APPENDIX G

Hydraulic Model Methods and Results

GOODELL CREEK HYDRAULIC MODEL METHODS AND RESULTS

Methods

The hydraulic model *RiverFlow2D Plus* was used to approximate hydraulic characteristics of the Goodell Creek alluvial fan. RiverFlow2D Plus is a two-dimensional hydrodynamic finite volume model that can be used to route floods and provide high resolution of flood hydraulics. RiverFlow2D was developed and released in 2013 by Hydronia LLC to provide a tool to approximate detailed hydraulics using a flexible triangular finite element mesh without the stability limitations of older two-dimensional finite element models. A flexible triangular mesh allows the hydraulic modeler to refine the density and resolution of the model to approximate detailed flow fields around key river features in complex river environments.

RiverFlow2D is commercial and technically supported hydraulic modeling tool that is very stable with shallow, broad floodplains by automatically deactivating elements within a specified shallow depth threshold. RiverFlow2D Plus is based on a finite volume solver that inherently accounts for local volume conservation for each element and virtually 100% volume conservation throughout all areas of the model domain which is a limitation of most finite element schemes. The "Plus" version uses the graphic processor unit (GPU) as the computing horsepower versus the computers central processing unit (CPU) to increase model speed by 30 to 50 times and allows the model simulation to be completed within hours versus days.

Two-dimensional numerical models like RiverFlow2D require boundary conditions such as a geometric computational mesh (i.e., ground surface grid), roughness values, and a discharge hydrograph that define the computational domain. Boundary conditions and other input data developed for the models are described below.

Computational Domain and Mesh Development

The extent of the RiverFlow2D hydraulic model includes the head of the Goodell Creek alluvial fan within the gorge at the upstream end, and the entire Skagit floodplain at the downstream end so that interactions and potential backwater effects into Goodell Creek could be assessed. This is especially important for assessing backwater and potential scour and aggradation potential at the SR 20 Bridge and other risks associated with flow overtopping SR20. The density of the RiverFlow2D computational domain was adjusted with variable element sizes ranging from 40 feet in the floodplain, to as small as 4 feet in the main channel, side channels, and near the SR20 highway. The average element size was approximately 10.6 feet. The channel and floodplain area was represented with approximately 655,382 elements and 328,214 nodes. The length and width of the modeled floodplain is primarily bounded by the valley wall for the Skagit River and Goodell Creek alluvial fan.

One of the primary boundary conditions for a hydraulic model is the geometric representation of the floodplain topography and flow resistance along the floodplain surface (topographic boundary condition). The 2009 LIDAR (NPS 2009) was used in the hydraulic model with survey verification of the levee high points and bathymetry around the SR 20 Bridge. The 2009 LIDAR did not extend far enough to the west to cover the western extent of the fan, so the 2006 LIDAR (PSLC 2006) was merged and spliced into the topographic surface. The 2006 LIDAR appears to contain some quality issues so the 2006 LIDAR was only used where the 2009 LIDAR was missing data. This ended up not being a significant limitation to the model since very little flow interaction occurs in this portion of the floodplain.

Flow resistance at the topographic boundary was estimated using Mannings n-values roughness coefficients (Chow 1959). The n-values used included 0.02 for road surfaces, 0.03 for gravel channel and bar areas, 0.04 for grassy and open floodplain areas, 0.1 for the forested floodplain, and 0.12 for local roughness around LWD and engineered logjam structures. A screenshot of the n-values within the hydraulic model computational domain is provided below.

Upstream Boundary Conditions

The model was developed with two upstream inflow boundary conditions: Goodell Creek, and Skagit River. Both upstream boundary conditions were assumed as a steady state "Type 61" inflow boundary condition. Four inflow conditions were assumed and modeled in the RiverFlow2D model as described in detail in Table E-1 of Appendix E.

Downstream Boundary Conditions

The downstream model boundary was established at River Mile (RM) 92 of the Skagit River. A "Type 12" normal depth energy grade slope of 0.01 (1.0%) was assumed for the downstream boundary condition as obtained from the LIDAR data. LIDAR does not effectively penetrate water, so it typically provides good water surface elevation gradient information for use as a normal depth energy grade. However, the assumed gradient for the downstream boundary condition likely has no effect on the hydraulics in the Skagit River near the confluence with Goodell Creek or even the overflow paths over SR 20 because the model was extended far enough downstream such that the accuracy of the downstream boundary conditions will have no bearing on the hydraulic results near the project area.

