Albuquerque Academy Team 1

Water Runoff and Diversion Simulation

New Mexico
Supercomputing Challenge
Final Report
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Albuquerque Academy

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Executive Summary ------------------------

Problem

As Global Warming becomes increasingly more prominent, the weather in Albuquerque has gotten more and more extreme. This year, random bursts of snow and precipitation marked another unusually warm spring. For communities all over the city, and especially those close to the river, flash flooding and weather related property damage are increasingly more of a threat. As the climate continues to change, our water diversion and urban/suburban infrastructure must rise to meet the challenge. But how will we know what needs attention for the next downpour?

Solution and Methodology

My simulation aims to help by predicting what parts of our city and water diversion network need work to truly protect the residents of Albuquerque. The simulation calculates flow and accumulation and marks areas where excessive water collects or where the water flows too fast as problem areas that need some form of intervention to be safe. It also measures the total water absorbed to determine the effects of various changes on the recharge of the aquifer. My model reconstructs the topography through a grid elevation approximation. It then iterates through each grid cell, applying the given rainfall and absorption and moving the water according to elevation and current water depth.

Validation and Verification

With basic geometries as a foundation, my model reconstructs flow based on equations of incline flow over time. Data from The Albuquerque Journal for a flash flood in the Embudo Arroyo (2021) will be used as a real scenario to test against.

Results

My model predicts important areas of Albuquerque that would benefit from redesign and improvement of runoff management infrastructure. The Snow Heights neighborhood, as well as a large region of riverside communities aren’t sufficiently prepared for storms that would put pressure on their current systems. Another significant issue is erosion in both the mountains and in underdeveloped areas where the soil has less vegetation to secure it.

Problem ------------------------------------

All over the world, temperatures have risen over the past century. As a result, more and more water is being evaporated from the oceans, dumping huge amounts of water into local water cycles[1]. Increasing numbers of hurricanes are hitting both of the coasts of the US, and with this, more and more storms are continuing inland towards the dry and arid landscapes of New Mexico and its neighboring states. These storms threaten to overrun the rustic water infrastructure that already seems insufficient. There were 1210 flash floods in the years 1993 to 2017 in New Mexico[3]. It is essential that communities all across the traditionally arid west work to overcome these sporadic, unpredictable, and extreme storms when they do come, effectively preventing both erosion and harmful accumulation. Flash floods are the most costly severe weather in the entire US, causing $5 billion in damages a year[11]. Additionally, these increasingly common extreme weather events have begun to pose a significant threat to the US agricultural industry[2]. The management of erosion and flood waters is crucial to maintaining the local New Mexican agricultural industry as well.

On top of that, Albuquerque's aquifer is always in need of additional supply for the hundreds of thousands of New Mexicans who rely on it. Albuquerque needs to ensure that these new storms can most effectively replenish our dwindling supply. Although aquifer levels are making a bounce back due to effective conservation efforts[4], truly securing these water resources for all residents of Albuquerque requires considering additional means to revitalize the aquifer. By reducing reliance on the Rio Grande through accelerating the shift to complete aquifer sustainability, we will allow more of those water resources to go to people in need.

Methodology and Algorithms -----------

I developed my water runoff model in python in Anaconda/Jupyter Cloud Notebooks for the majority of the project, switching to BBEdit and my computer's terminal in the last stretch. I built my model completely from scratch. To produce many of the final results, I ran my simulations on a desktop computer (Alienware AMD Ryzen 7 5800 3.4 GHz 8 Core Processor) which was significantly more powerful than the Macbook Air (1.1 GHz Dual-Core Intel Core i3)

I used for much of the initial development. The two computers both able to run my model significantly helped in getting all the verification, validation, and results simulations.

My simulation uses a square grid approximation for the desired topography (Albuquerque in this case). The elevation is input from a .csv file of restructured data from USGS ⅓ Arc second DEMs[12] (Figure 1 shows this elevation data; however, the simulations later on run on a subset of this data (boxed in red), as the full set proved too slow for the number of simulations needed). My program adds water over the area to simulate rainfall. A portion is subtracted to simulate absorption. Soil can absorb water fastest when it first encounters water, but then slows as the topsoil becomes saturated and the only absorption is from space made by water draining down from those saturated layers to lower layers. My simulation approximates that process according to absorption (A) as a function of time in minutes (t) with initial absorbance a_i:

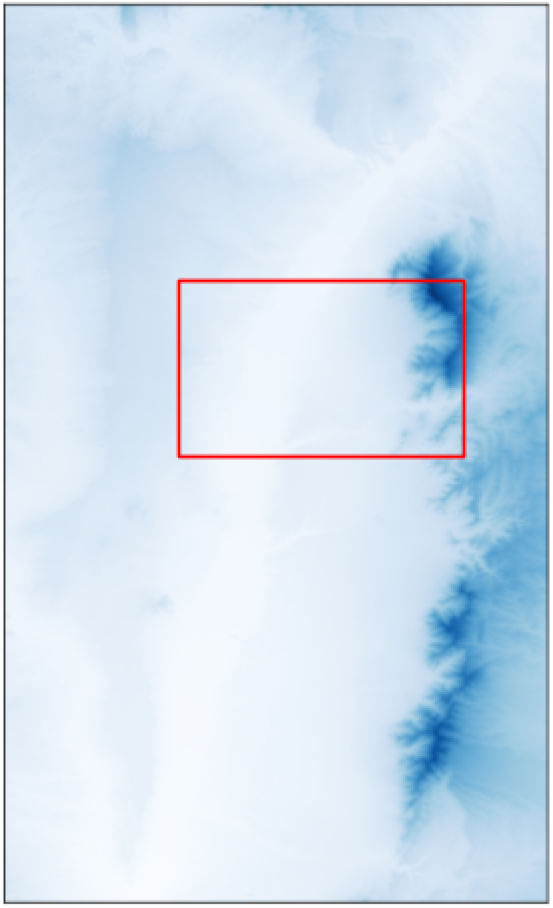
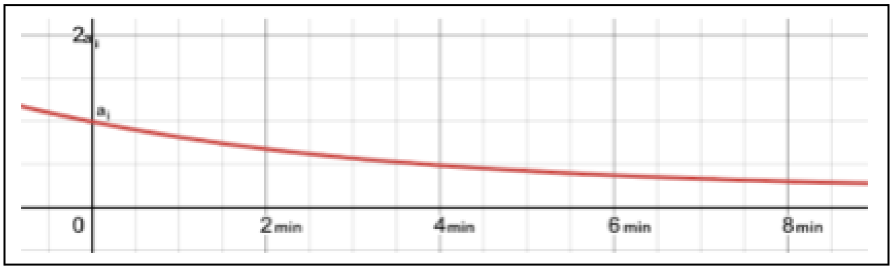


Figure 1 - Scale: 1437.7 - 3254.7 m

$$A(t) = \frac{4}{5}a_i e^{-\frac{t}{4}} + \frac{a_i}{5}$$

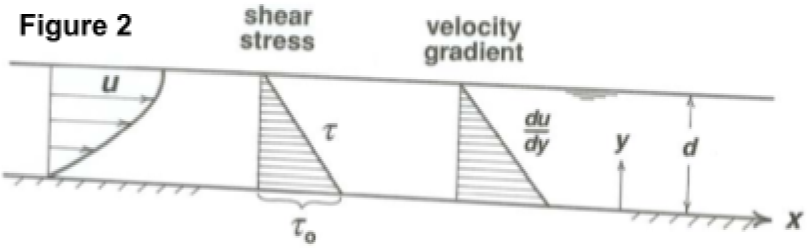


As time goes on, the absorption rate goes to ⅕ of a_i as seen in the accompanying graph. It is important to note that this is an assumption and not verified. This is due to the difficulty of making generalizations about a sample size as large as the Albuquerque area where soil types and compositions can vary drastically from one subset to another. However, it is accurate in that the absorbance of some soil starts relatively high then trends down to some value called (for the whole system) the steady state drainage rate. My model gets a_i from

USDA data on Hydrologic Soil Group[8] for Albuquerque and the surrounding Areas. However, due to issues normalizing the two data sets, I made a generalization of Hydrologic Soil Group to elevation (which are quite strongly correlated for much of the Albuquerque Area). The Hydrologic Soil Group can then be converted to an infiltration rate[9]. This allows my model to directly apply absorbance data based on the preexisting elevation data without the need for normalization.

