The ‘Ike Wai Hawai‘i Groundwater Recharge Tool

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***Abstract*—This paper discusses the design and implementation of the ‘Ike Wai Hawai‘i Groundwater Recharge Tool, an application for providing data and analyses of the impacts of land-cover and climate modifications on groundwater-recharge rates for the island of O‘ahu. This application uses simulation data based on a set of 29 land-cover types and two rainfall scenarios to provide users with real-time recharge calculations for interactively defined land-cover modifications. Two visualizations, representing the land cover for the island and the resultant groundwater-recharge rates, and a set of metrics indicating the changes to groundwater recharge for relevant areas of the map are provided to present a set of easily interpreted outcomes based on the user-defined simulations. Tools are provided to give users varying degrees of control over the granularity of data input and output, allowing for the quick production of a roughly defined simulation, or more precise land-cover models that can be exported for further analysis. Heuristics are used to provide a responsive user interface and performant integration with the database containing the full set of simulation data. This tool is designed to provide user-friendly access to the information on the impacts of land-cover and climate changes on groundwater-recharge rates needed to make data-driven decisions.**

***Index Terms*—groundwater, recharge, land cover, hydrology, sustainability**

I. Introduction

Land cover changes can have a major impact on the rates of groundwater recharge, the hydrological process of surface water entry into the groundwater system. Rates of groundwater recharge can have a major impact on the water sustainability of an area. The availability of water within groundwater systems is vital for maintaining the ability to meet human and ecological needs.

The ‘Ike Wai Hawai‘i Groundwater Recharge Tool has been designed as a publicly available tool to facilitate rapid assessment of the impacts of changing land covers and climate conditions on groundwater recharge. This application provides easy accessibility to data on groundwater-recharge rates via a web interface providing simulated outcomes of a set of 29 land covers over the island of O‘ahu for two climate scenarios [1,2]. Users are able to simulate changes in land cover and climate and retrieve a set of updated groundwater-recharge values based on pre-developed simulations of the relationship between land cover and groundwater-recharge rates relative to the geospatial position of the modification. These simulation values were produced using the soil water-balance program developed by Westenbroek and others [3]. Rainfall is a major contributing factor to the hydrological processes that produce groundwater-recharge values. Simulation data are provided for two different rainfall conditions: based on rainfall data collected for 1978-2007 – the application default – and rainfall projections for 2041-2071, based on possible carbon-emission levels [4].

The ‘Ike Wai Hawai‘i Groundwater Recharge Tool is built using the angular framework, a TypeScript-based framework for building modular web applications, and is built on Agave [5,6] as part of the ‘Ike Wai gateway [7] suite of tools. This paper will present the experiences in developing this tool to provide a set of versatile and easily interpreted visualizations and metric-based analysis points for the potential impacts of a simulated land-cover change.

II. Data Views

The application uses a multiple-document interface allowing for simultaneous simulation and comparison of different land-cover patterns. The application holds a set of elements containing independent maps, land-cover, and recharge data that can be freely positioned within the browser (Fig. 1). The primary workspace is designed to be expanded allowing windows to be placed outside of the immediate reference frame of the browser. The user can add or remove these maps to adjust the set of simulations being tracked. Since these map instances are designed to be independently manipulated, further discussion of the data schema and control mechanisms for the application may be considered as local to an individual map instance unless stated otherwise.

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Two primary visualization instances are provided to the users, based on the two types of data tracked by the application: a visualization of the land cover and a visualization of the groundwater-recharge rates. A foundational map of the island of O‘ahu is set using Leaflet, an interactive map library for JavaScript. Each visualization provides a raster overlay of the respective data set. Data for the application are provided as a grid of values at 75m x 75m resolution defined by cell centroids using the WGS84 geodetic datum. Each value is colored using a categorical color scheme, for the land-cover visualization, or using a continuous color scheme, for the groundwater-recharge visualization – the generation of these color schemes will be discussed in the next section. The land-cover visualization serves as the default view of the map, with the groundwater-recharge visualization serving as a view of the outcomes of modifications made to the land-cover values. The land-cover visualization uses a modified version of Leaflet's drawing tools to allow users to draw polygons on the map representing areas for land-cover updates to be applied. These areas can then be selected or deselected for receiving updates and are tracked in the output as individual metrics. Controls are provided for modifying the land-cover types for the selected areas. Land-cover values in a selected area can all be updated to one of the available land-cover types, or a mapping of the currently represented land-cover values to new ones can be constructed. For example, a selected area that both contains grassland and shrubland could be updated to golf course or mapped to golf course and diversified agriculture respectively. To provide finer-grain control, the application also allows for custom land-cover raster data to be imported and shapefiles, an ESRI geospatial data storage standard [8], to be used to define areas. An option is provided to change between the two included rainfall scenarios, which is applied globally to the user simulation. Further, an option is provided to modify the baseline data to this new rainfall scenario as well; thus, a user can evaluate the impacts of land-cover and rainfall scenario changes separately or in combination.