Results

Existing Conditions and No-Action Alternative

The hydraulic model results for existing conditions water depths are summarized in Figures G-1 through G-4, and velocities are summarized in Figure G-5 through G-8 for each of the four inflows summarized in Appendix E. These results are denoted as "*Time: Zero*" on the figures. The No Action Alternatives assume no project elements and aggradation over a time period of 5 to 15 years after sediment storage in the upstream reach and landslide-dammed lake has filled and started to deliver sediment to the fan as described in the body of the report. The hydraulic model results for no action alternative for water depths are summarized in Figures G-9 through G-12, and velocities are summarized in Figure G-13 through G-16.

For existing conditions, discharges less than the 2-year flood event are primarily confined to the main channel due to the presence of left and right bank levees. Flow is noted to breach the mid to lower half of the right bank levee for the 2-year flow in a location consistent with field observations (Figure G-2). This overbank flow cannot flow back into the Goodell Creek channel and flows down to and crosses SR 20 highway via a 48-inch diameter corrugated culvert (that can become a fish trap or barrier, Barkdull et al. 2012) and drains through an ephemeral channel in the lower Goodell Creek Campground to the Skagit River. For the 100-year flow, the overbank flow overwhelms the culvert, and the resultant headwater at the culvert backwaters the floodplain and flows over the SR 20 roadway (Figure G-3). Inundation for the bulked flow (Figure G-4) changes very little from the 100-year flow but demonstrates a significantly greater flow over the SR 20 roadway. These results suggest that the flow distribution and proportioning of progressively larger flows events is directed over the right bank and towards the SR 20 highway as shown in Figure G-4, not under the existing SR 20 bridge crossing.

Existing conditions velocities range from 4 to 12 feet per second (fps) in the main channel for the 2-year event (Figure G-6), and up to 10 to 18 fps for the 100-year event (Figure G-7). Velocities under the SR 20 bridge crossing are estimated to be 14 to 18 fps for the 100-year flood event suggesting erosion risks near the right bank abutment. Velocities over SR 20 for the 100-year event exceed 6fps suggesting an existing risk of shoulder and road prism erosion. Velocities for all flood events (2-year, 100-year, and bulked flows) demonstrated a significant decrease in velocities in the mid-fan area where significant aggradation was evident between the 2006 and 2009 LIDAR data sets as described in the main body of the report. These results suggest that the aggradation is a positive feedback and will continue over time. This location is also adjacent to the area along the right bank levee where overbank flow directed towards SR 20 is first initiated. For the No-Action and alternatives, aggradation was assumed to be equally distributed in the channel with an exception for the SR 20 bridge crossing. As such, the hydraulic results for the aggradation over time scenarios are conservative in that they do not bias or over-exaggerate avulsion or downstream flood risks.

No-Action Alternative results suggest that over time, aggradation will result in increased right bank overflow and potential avulsion risks to the south towards SR 20. Significant changes are noted even for the 2-year event comparing the results between Figure G-2 and G-10 for flood depths and Figure G-6 and G-14 for velocities. The results even suggest that the culvert under SR 20 will be overwhelmed in the 2-year event with flow velocities exceeding 5 fps. Flow velocities over the road not only increase for the 100-year and bulks flows, but the length of highway subject to the high velocities also greatly increased under the No-Action scenario indicating an increased frequency of erosion and risk to the highway over time.

Hydraulic Characteristics for Alternatives

The topography and roughness components in the computational domain of the RiverFlow2D model were modified to reflect project as-built conditions for each of the four alternatives described in the main body of the report.

