Joining fragmentary river segments with elevations and water flow directions using induced terrain

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1. INTRODUCTION

We present an algorithm and implementation for completing a hydrologically consistent river network from river segments with the help of partial heights and water flow direction data. Our approach is to induce a terrain from the available information, and then to derive the output hydrography from that terrain. This guarantees that the output is hydrologically consistent. This problem is important because in aerial photography of tropical rain forests, large trees often cover small rivers. However, the complete river network is necessary for transportation, land use planning and flood control. Previous solutions using morphological techniques to grow the river fragments do not ensure hydrological consistency.

Previously we reported inducing terrains from basic inputs such as pieces of rivers (as undirected polylines in 2D) and height samples [2]. This paper extends those results to embrace water flow direction, or drainages, as well. The drainage of a location may be deduced by analysing traces of flows on the water surface. In landmarks such as waterfalls, those traces are clear. If the river has just flooded, damage to hedges, ditches or dikes may provide useful clues [4]. The river branch angles can also help, as specific branch angles are found to occur more likely with particular drainage patterns [3].

2. BASIC INDUCED TERRAIN

Our approach, named the *induced terrain approach* (Figure 1), incorporates the given partial heights in its first step called *structure reconstruction*. This step completes a height grid from the partial heights with a *terrain reconstruction* algorithm. Since partial river locations ought to be lower than adjacent non-river locations, we need *hydrological correction*. We previously found that with sparsely and evenly distributed height samples, we obtained the best result by first reconstructing a preliminary terrain from the given partial heights with natural neighbor interpolation, and subsequently effecting the hydrological correction by lowering the height of given river locations by a trench amount, a technique known as stream burning. We named this scheme *NN-SB*.

Then, in the second step of *information derivation*, we compute a river network from the reconstructed terrain. The *river derivation* algorithm used to compute the complete river network from the full terrain surface should be *biased*: We offer each given river location an initial water amount that is exactly the critical amount instead of a typical, smaller value. That location is then guaranteed to have sufficient water to be identified as a river location. In addition, we protect the given river locations from being trimmed away in the final river thinning process. The resulting river network passes through and hence reconnects all the given river locations, while maintaining the river network constraints imposed by the river derivation algorithm: The network consists of a number of tree branching structure. Every river location has a single way out to the edge.

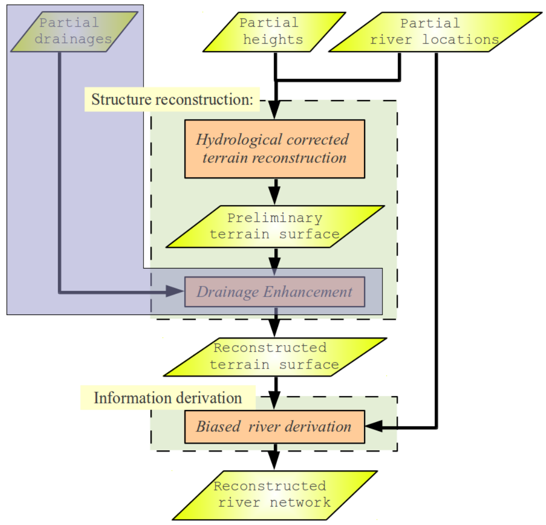

Figure 1: The induced terrain approach. The area enclosed by the blue polygon is the drainage-enhanced extension.

3. EXTENDING INDUCED TERRAIN

We propose an additional step called *drainage enhancement* in the structure reconstruction process. As shown in Figure 1, before deriving a river network with the reconstructed terrain, we use Algorithm 1 which aims to make sure that for every drainage-augmented location p, its neighbor at the drainage direction p_{idown} is not only lower than p but also the lowest among all the neighbors of p (lower deepest neighbor). We lower the height of p_{idown} accordingly whenever that condition is violated. The modified reconstructed terrain is then more likely to replicate the given drainage directions in the biased river derivation process. We decide to overwrite the heights, because we consider the drainages more accurate than both the interpolated and given known heights from the hydrological corrected terrain reconstruction output.

4. EVALUATION

Our test datasets are twelve 400 × 400 DEMs extracted from two SRTM1 cells and two SRTM3 cells. We derived the full eight-connected river networks with complete elevation data since we need the accurate ground-truth river networks for comparison with the reconnection results. We then sampled for observed river locations