Once one step of rain and absorption is complete, my program calculates the individual flow between grid squares. To speed up the algorithm, the portions of flow are calculated before the main program begins (a process from here on referred to as precalculation). This is to prevent the algorithm from calculating the way the flow is sent 100 times when it could have only been calculated once. The flow itself is given by a formula from Newtonian fluid dynamics[5]:

Figure 2



$u = \frac{\gamma\, sin\alpha}{\mu}(yd + \frac{y^2}{2})$

Where u is the flow rate at a given point (in m/s), γ is the gravitational force per unit volume of the substance (for water: 9.8m/s^2*1g/cm^3 or 9800000g/m^{2}s^2), μ is the dynamic viscosity (1.308$mPa \cdot s$ or 1.308g/ms assuming the water is at 10ºC (or 50ºF))[6], d is the depth of water (cm for my model), and y is the variable for how deep in the depth of water you are (For all letters see Figure 2) . By integrating the expression with respect to y from y=0 to y=d (the whole depth), we get an expression for the flow rate per width:

$$\int_0^d u\, dy = \frac{\gamma\, sin\alpha}{\mu}\int_0^d (yd + \frac{y^2}{2})dy = \frac{\gamma\, sin\alpha}{\mu}(\frac{d^3}{2} + \frac{d^3}{6}) = \frac{2\gamma\, sin\alpha d^3}{3\mu}$$

However, since it is giving only the flow per width (hence the strange units of m^2/s), there is one last manipulation. That last step is multiplying by the length of the flowing side which, since a tile has 8 ways to flow and a perimeter of $4 \cdot tileDim$ (side length will be referred to as tileDim), is ½ tileDim (As seen in Figure 3: each path of flow receives half of a side length to flow through). So the total flow for one direction is $\frac{\gamma\, sin\alpha d^3 \cdot tileDim}{6\,\mu}$. Finally, since my model uses

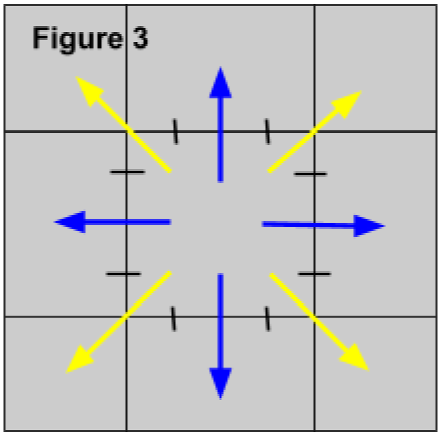
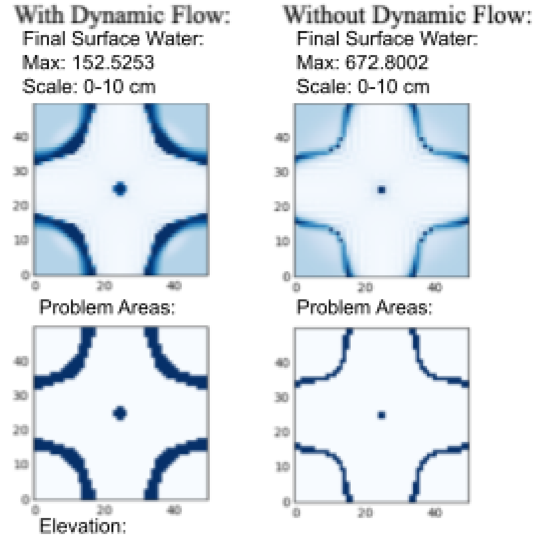


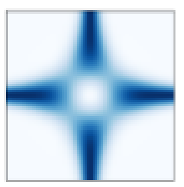
Figure 3

depth rather than volumes, the total volumetric flow needs to be divided by the area it affects to get a change in depth: flow for one direction $= \frac{\gamma\ sin\alpha d^3 \cdot tileDim}{6\ \mu \cdot tileDim^2} = \frac{\gamma\ sin\alpha d^3}{6\ \mu \cdot tileDim}$. It is important to note that this is a formula for laminar flow on a flat and smooth surface and will thus be less accurate for faster flows where turbulence and obstructions pose more of an obstacle[5].

Since the $\frac{\gamma\ sin\alpha}{6\ \mu \cdot tileDim}$ is constant for constant elevation difference, it is able to be precalculated. This significantly cuts down the number of calculations being done inside the time loop. It is, however, forfeiting a bit of accuracy as calculating this way neglects the effect of dynamic water accumulation. There are several cases where this method of precalculation crucially overlooks changes caused by accumulated water on the flow. To get around this, my model has a checking segment that looks at the current water levels around it and searches for cases where the precalculated value is misrepresentative of the true flow (See Appendix A for more information). Through this segment, it retains the accuracies of dynamic flow while maintaining the significant speedup that precalculation brings. In the results of identical simulations -- one with dynamic flow and one without (Figure 4 -- for more clarification on reading these outputs see Appendix B) -- it is clear the impact that dynamic flow has on bringing more accurate results (look especially at the maximum depth of water in the non-dynamic flow results and areas around that seem to have lost their water despite being so close to the minimum where water should be collected).

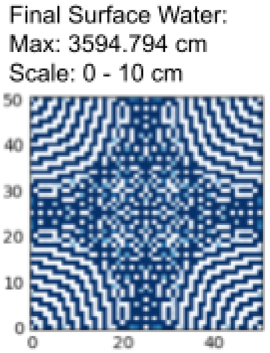
Figure 4





However, this approach is not without its drawbacks. Due to the ability of water in this way of calculating to travel forward and then back, the simulation allows 'waves' to form. These 'waves' aren't natural waves that form on disturbed fluid surfaces but rather oscillations due to instability in time iteration. Figure 5 is a calculation run on the same elevation as Figure 4, but waves have formed and ruined the output quite absolutely

Figure 5



-- it is now in no way representative of what the water would do. The waves are caused when the time step size is too large: water that is flowing down a slope with high time step size will send almost all of its water to the tile beneath it. This begins to overfill tiles who then let all their flow out similarly. Figures 6.1-7 provide the steps of the formation of one of these waves. The input from the right stops step 4, and repetition is seen through steps 5 and 7. These waves only form at conditions of high water flow rates and relatively small change in elevation across grid squares (such that the water can easily surmount the change). The former of which can be caused by high depth of rain or high time step size. While the amount of rain that falls or the quantity of flattish regions isn't changeable, the time step size can be adjusted to prevent the formation of waves.

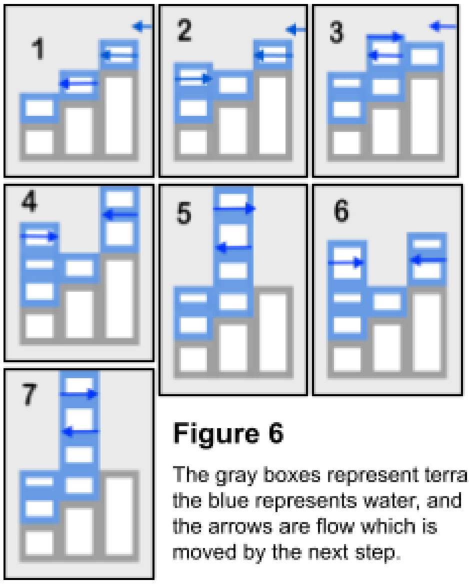


Figure 6

The gray boxes represent terrain, the blue represents water, and the arrows are flow which is moved by the next step.