Alternative 2 Results

The hydraulic model results for Alternative 2 (left bank only restoration) for water depths are summarized in Figures G-17 through G-23, and velocities are summarized in Figure G-24 through G-30. In general, the results for Alternative 2 do not significantly vary compared to the time zero as-built existing conditions and the geomorphic response scenario. For example, the low flow results in Figure G-17 (Alternative 2) are unchanged compared to Figure G-1 (existing conditions), and the geomorphic response results for Alternative 2 for low flow (Figure G-18) are very similar to the No-Action geomorphic change scenario (Figure G-9). This observation is consistent for the 2-year flow too, suggesting that floodplain inundation into the left bank floodplain for lower flows is limited since the general gradient and preferential floodplain flow is towards the right bank. Based on the results for the geomorphic scenarios, it would likely take some time before consistent inundation of the left bank would occur and immediate restoration benefits would likely be limited. Floodplain inundation into the left bank for the 100-year flow was more prominent than for the low flow and 2-year flood event. For example, Figure G- 21 compared to Figure G-22 demonstrates that the inundation will increase over time, but comparison of Figure G- 21 (Alternative 2) compared to Figure G-3 (existing conditions) demonstrates that the inundation will significantly increase immediate for large flow (this is different than the results for the smaller flows). However, this increased inundation and flow to the left bank does very little to reduce or alleviate the velocities over SR 20. At time zero, the velocities over SR 20 for Alternative 2 (Figure G-28) are very similar to the velocities for existing conditions (Figure G-7). The geomorphic response scenario velocities over SR 20 also do not change between Alternative 2 (Figure G-29) and No-Action (Figure G-15).

Alternative 3 Results

The hydraulic model results for Alternative 3 (full left and right bank restoration) for water depths are summarized in Figures G-31 through G-37, and velocities are summarized in Figures G-38 through G-44. In general, the results for Alternative 3 show that side channel and floodplain inundation (available habitat area) increases for all flows for both time zero and long term aggradation scenarios. The more dramatic changes occur for the 2-year flow scenario (Figure G-33 compared to Figure G-2 for time zero, and Figure G-34 compared to Figure G-10 for the geomorphic changes over time). This suggests that the immediate habitat gains and long term geomorphic response and creation of habitat is more prominent for Alternative 3 than any of the other Alternatives. Inundation and velocities over SR 20 are also eliminated for the 2-year flow and at time zero for the 100-year flow. Flow does breach SR 20 for the 100-year aggradation scenario, but the velocities are greatly reduced (Figure G-43 for Alternative 3 versus Figure G-15 for no action). Protection of the SCL towers is also greatly improved for Alternative 3 since the floodplain overflow and potential avulsion path can be controlled and directed away from the towers. Alternative 3 also demonstrates the least differences as far as floodplain inundation and velocity between time zero and the geomorphic changes (aggradation) over time (i.e., Figure G-40 compared to Figure G-41 for the 2-year flow). This suggests that Alternative 3 demonstrates a higher level of resiliency to change over time.

Alternative 4 Results

The hydraulic model results for Alternative 4 (right bank restoration only) for water depths are summarized in Figures G-45 through G-51, and velocities are summarized in Figure G-52 through G-58. The hydraulic results are very similar to Alternative 3 because the dominant hydraulic gradient is to the south over the right bank so the removal of the right bank levee appears to dictate the hydraulic response of the Goodell Creek alluvial fan. The inundation in the right bank is slightly higher in Alternative 3 than Alternative 4, so the breaching of SR 20 would likely occur earlier for Alternative 4 compared to Alternative 3 and at a slightly smaller discharge, but the results suggest this difference is minor. These results also suggest that replacement of the existing SR 20 Bridge crossing has minor hydraulic differences (Alternative 4 compared to Alternative 3) with the placement of a new bridge west of the existing bridge. Replacing the existing bridge would likely have a more natural geomorphic responses, but the overall hydraulic effects at high flows are marginal given that the long term preferential floodplain flow path is to the south and southwest.

Alternative 5 Results

The hydraulic model results for Alternative 5 (right and left bank restoration with new culverts) for water depths are summarized in Figures G-59 through G-66, and velocities are summarized in Figure G-67 through G-74. The hydraulic results are very similar to Alternative 3 for the low flow scenario for floodplain and side channel inundation. The results for the 2-year flow, and somewhat for the 100-year flow is similar to Alternative 3 for the as-built time-zero, but very different for the 2-year flood with aggradation over time (Figure G-62). The increased right bank overflow for the aggradation scenario demonstrates that the three new culverts are overwhelmed and the 2-year flood flow breaches SR 20. The culvert sizes could be increased to reduce the frequency of a flow breach over SR 20 proposed, but the practical and feasible reality for culvert replacements is that a flow breach over SR 20 would likely still occur for flows less than a 100 year event, and likely for flows in the 10-year to 20-year range. More importantly, the results suggest that over time, a series of culverts instead of a larger bridge does not provide the required conveyance capacity when the main channel aggrades and the proportion of right bank overflow increases. Considerably more analysis would be required to optimize culvert sizes, costs, and floodplain measures to deflect flow back towards the existing SR 20 crossing. The results also suggest less overtopping of SR 20 for the 100-year flow, but only for the as-built condition and likely short-term before the 5 to 15 years of aggradation occurs. The 100-year results are very different for Alternative 5 compared to both Alternative 3 and No-Action (Alternative 1). The combination of a right bank levee, a lack of conveyance under SR 20, and increased right bank floodplain flow over time results in significantly more inundation over SR 20 (Figure G-64 compared to Figure G-11) and higher velocities (Figure G-74 compared to Figure G-16). In summary. The Alternative 5 results suggest that there are likely big habitat gains due to floodplain inundation and short-term flood and risk benefits, but over time, the risk to SR 20 and the SCL facilities are greater than the No-Action alternative.