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for *each segment* S **do**
  Initialize the queue Q with the set of locations not pointed by drainages of others on S;
  while Q *is not empty* **do**
    $p \leftarrow$ a location dequeued from $Queue$;
    $p_{idown} \leftarrow downstream(p)$;
    while p_{idown} *is not NULL* **do**
      // ensure p_{idown} is lower than p
      if $height(p_{idown}) \leq height(p)$ **then**
        $height(p_{idown}) \leftarrow height(p) - DELTA$;
      end
      // ensure p_{idown} is p's deepest neighbor
      $minHeight \leftarrow$ minimum value in the 3×3 grid centered at p;
      if $height(p_{idown}) \geq minHeight$ **then**
        $height(p_{idown}) \leftarrow minHeight - DELTA$;
      end
      // proceed to the downstream neighbor
      $p_{idown} \leftarrow downstream(p)$;
      // defer processing of p_{idown}
      // if it has more than one upstream neighbor
      if $numUpstream(p_{idown}) > 1$ **then**
        if p_{idown} *is not in* Q **then**
          Insert p_{idown} into Q;
          $p_{idown} \leftarrow$ NULL;
        end
      end
    end
  end
end

Algorithm 1: The drainage enhancement algorithm that modifies the hydrological-corrected reconstructed terrain according to given partial drainages. The function $height(p)$ returns the height of the location p, while $downstream(p)$ gives the unique downstream neighbor of p, which is the location that its drainage points to. $numUpstream(p)$ evaluates the number of upstream neighbors of p. $DELTA$ is a value that is much smaller than the height resolution, so as to minimize the height change needed to correct the drainage.

(and respective drainages) and elevations to simulate occlusions by clouds or canopies. Since we are dealing with sparse but evenly distributed height samples, we adopt NN-SB as our hydrological-corrected terrain reconstruction scheme. We evaluate accuracy by the percentage of correct immediate downstream segment reconnections. Columns 2 and 3 of Table 1 illustrates the effect of drainage enhancement. We obtain more correct reconnections with drainage enhancement in general.

DEM	Drainage-enhanced NNSB	NNSB	Drainage-enhanced ANUDEM	ANUDEM
hill1	**75.60%**	75.12%	69.38%	64.59%
hill2	**88.74%**	84.85%	80.09%	78.79%
hill3	**56.25%**	52.94%	48.90%	49.26%
hill4	**76.64%**	75.91%	72.26%	69.71%
hill5	**86.23%**	85.02%	84.21%	84.21%
hill6	**87.50%**	84.38%	81.25%	74.61%
mtn1	**92.92%**	90.83%	86.68%	86.67%
mtn2	**96.02%**	95.13%	94.25%	91.15%
mtn3	**90.18%**	89.29%	93.30%	89.73%
mtn4	**80.95%**	77.89%	78.57%	76.87%
mtn5	**94.59%**	92.66%	89.58%	86.87%
mtn6	**90.76%**	89.56%	84.74%	83.13%

Table 1: Percentage of correct immediate downstream segment reconnections.

We also try replacing NN-SB with the original ANUDEM [1] which

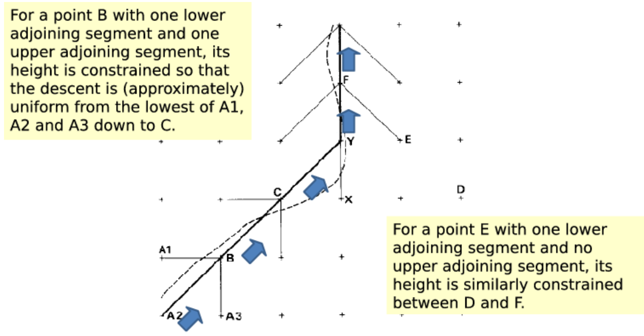

Figure 2: Incorporating drainage-augmented streamlines in ANUDEM.

also takes drainages into account. ANUDEM uses iterative finite-difference interpolation together with the drainage enforcement algorithm illustrated in Figure 2 to generate drainage-aware terrains. Note that ANUDEM just sets up a descent along the given river segments. It does not check if the downstream location is the lower deepest neighbor as ours. As a result, there could be chances for a location rather than the given downstream location to receive the water. That may explain why we can further improve ANUDEM's surface with our drainage enhancement algorithm in most cases (Columns 4 and 5). Finally, our drainage-enhanced NN-SB scheme consistently generates better surfaces for river derivation than ANDUEM (Columns 2 and 5).

5. CONCLUSION

We have detailed our first extension of the induced terrain approach that includes drainages of the given river segments. The idea is to acknowledge the relative heights of a river location and its respective neighbors that can be inferred from the observed drainages, and adjust the hydrologically-corrected terrain accordingly. The final reconstructed terrain is thus more capable of generating a complete river network that honors the additional information, which leads to higher accuracy. The success of our algorithm is demonstrated by the improved immediate downstream segment reconnections. Our drainage-enhanced NN-SB surfaces consistently work better than ANUDEM's.

As for future work, note that the scheme above assumes that partial drainages are more accurate than all the reconstructed and given heights. However, the reality could be much more complicated. For instance, reconstructed heights are less reliable than given heights. How this affects the way we select the final reconstructed heights is worth studying.

6. REFERENCES

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