Another crucial detail of my model is the use of a delayed write to the water arrays. The depth of water in the tile that is flowing outward and the depth of the water in the tile receiving it are both important to accuracy in the aforementioned checks. Thus, my model maintains separation between the data being used to make the calculations and the resulting changes to the data to ensure that water flowing into a square is not allowed to flow out of that square in the same time step.

Finally, erosion problems are marked from flows that exceed 40 cm/s which is the speed that erodes .01 mm silt to 3.5mm gravel[13]. The soils around Albuquerque are mainly between these sizes (sands fit right in the middle of that size range).

Verification and Validation -------------

There are three tests that make up the Verification and Validation of my model. Two are done on mathematical geometries to be sure of the logical flow of water in my model. The final test is done on real elevation and absorption data for Albuquerque, testing a recorded flash flood scenario[7]. That final test will be to assure the true accuracy of my model in predicting the results of a downpour.

To dive into the physical accuracies of my model, I will focus on the fluid dynamics and absorption will be disabled for these two verification tests. To the right is the flat plane defined by $z = .2x + .2y$ (See Figure 7.1) over a 5x5 grid. The area to fill the shape to z = .8 meters (See Figure 7.2) can be calculated with $V = \frac{1}{3}Bh$ with height h = .8 and the base B = $\frac{4 \cdot 4}{2} = 8$, so $V \approx 2.13\text{m}^3$. Thus, to fill this area exactly with rain over a 5m by 5m area, 0.0853m or 8.53cm would need to be dropped. Plugging all of that into my model for 5 divisions (5 grid tiles per edge), the results can be seen in Figure 8.

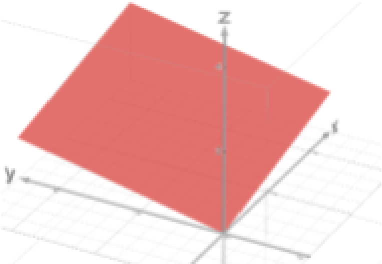


Figure 7.1
$z = .2x + .2y$

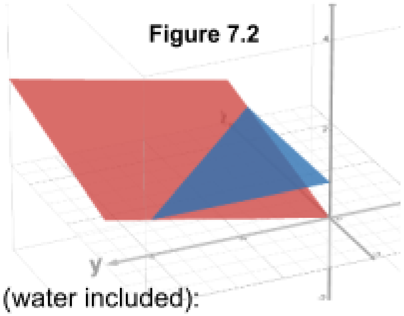
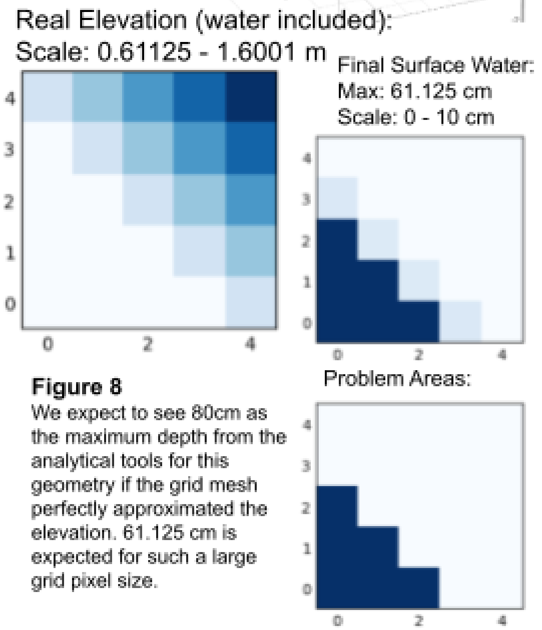


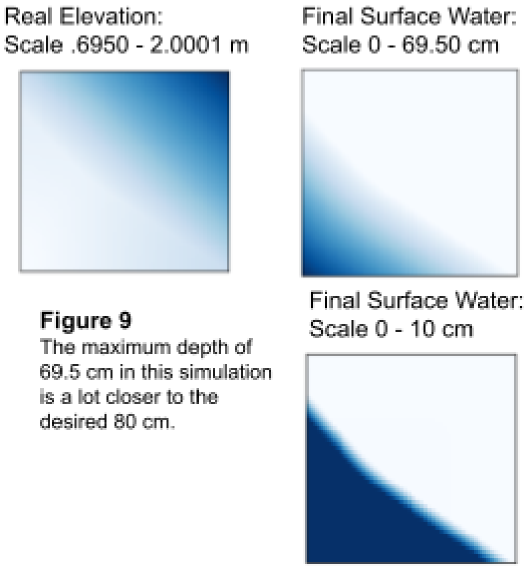
Figure 7.2


Real Elevation (water included):
Scale: 0.61125 - 1.6001 m

Final Surface Water:
Max: 61.125 cm
Scale: 0 - 10 cm

Problem Areas:

Figure 8
We expect to see 80cm as the maximum depth from the analytical tools for this geometry if the grid mesh perfectly approximated the elevation. 61.125 cm is expected for such a large grid pixel size.


Real Elevation:
Scale .6950 - 2.0001 m

Final Surface Water:
Scale 0 - 69.50 cm

Final Surface Water:
Scale 0 - 10 cm

Figure 9
The maximum depth of 69.5 cm in this simulation is a lot closer to the desired 80 cm.

Seen on the real elevation plot, the elevations compare fairly well to the elevations in Figure 7.2. There is a discrepancy between the real water height at the end and what was calculated with the true triangular pyramid volume formula due to the finite number of grid squares. The grid approximation will always add a bit of error that really can only be cut down with more tiles (As shown in Figure 9 where the sides are divided up into 50 pieces rather than 5). In it, one can see how the water much more closely covers its 32% of the area and ⅘ of the adjacent sides, and how the water also quite evenly spreads out, making the bottom left of the real elevation almost all the same color (meaning that it is flat -- accurate to the flat surface of the pool of water in Figure 7.2). Increasing the number of squares makes this approximation a lot better. It is very important, too, to see that the expected maximum value in the corner is approaching the desired 80 cm, as the elevation approximation gets better. The most important element of these results, however, is the settling of the water cleanly and evenly into the corner. This shows much of the power of the dynamic corrections -- without them all the water would flow into the corner with no heed to the fact that it had surpassed the level of the tiles around it.

A good check for the simulation in Figure 8 is to ensure that all the water that was input is accounted for at the end. Since the grid cells are 1m by 1m the volume of water in a cell is simply $depth \cdot m^2$. Thus, by calculating the sum of each square, the final volume is 2.1325m^3. That is very close to the actual input of 2.13m^3. The bit of error is easily attributed to rounding etc. as rain values are divided up not only across the terrain but additionally for a smaller time step.

Another great example which has already been shown in Figure 4 and 5 is the mathematical terrain to the right (Figure 10). It boasts quite the wide variety of features: steep areas, flat areas, and even a cup of sorts. This test is a bit more complex. To test my simulation's ability to handle these three features, I have calculated the volume that the 'cup' shape can hold and a minimum rainfall to fill it. The model runs with these inputs to give the logical progression of water through the terrain.