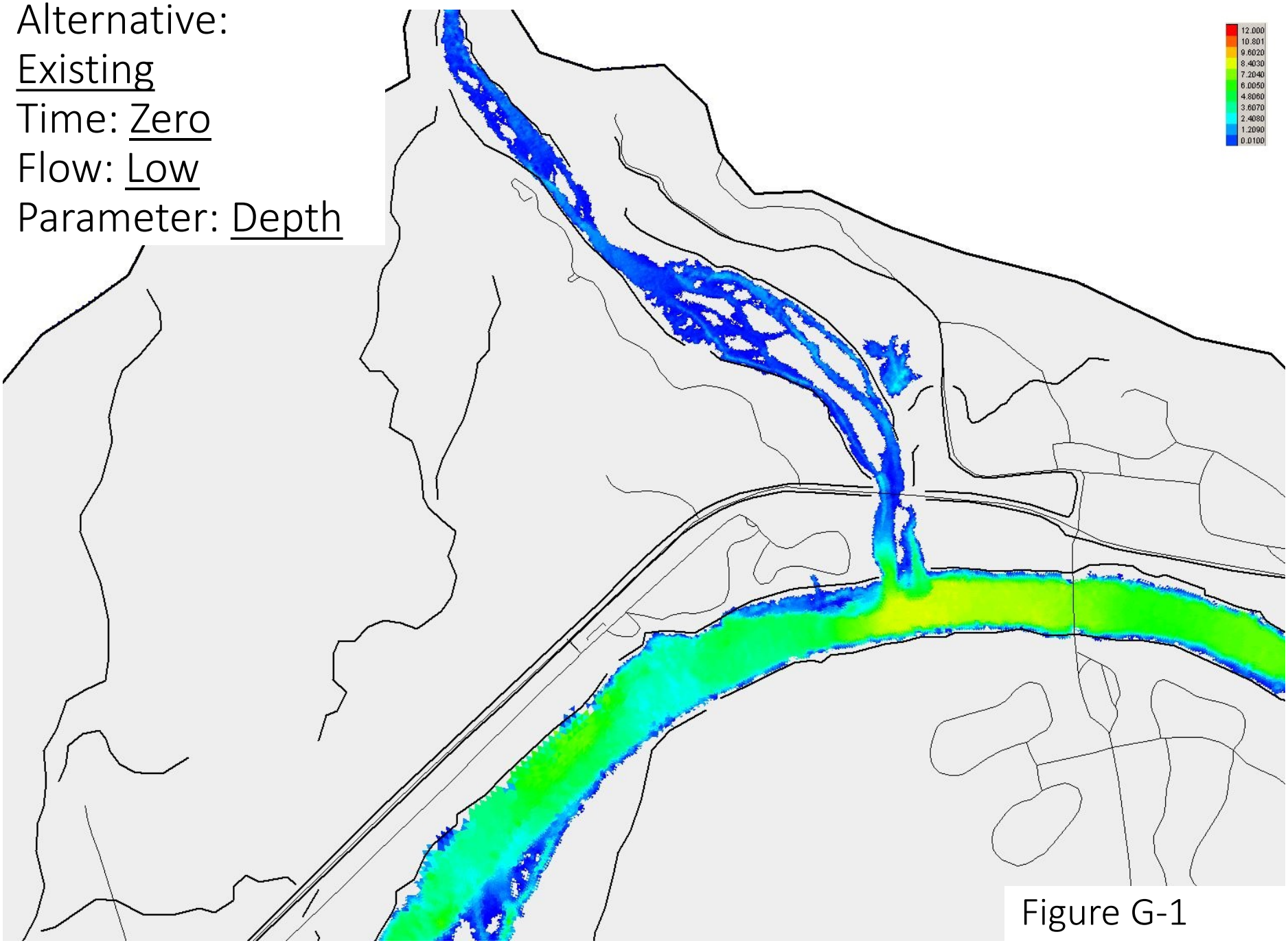
Alternative:
Existing
Time: Zero
Flow: Low
Parameter: Depth
12.000
10.801
9.6020
8.4030
7.2040
6.0050
4.8060
3.6070
2.4080
1.2090
0.0100

