage administrators a tool to anticipate and possibly to mitigate damages.

C. Summary

Successful integration of a reliable forecast model and a straight forward display platform has created an efficient tool for flood management. Until recently, drainage authority personnel took educated guesses as to the extent, location and severity of impending storm events, and the possible damages. By viewing the relatively precise forecasts created by WRF-Hydro in the convenient format of a web page, those personnel now have a clearer picture of any impending circumstance. The hydro-graphs for each individual drainage outlet show if and when a rise in water level will occur. Timely email alerts give the drainage authority managers the focused information they need to take preventative measures in a timely manner. Thus, authorities are not inundated with incomprehensible information, rather they can deal directly with the actual events.

D. Future Research

We hope to enhance the application of this DSS by publishing, in the web interface, actual measured runoff flow rates along with the predicted hydro-graphs. Future work on this system should include collection of the surge height of stream flow on an hourly basis during flood events. These height data will be converted to discharges using tables of discharge rates for each surge height using stream cross sections. The resulting actual hydro-graphs can then be plotted dynamically against the predicted discharges to evaluate the reliability of the model simulations. We expect to allow web site users to chose from a list of hydrometric stations, select any past date/time range, and then to view the measured and predicted hydro-graphs for that station and time period.

Running simulations twice a day, with a three day forecast period creates, in fact, six different simulations for any hour within those forecast periods. As the storm event approaches, fresher meteorological data is used for subsequent forecasts. However, a preliminary comparison of the simulations for a given hour has raised the question which of the six forecasts produces the best match to actual runoff. We see potential for future research into a robust comparison of the simulations at varying intervals in advance of an event, and for varying forecast periods.

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