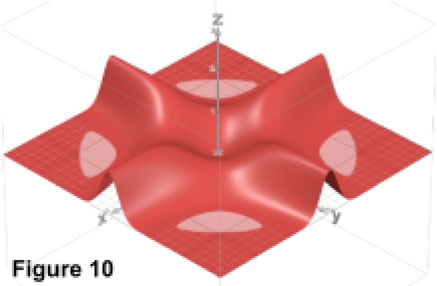


Figure 10

$$f(x,y) = \left(e^{-\left(x^2y^2\right)} - e^{-\left(x^2+y^2\right)}\right)$$

First the volume: the edge is shortest at $\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}$; thus, the volume is given by:

$$\int_{-\frac{1}{\sqrt{2}}}^{\frac{1}{\sqrt{2}}} \left(\int_{-\frac{1}{\sqrt{2}}}^{\frac{1}{\sqrt{2}}} \left(f\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right) - f(x,y) \right) dy \right) dx$$

(Yes, surprisingly the "cup" is square)

Which evaluates to .339m^3 over that square of area ½m^2. Which, in turn, gives 0.6780 m or 67.80 cm of rainfall needed to fill the cup. Plugging that into my model, Figure 11 shows the result. The real elevation graph shows the inside of the cup is almost entirely evenly distributed and similarly with the flat areas outside the cup. It is crucial to notice the scale for the real elevation and how the slight differences in those flat areas really accounts only for small changes.

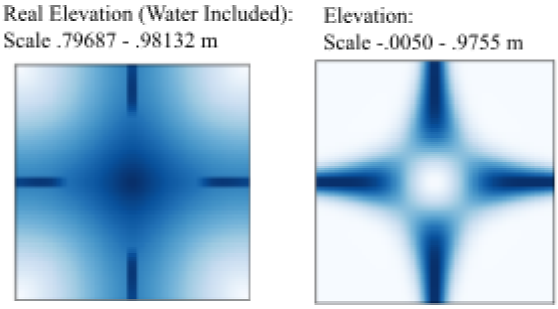


Figure 11

Across these two mathematical models, my simulation demonstrates the logical flow of water on these surfaces to the desired degree of accuracy. With these results so close to their true mathematical identities, my model can be certain to make accurate predictions regarding flow and accumulation.

Model geometries are nice to verify performance but can't really be used for any kind of practical predictions. While tested and initially verified on simplistic mathematical terrain, my simulation is meant to model real and important topographies. For the following validation simulation absorption is turned back on. To validate the true capabilities of my program (including absorption and flow with respect to time), the flash flood in the Embudo Arroyo will be simulated and compared to the actual rainfall accumulation recorded. Albuquerque Authorities[7] state that the foothills got more than an inch of rain in less than 15 minutes. The resulting flow in the North Diversion channel was 6 feet high. For this scenario, my model runs with 2.7 cm of rainfall over 15 minutes. Here is the prediction of the resulting water depth (Figure 12.1) with colors indicating water depths 0-10 cm (the maximum depth in this data set is 5163.6 cm), and data was taken 45 min after the rain stopped (data accompanied by corresponding elevation (Figure 12.2) and satellite imaging map (Figure 12.3)):