Figure G-1

Alternative: Existing
Time: Zero
Flow: 2-year
Parameter: Depth

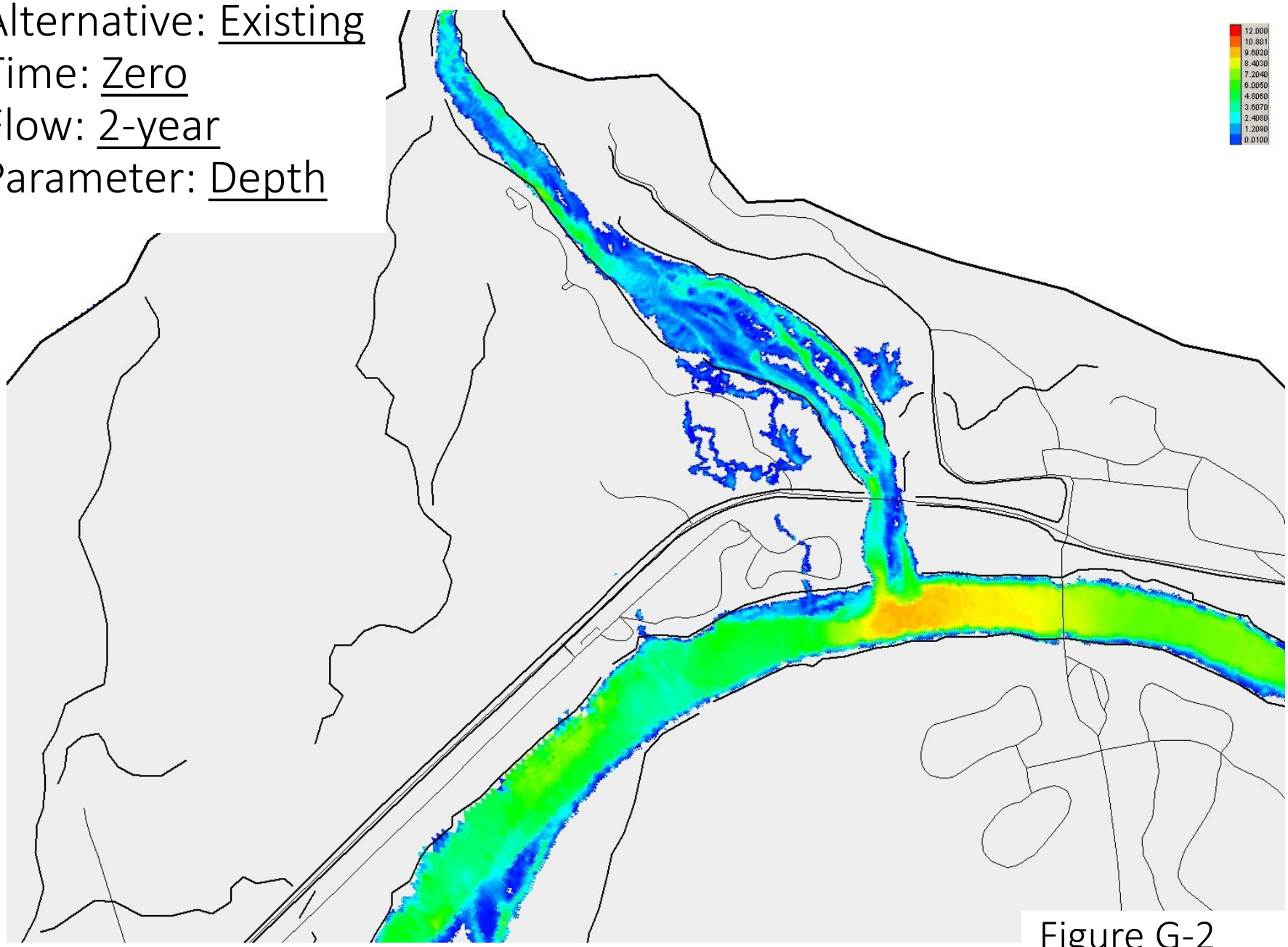

Figure G-2

Alternative: Existing