The groundwater-recharge visualization reflects the simulated land-cover modifications, providing a view of the resultant groundwater-recharge rates for the island and the metrics associated with these modifications. The user can change between metric modes that display various metrics for the entire island, a single selected data point, a set of selected aquifer systems, or a set of selected user-defined areas. These metrics display the groundwater-recharge rates at baseline and for the current modifications, the area, and the volumetric difference and percentage change in recharge rate respective to baseline. A graph of the baseline and current analysis values is also provided. Additionally, the data overlay can be changed to represent the groundwater-recharge values, percentage change, or difference from baseline for each value. A report containing a complete breakdown of these metrics for all relevant areas can be brought up in a separate document within the page for side-by-side analysis, and can be downloaded in Portable Document Format (PDF). All land-cover, groundwater-recharge, and user-defined area data can be exported from the application for further analysis or to restore the application state at a later time.

To allow for an intuitive control schema for each of the visualization styles, the set of user controls is broken into two parts: one which is unique to each visualization, and one which contains global controls for the entire map instance, such as the ability to change unit types or hide user-defined areas. The unique controls are placed in a collapsible menu on the left side of the map and the global controls in a collapsible menu on the right. The metrics view for the groundwater-recharge visualization is displayed in an additional collapsible panel along the bottom of the map.

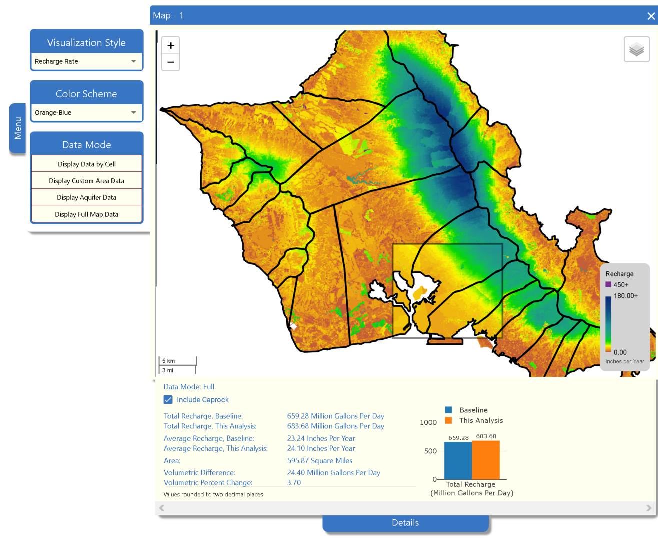

Fig. 1. The ‘Ike Wai Hawai‘i Groundwater Recharge Tool interface displaying the recharge visualization and calculated recharge metrics.

III. Data Coloring

Due to the relatively large number of potential land-cover types, displaying each as its own categorically distinguishable color is challenging. It is estimated that a color palette of as few as seven different colors is the maximum for quick distinguishability when colors are not distributed in a regular manner [9]. Since users may be working with an arbitrary number of the potential land-cover types at a given time it is also difficult to limit the working set of land covers. It is therefore acknowledged that any potential color scheme used for the land-cover raster will result in sets of colors difficult to quickly distinguish. The primary drawback of this is in the ability to determine land cover via a color legend. Identifying a plot of land's constituent cover types using this mapping would be a slow and difficult process where sets of colors that are not easily distinguishable are involved. To work around this issue, a mechanism was implemented to quickly identify the land-cover type associated with a particular spot on the map. Hovering over a point on the map will highlight the value under the pointer – the 75m x 75m grid cell centered nearest the pointer location.

In order to produce a set of colors as distinct as possible, the color scheme was produced via a permutation of subdivided color channels. Excluding black and white, the number of potential colors for a set of red, green, and blue (RGB) color channel values is equal to the product of produced values for each color channel minus two, assuming the two extreme values are included. This means that, for the 29 required colors, the number of subdivisions in the color channel must be composed of the set $\{3, 3, 4\}$. Green blue color combinations were found to be the most difficult to differentiate, so the red color channel was selected for the larger division set. Divisions were made using linear RGB color space for the red color channel, and standard RGB color space for the green and blue color channels. Linear RGB color space corrects for the differences in computational and human perceived brightness; however, due to the overwhelming effect of green in comparison to blue on relative luminance, colors brighter in the green and blue color channels were more difficult to differentiate than those with lower values. Blue-green color combinations with higher green values will have more similar relative luminance values which relates to lower contrast [9]. The darkening effect of proportionally dividing these channels in standard RGB color space was used to offset this, whereas the red color channel was scaled on perceptual brightness using linear RGB color space.