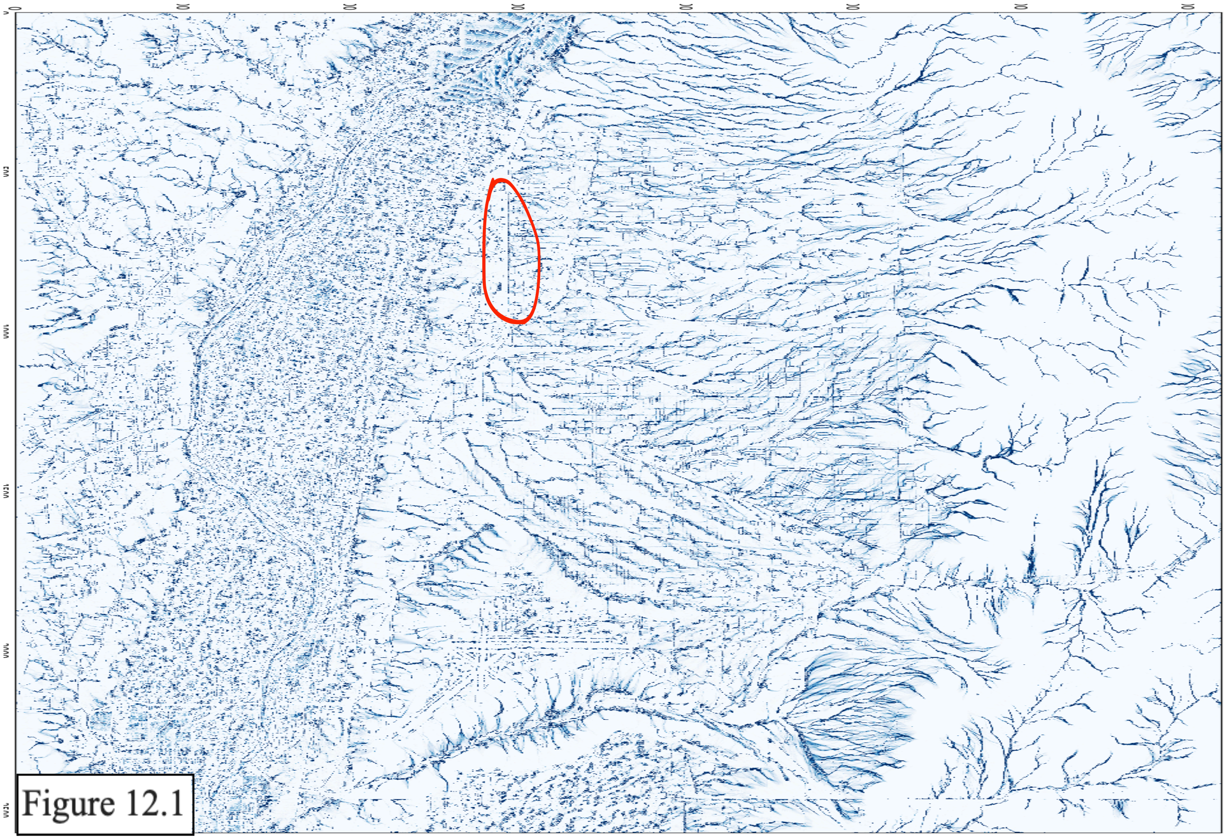


Figure 12.1

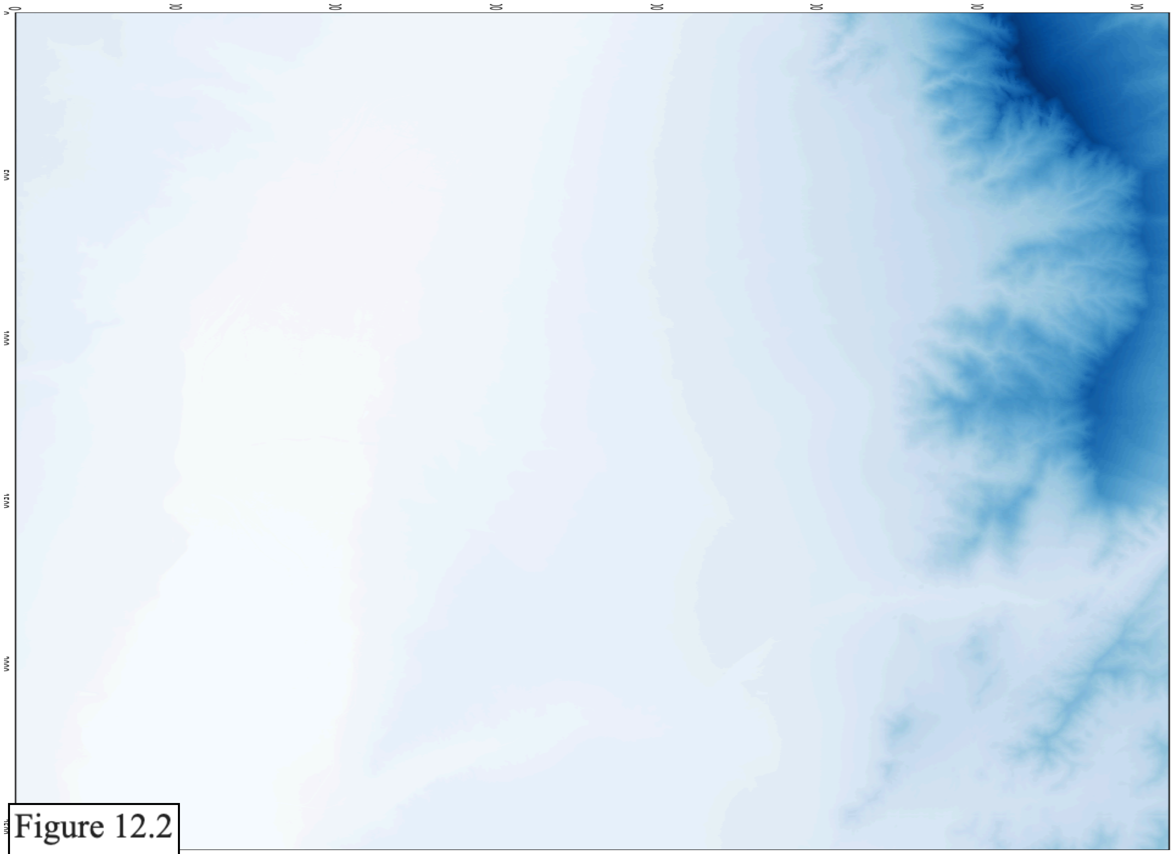


Figure 12.2

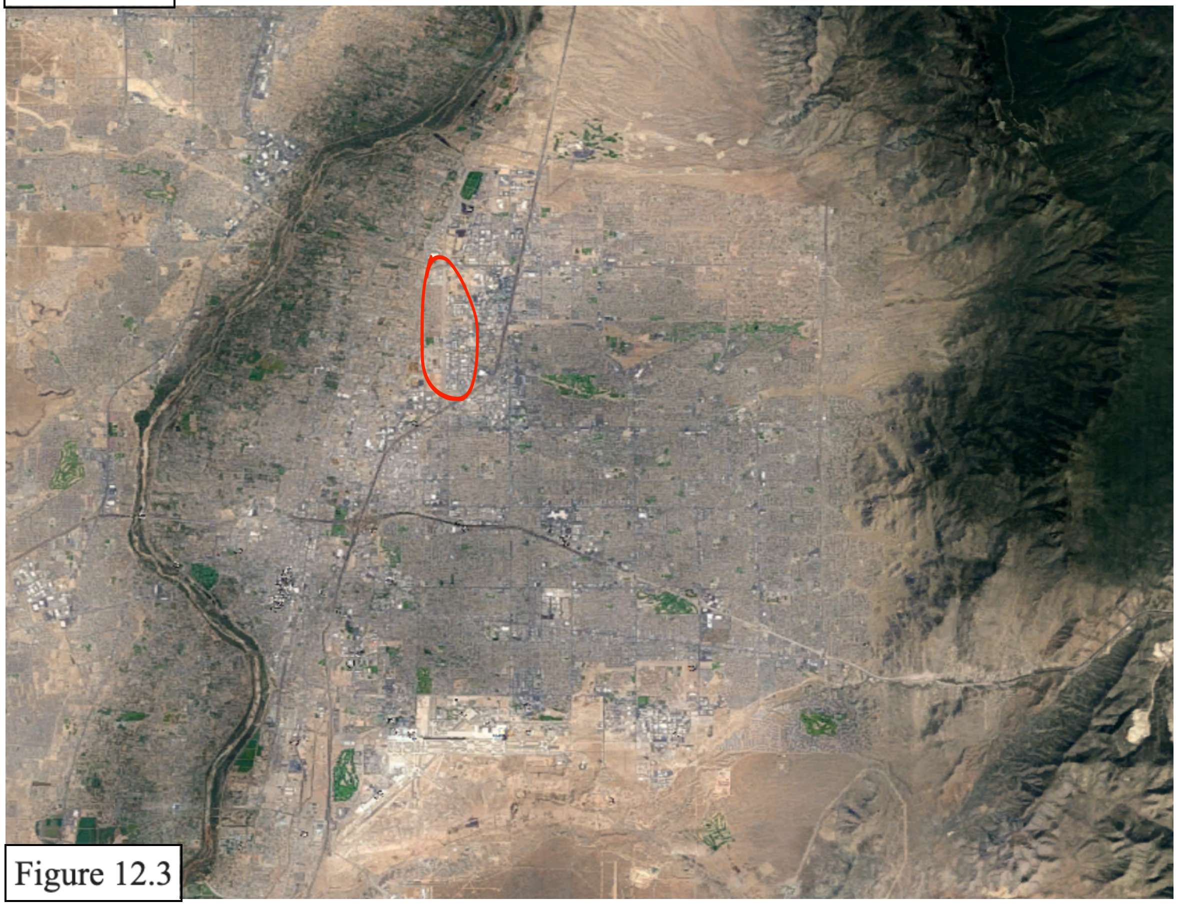


Figure 12.3

Using the reference map we can find the North Diversion Channel fairly easily (the vertical line circled in red on the water and satellite maps). Zooming in (Figure 13.1), there is already an important problem: there are the trademark patterns of waves from too large a timestep. Waves, when limited to small areas like this, can slow down flow rates to an extent and potentially cause water to flow over things that it normally wouldn't. It shouldn't affect the amount of water in an area too much. Zooming in further (Figure 13.2), it can be seen that there are about two pixels that make up the channel and the values of the filled squares are quite varying. To achieve a prediction in terms of depth in the real North Diversion Channel, the water present must be put over the true channel geometry. The average depth of water from my model is (64.95cm or 2 ft 1.98 in). When put over the new geometry (from a 24.60m linear strip to a channel of depth ~12m and sloping sides that make up 14.1m margins with a 7.8m flat bottom[10](approximations from Google Maps, See Figure 14)), it yields 1.64m or 5.47ft. 5.47ft is within 5.15% of the real result of 6ft. The minor deficit reported by my model can be attributed to the formation of waves in the simulation or the vagueness of the information about this validation scenario with respect to the time the flood waters reached 6 feet.

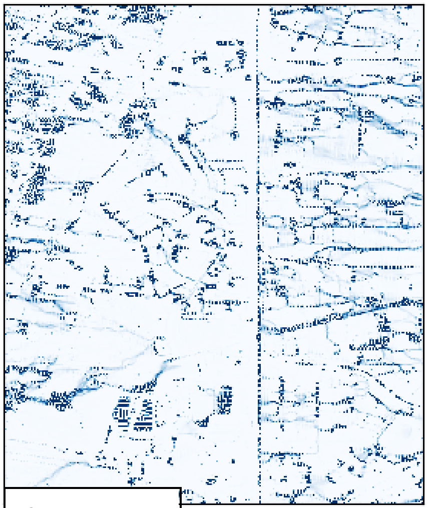


Figure 13.1

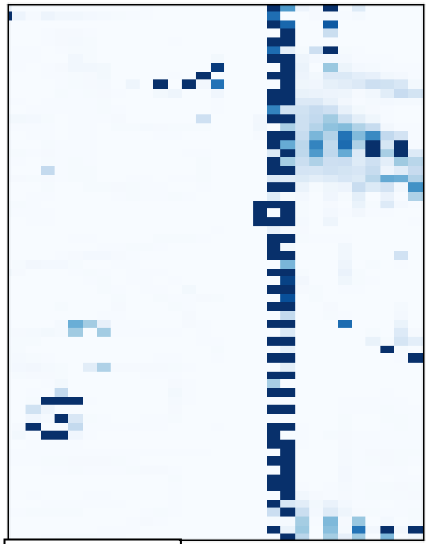


Figure 13.2

In any event, the results obtained from even a simulation with wave formations were quite accurate. With this accuracy for this problem, it is safe to use my model for true predictions or analysis of the current water management systems.