Time: Zero
Flow: 100-year
Parameter: Depth

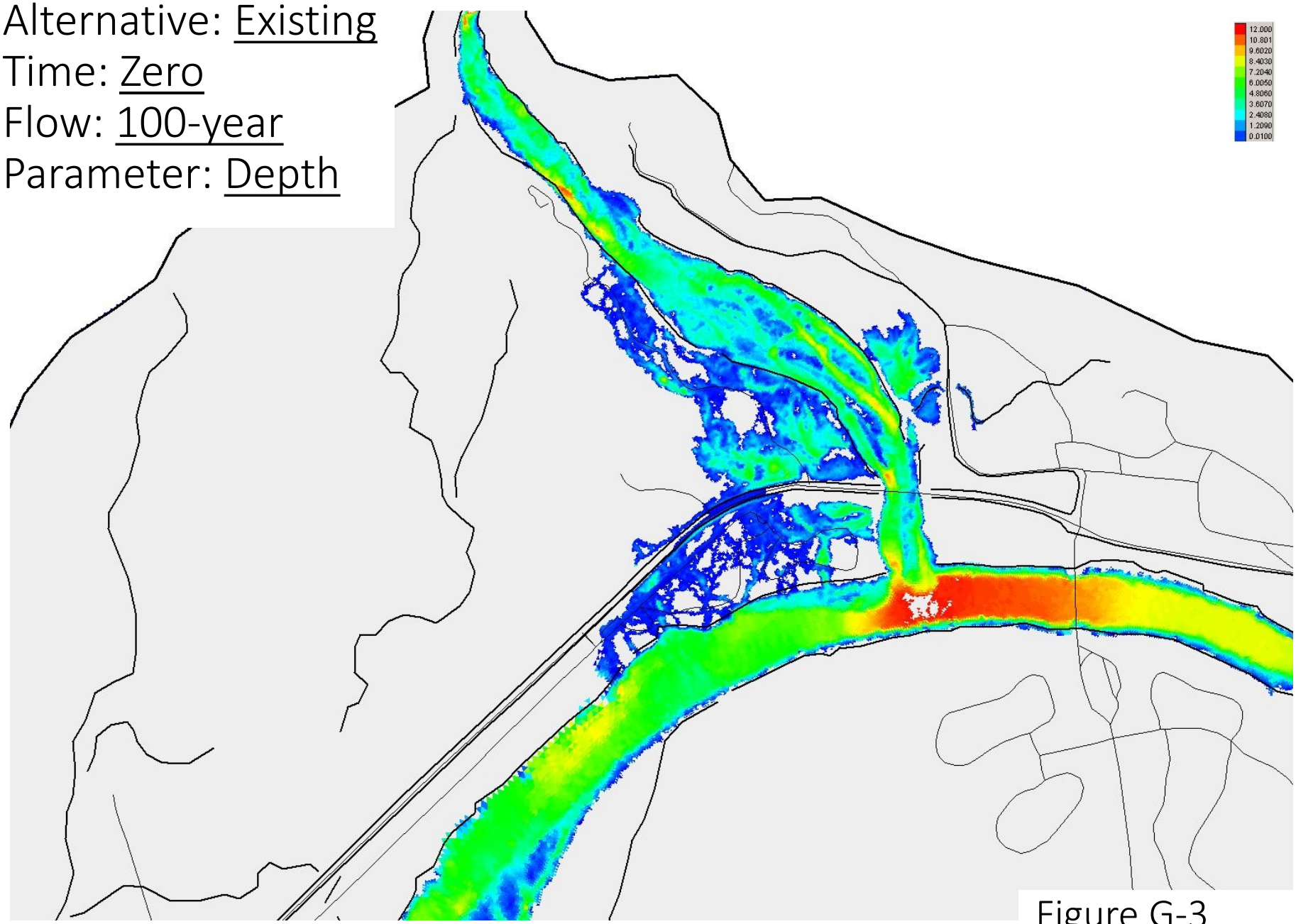

Figure G-3

Alternative:
Existing
Time: Zero