Color scaling for the groundwater-recharge visualization was provided in two different color schemes: rainbow and monochromatic. The rainbow color scheme, a polychromatic color scheme scaling through the standard rainbow progression (red, orange, yellow, green, blue, indigo, violet), is provided due to its prevalence in water science and related fields. The target audience of the application is likely to be familiar with this color scheme; as such, it is provided to increase user comfort with the interface. Research has shown, however, that this color scheme has the potential to be misinterpreted due to human perception of the colors in the progression. Colors such as yellow and green have a relative luminance greater than that of the surrounding colors, creating perceptual artifacts in the color mapping since these colors are prone to drawing attention [10]. In contrast, monochromatic color scales are more perceptually consistent and can be translated to greyscale without loss of data [11]. To produce the monochromatic scaling, a sequential color scheme was selected using Colorbrewer, a tool providing concise color schemes for cartographic visualizations [9]. This tool provided a nine-part single-hue blue color scheme. This set of colors was then scaled to an exponential gradient in Lab color space. Lab color space is designed to yield a perceptually consistent color scale [12]. This was used to create a consistent transition between the provided set of colors. An exponential scaling is employed for groundwater-recharge data since most of the values fall in lower ranges; however, the entire range of values differs by a couple orders of magnitude. Without an exponential scaling, a majority of the features in the visualization would be lost. Recharge values were capped at 180 inches per year, with higher values taking on the maximum color.

The color scheme for the final two visualization components, the difference and percentage change mappings, was constructed using a diverging color scheme between red and blue. The difference scale was capped at $+/-10$ inches per year and the percentage change scale at $+/-100\%$. This color scheme was similarly adapted from a color mapping provided by Colorbrewer. To create a smooth color gradient, the two color extrema for an eleven-class diverging color scale were taken, and each extremum scaled to white using Lab color space. A 200-part total mapping was used to provide a smooth transition between the colors.

IV. Database Interaction and Index Packing

Having a large set of total simulation data – data for the island of O‘ahu at 75m x 75m resolution over 29 land-cover types for 2 rainfall scenarios – only the current working set of groundwater-recharge values, made up of the baseline values and updated values based on modifications to the land cover for each rainfall scenario, are tracked by the application. Any updates to land cover trigger a request to the MongoDB database holding the primary simulation data. Database values have a geospatial index applied to them, and a spatial query, containing the geometry of the updated area, is used to fetch appropriate data. Two primary limitations are imposed on constructed queries that must be handled by the application: a maximum of 10,000 values can be returned by any single query and, having the geometry encoded into the request uniform resorce identifier (URI), the request must be limited to a safe number of characters handleable by the browser and database application programming interface (API). To this end, modifications that contain a large number of data points or that contain very complex geometries must be repackaged into a query that falls within these limitations. The repacking process employed constructs a bounding box for the set of values that must be included in the query. This bounding box is then broken into a set of subsections containing no more than half the maximum number of values allowable by the database API, 5,000. Once the set of subgrids is computed, a bounding box of the modified values in each subgrid is computed. This set of sub-bounding boxes is then used as the set of objects constructed into queries. While this method does not necessarily construct a tight boundary for the modified values, it provides a quick estimate that is guaranteed to contain the full set of modified values. Using rectangular geometries also reduces the overhead required to verify the query length and the complexity of query parsing. Limiting the maximum subgrid size to 5,000 as opposed to the API maximum values also potentially reduces the number of superfluous values being included in the query geometry and the download size of each query result while not increasing the number of required queries by a significant amount.

When a land-cover update is triggered for a given area, the set of internal values is computed using the bounding box of the updated area and a raycasting algorithm. In the case of a set of multiple features being updated at once, a determination must be made of whether to perform local or global value repacking when a feature violates the query limitations. Queries are constructed from each feature geometry; however, performing local value repacking, that is, repacking only features that require it, could result in overlapping indices being queried if features are close to each other due to the bounding box heuristic utilized by the repacking algorithm. Global repacking solves this issue by repacking every modified value if a single feature in the current update fails the validation check. This incurs extra overhead if values that would not need to be included in the query under local repacking end up within the repacked geometry set. This would likely be the case if some set of small features that did not require repacking were sufficiently far away from a set of features that did. Weighing the pros and cons of each of these methods with the likely use cases of this application, global repackaging of values was employed. In general, a set of areas being modified within a single query instance are reasonably likely to be in a geographically similar area. Additionally, due to the bounding boxes of each individual sub-grid being computed to get a reasonably tight bound of the updated values, and the fact that features that do not require repackaging may not be particularly large or intricate, it is likely that the additional overhead of unnecessary values will be small.

A further situation where this method must be employed is the case where an imported data set contains a set of updated land-cover values without a bounding geometry. While an index-based query can be constructed from the updated values, this is typically infeasible due to the limitations on query length and the resolution of the data set, which results in a typically large set of individual values being updated. It is more efficient to pack the updated values into a set of bounding geometries than to perform a set of satisfactory index queries that could be on the order of hundreds or thousands of subqueries.

A. Future Opportunities

To broaden usage and the impact of the tool, the addition of other islands can be explored as recharge data becomes available. Additionally, a feature to ingest new recharge datasets for other areas to make the tool more adoptable for the broader community can be undertaken.

V. Conclusion

The ‘Ike Wai Hawai‘i Groundwater Recharge Tool attempts to overcome some of the challenges that are present in developing models for analysis of the affects of land-cover and climate changes with currently available data sources. Improving the accessibility and interpretability of this data should reduce the overhead required for researchers working with groundwater-recharge analyses. Presenting a set of concise metrics and allowing for the exportation of data for more specialized analysis, in a user-friendly and responsive interface, should allow for more rapid construction of models for the impacts of simulated changes on groundwater-recharge rates.

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