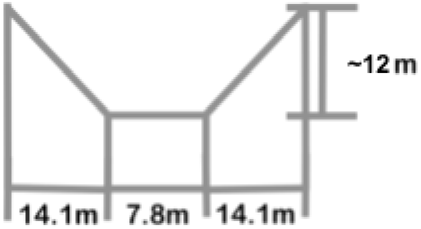


Figure 14

Results: Data and Analysis -------------------

Running simulations of more generic storms over the Albuquerque Area exposes some significant weaknesses in the water management system. Here, with a storm with 1 centimeter of rainfall over 30 minutes (data was taken right after the rain stopped), it can be seen that water is building up over and around the Ebudo Arroyo a little before where it meets 1-40. The first plot is final surface water with scale 0-10 cm. The second is the corresponding satellite map. It looks as though the infrastructure a bit up the Ebudo Arroyo failed at capturing these floodwaters and they ended up running through the surrounding neighborhoods, potentially causing significant damage. This is fairly unsurprising because the validation scenario was specifically recorded due to 3 deaths of people being swept away by flash flood waters in that area. It is evident that this area especially would benefit from redesign and improvement to be safe for the Snow Heights neighborhood through which it passes.

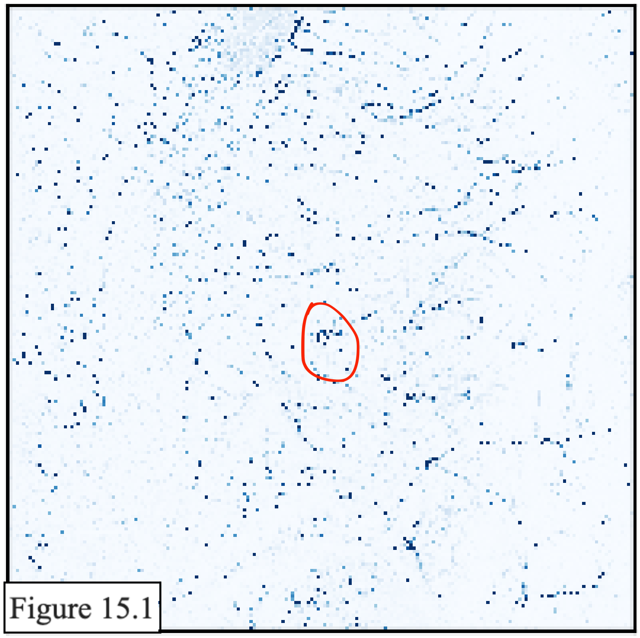


Figure 15.1

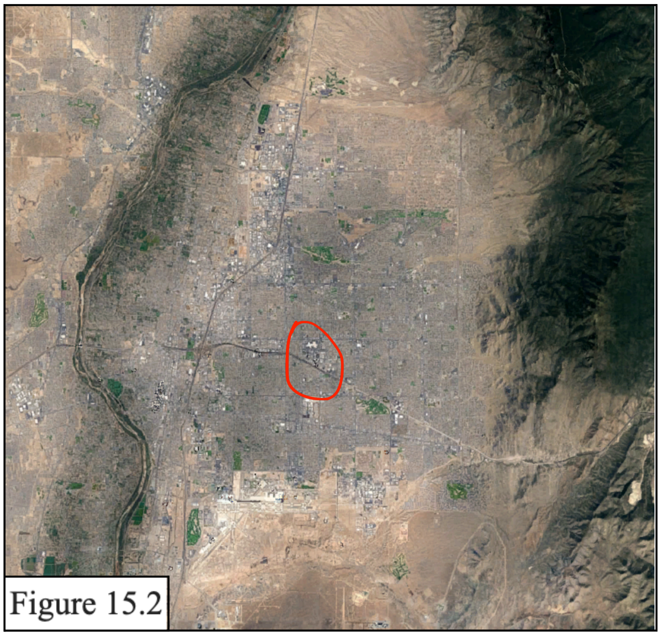


Figure 15.2

Another important detail of this simulation is the flood waters accumulating on the northern stretch of the Rio Grande Floodplain (the following data was taken 30 min after the rain stopped -- Figure 16.1: the area in question is circled in red). The first plot is final surface water with scale 0-10 cm. The second is the corresponding satellite map.

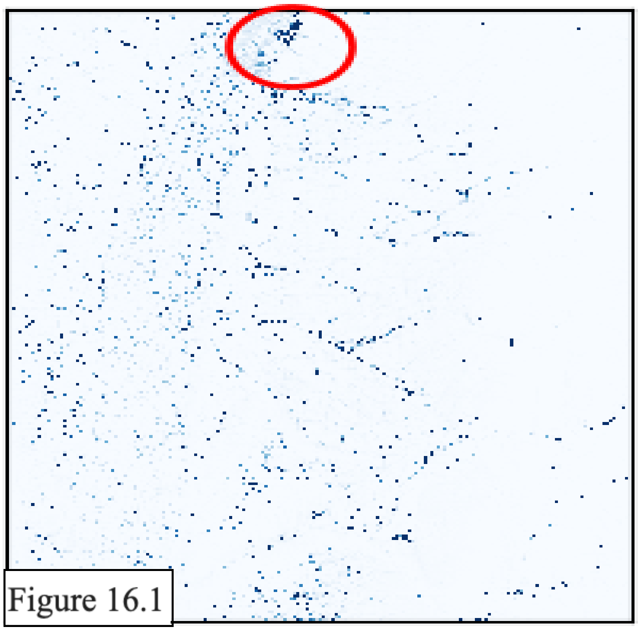


Figure 16.1

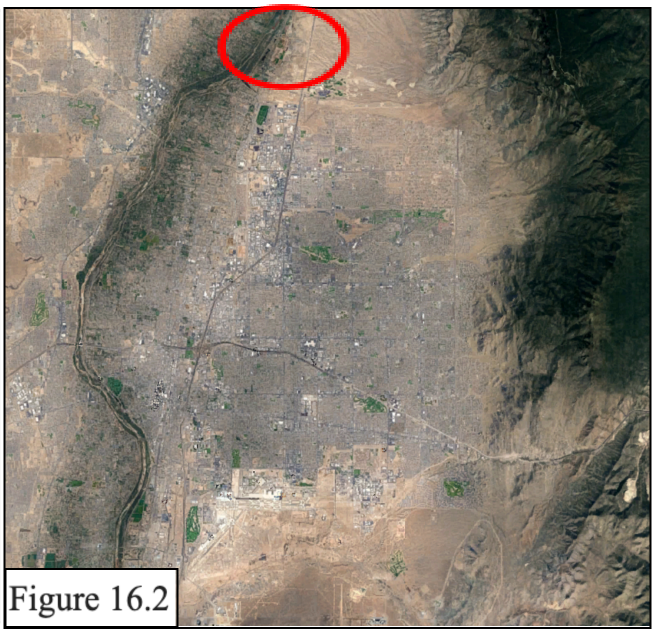


Figure 16.2

A lot of water is accumulating on the diversion routes to the east of the river and ending up on the farming/ranching lands close to the river. The water management infrastructure ends as it comes up on those lands. As seen below (Figure 16.3), the North Diversion Channel's outflow (circled in red) into the Rio Grande marks the last significant water diversion construction to the north. There are a couple smaller arroyos and two detention basins (marked in yellow); however, beyond the blue line there is really no more water diversion infrastructure[10]: only farms and some residential areas. The final step to get this water safely to the river is missing, and it is clearly causing some significant problems for these areas as seen in my model. It is crucial that this lack of water diversion infrastructure is addressed to protect both the agricultural ventures in this area and the people living there. It is also important to note that this area is also inhabited by a poorer part of the population, making them

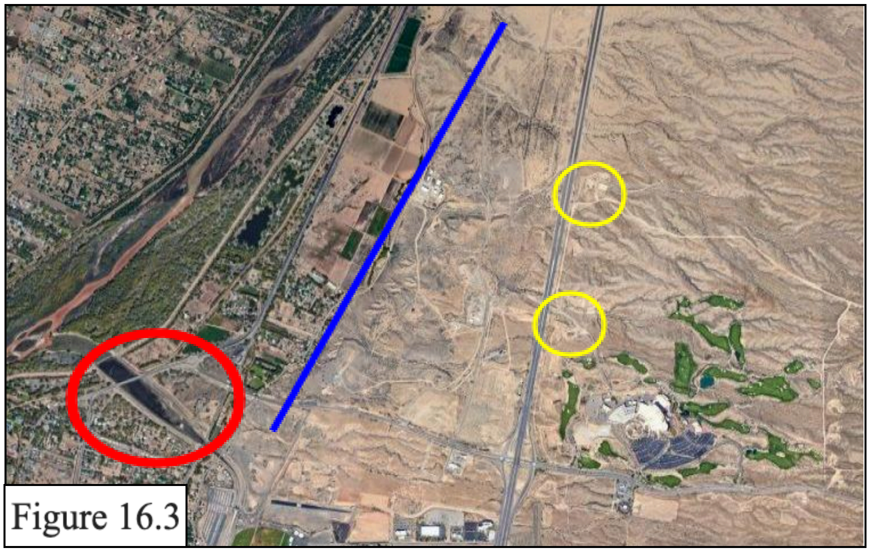


Figure 16.3

much more vulnerable to property damages and other consequences of uncontrolled flood waters.

A final important issue to address in the Albuquerque Area is erosion. With the desert's relatively poor quality soil, many of the more mountainous areas of the Albuquerque area are at significant risk of erosion. In a simulation of a storm with 1 cm of rainfall over 30 minutes, the following graph of Erosion Problems resulted (Figure 17.1 with corresponding satellite map: Figure 17.2).

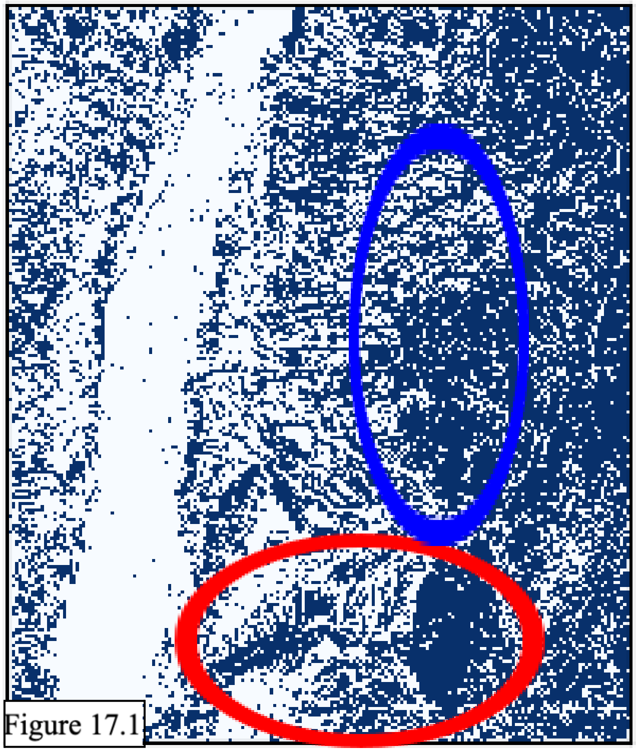


Figure 17.1

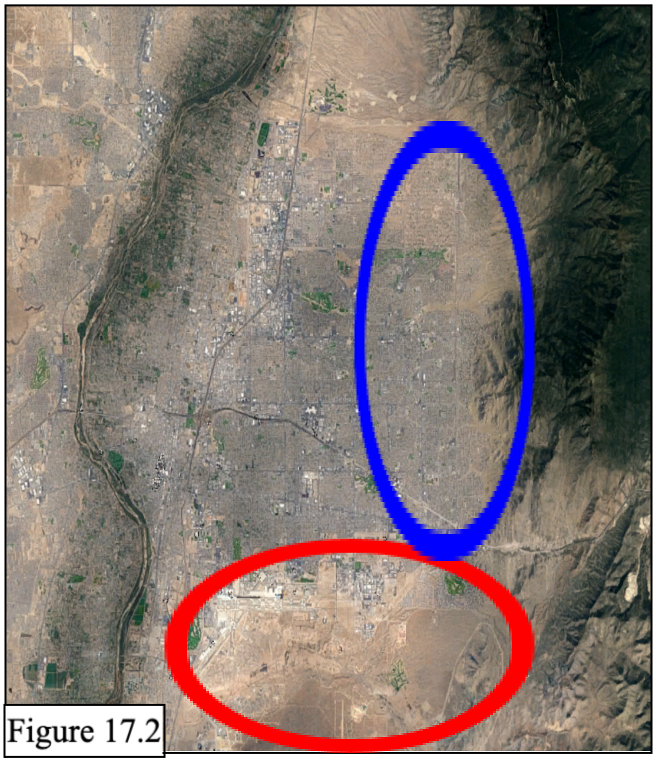


Figure 17.2

This Erosion Problems data marks tiles with a flow velocity greater than 67cm/s (slightly different than normal) which corresponds to .007 mm - 6.5 mm particles eroded[13]. This data says that there are high enough water flow rates to erode soil across the city and more prominently in the foothills and mountains (look especially at the Tijeras Arroyo and Watershed (circled in red)). It is important to note that this erosion warning does not differentiate between whether or not the soil particles are within the size range described above. For many neighborhoods in Albuquerque, concrete and xeriscaping dominate. These materials are not eroded so easily. It is important, however, to see the areas where that isn't the case. A prominent example of this is the aforementioned Tijeras Arroyo. For a good portion of its length, it is not reinforced with concrete, rather cutting through the desert (Tijeras arroyo has a soil bed for the entire length of the blue line in Figure 17.3, only switching to concrete after 1-25).

Figure 17.3

A storm as simulated by my model would simply exacerbate the condition of the Tijeras Arroyo upstream and potentially flow large amounts of sediment into water management infrastructure closer to the river. Much of the older water management infrastructure in the Albuquerque Area is similarly earthen and susceptible to heavy rainfall and flow to cause erosion. This infrastructure would clearly benefit from improvement and reinforcement to better prevent erosion.

Another significant area under threat of erosion is the foothills (circled in blue on Figure 17.1,2). The majority of residences in the foothills don't boast extreme vegetation or other changes that would protect them from erosion. Additionally, many of the hiking trails going into the mountains from there have clear evidence of significant erosion in many of the small gullies. The area doesn't have the best soil quality[8] which causes a cascade of problems: little significant vegetation to hold the soil together, often sandy soils that erode easily, etc. More detention basins and other flow slowing methods would help this area greatly and also get more of the runoff from the mountains absorbed into the aquifer to also benefit people and vegetation in those areas.

Finally, to address the high coloring in both the city and in the mountains, the more western city does require some attention with regard to erosion of loose materials, but due to large amounts of road and pavement that can't be eroded under these conditions, the city most likely does not need significant change and redesign regarding erosion prevention. As for the mountains, the mountains are mainly rocky, but the soil there supports much more significant vegetation, from grasses, to bushes, to trees. These all prevent soil in the mountains from being eroded, and in doing so, protect much of the watershed below. The mountain, despite its seeming susceptibility to erosion, is better protected.

Products: A Tool for Prediction ---------------

My model wasn't purely made for the examination of the Albuquerque Area and its local water infrastructure; it was made to predict precipitation results anywhere there is a storm and sufficient data to work off of. Coupled with the US NOAA, my simulation could add to their predictive weather services with results of the precipitation on local watersheds and artificial infrastructure. Besides my model and some fairly simple input and output data processing, there are no other products.

Given more time, I would like to reformat my code to run in parallel such that it would be able to run complex simulations much more quickly. Waiting for results was a significant obstacle during this process, and to truly use my simulation alongside NOAA as described above, it would need to be considerably faster. A generic simulation of flow over the Albuquerque Area takes around a day and a half to calculate, while they can get as lengthy as 3 days depending on the timescale the simulation is focused on. I would also like to try and impose more limitations on the formation of waves and try to root out ways to prevent them from occurring.

Personally, I think my greatest accomplishment of this journey was getting the precalculated and dynamic flow algorithm figured out, especially with respect to the unstable time iteration in 2d space.

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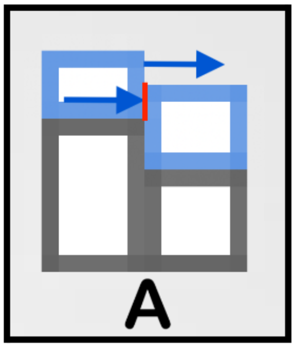
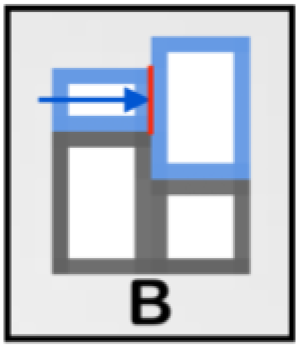
Finally, I would like to thank both Jonathan Wheeler and Karl Benedict at the UNM Library for their help getting absorption data and normalization tools for helping with compatibility, both of which I was unable to find on my own.

Appendix A -------------------------------------

This Appendix concerns precalculation which is the calculation of the constant piece of the fluid dynamics equation used for prediction water flow (See page 5,6 for more information on the flow equation). However, precalculation can be inaccurate when water begins to change what precalculation assumes to be constant elevations.

There are 6 cases in total for flow regarding water levels and elevations. There are three cases of those six where precalculation fails. For the examples below, they are viewed with increasing altitude being the top of the figure, the gray pieces represent terrain elevation, the blue pieces represent water accumulation on top of the terrain, the arrows represent flow, and the red lines are where flow tries but should not go. For these cases water flow will only be considered from the left tile to the right tile. My model only considers flow this way, as it iterates through all of the tiles and considers each potential flow one sided-ly. For case A, the precalculation says flow is all good to go; however, in

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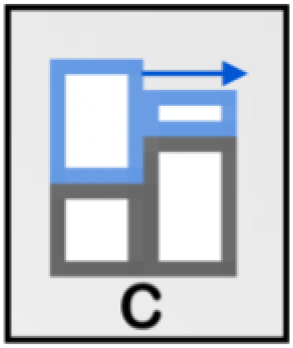
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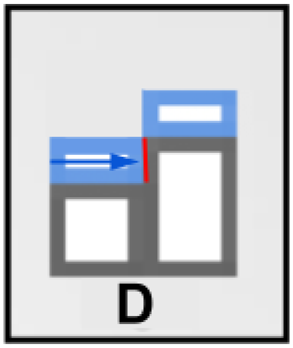
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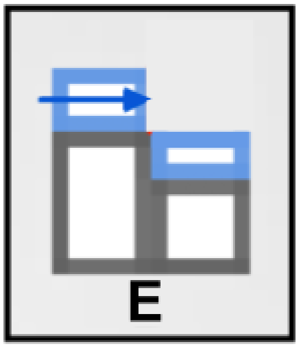
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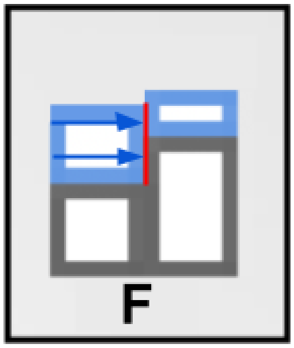
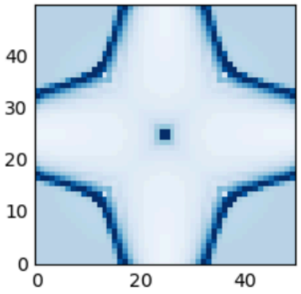

F

reality, the flow is impeded by previous accumulation of water on the right tile. Thus, case A needs dynamic recalculation. Case B is similar. Precalculation says that flow is good, but really, no flow can take place at all due to the fact that water wouldn't flow 'uphill' to the top of that higher water level. Since reality does not agree with the precalculation, dynamic recalculation is necessary. Case C is essentially the inverse of B. Precalculation says that no water should flow because the right tile is uphill. However, the water has reached high enough accumulation that it will flow into its neighbor -- recalculation is needed. Case D is different. Precalculation says no flow, and reality agrees. No recalculation is needed. Case E, too, is cooperative. Precalculation says that there will be unimpeded flow and reality agrees. Finally, Case F is a bit of an edge case. Precalculation gives no flow, and while there is sufficient water accumulation on the right to surpass the terrain, the water accumulation on the right is still enough to prevent any flow from left to right, so reality also says no flow. It ends up not needing recalculation. In Cases A, B and C, the precalculation overlooks an important way water needs to be handled in the model. Those cases are fairly easily defined which allows the program to go through a bunch of quite fast if statements rather than getting bogged down in calculating and comparing for every tile.

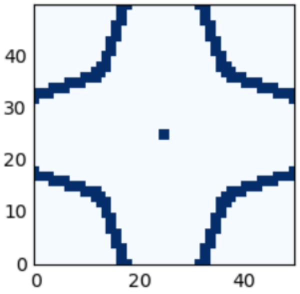
Appendix B -----------------------------------

Understanding the outputs of my model is crucial to understanding its capabilities and my analysis of it. I will run through what to expect from each named dataset here. First and most common is "Final Surface Water". Final Surface Water data sets come in two varieties: scale of 0-10 cm and scale of 0-max. The first has the colors on the plot corresponding to the value as it is on the scale 0-10 (numbers between 0 and 10 get assigned a corresponding color intensity based on where it is on the scale, whereas numbers above 10 get assigned the same color intensity as 10 cm, and similarly with values below 0 and the color intensity for 0). The 0-max variety of graph is the same however the maximum value of the data set is made to be the upper bound for graphing. Graphing over 0-10 cm is useful when the details are really in what is in that range 0-10, especially when the max is in the thousands and graphing with the range as the max makes everything else colorless by comparison. Often for graphs over the scale 0-10 cm, the maximum value will also be provided as a point of reference. The actual data on this graph indicates the depth of water predicted at the points on the graph.

Final Surface Water:
Max: 102.44277785402164 cm
Scale: 0-10 cm

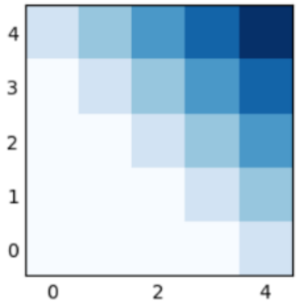


Problem Areas:



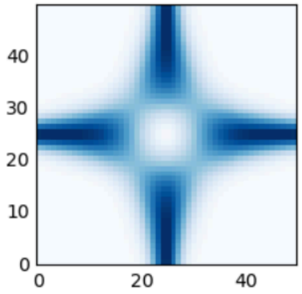
The next type of graph is the “Problem Areas” and “Erosion Problem Areas” data sets. These are provided with no scale and are simply interpreted as boolean graphs. Pixels with color are problem areas; pixels without color are not.

Real Elevation (water included):
Scale: 0.6112500559617084 - 1.6000646282673698 m



Next are “Real Elevation” data sets. These, much like “Final Surface Water” plots, will be accompanied by a scale to indicate the range on which it was graphed. These graphs will always be graphed from maximum to minimum value. The data on these sets is the water level (now in meters) added to the elevation to get a true idea of the water accumulation with respect to the terrain.

Elevation:
Scale: 3049.7452996079974 - 3098.776331460856 m



Final are “Elevation” plots. They are also always plotted from minimum value to maximum value. Their data is the elevation of the terrain at those points.