Flow: Bulked
Parameter: Depth

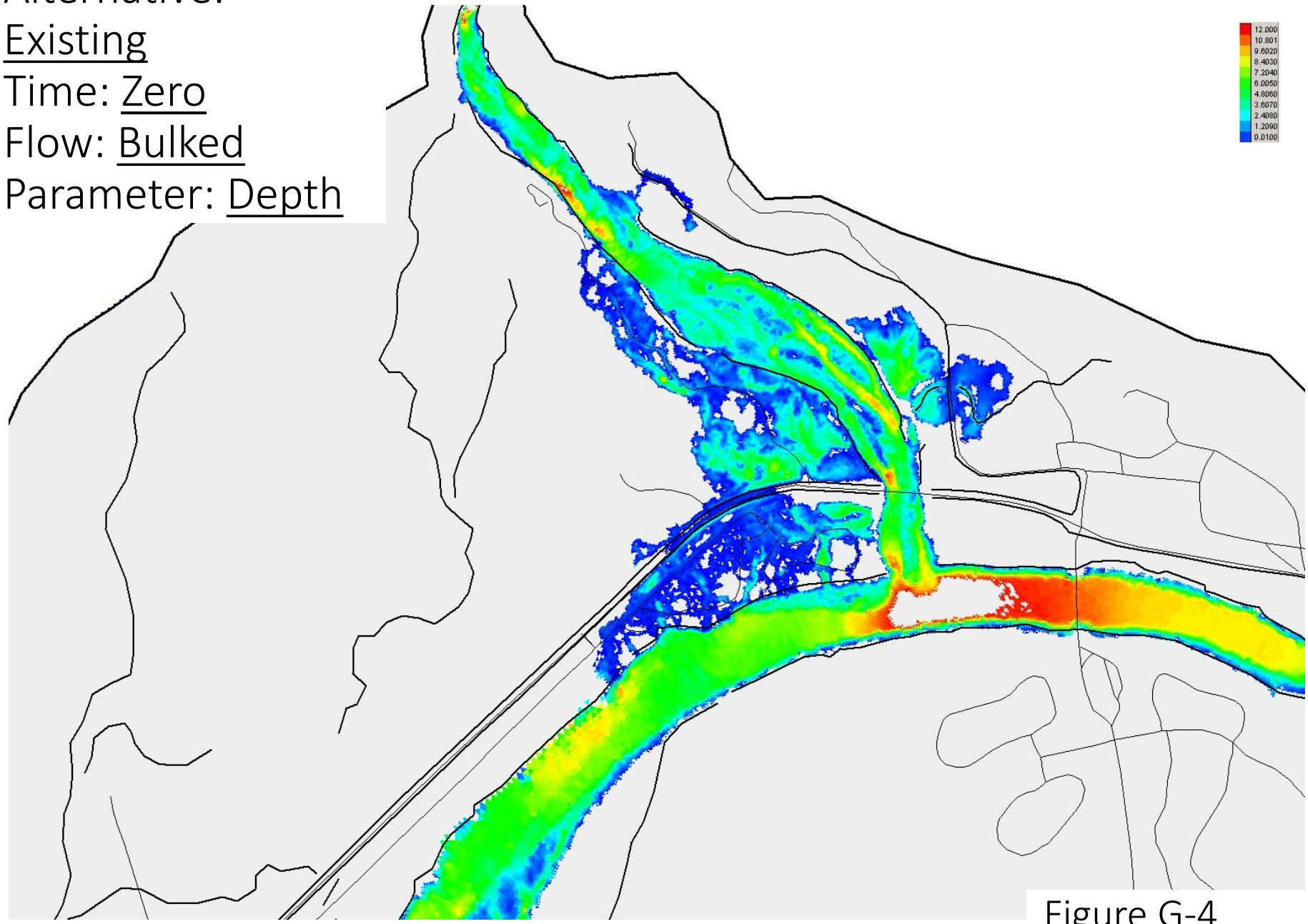

Figure G-4

Alternative:
Existing
Time: Zero
Flow: Low
Parameter:
Velocity

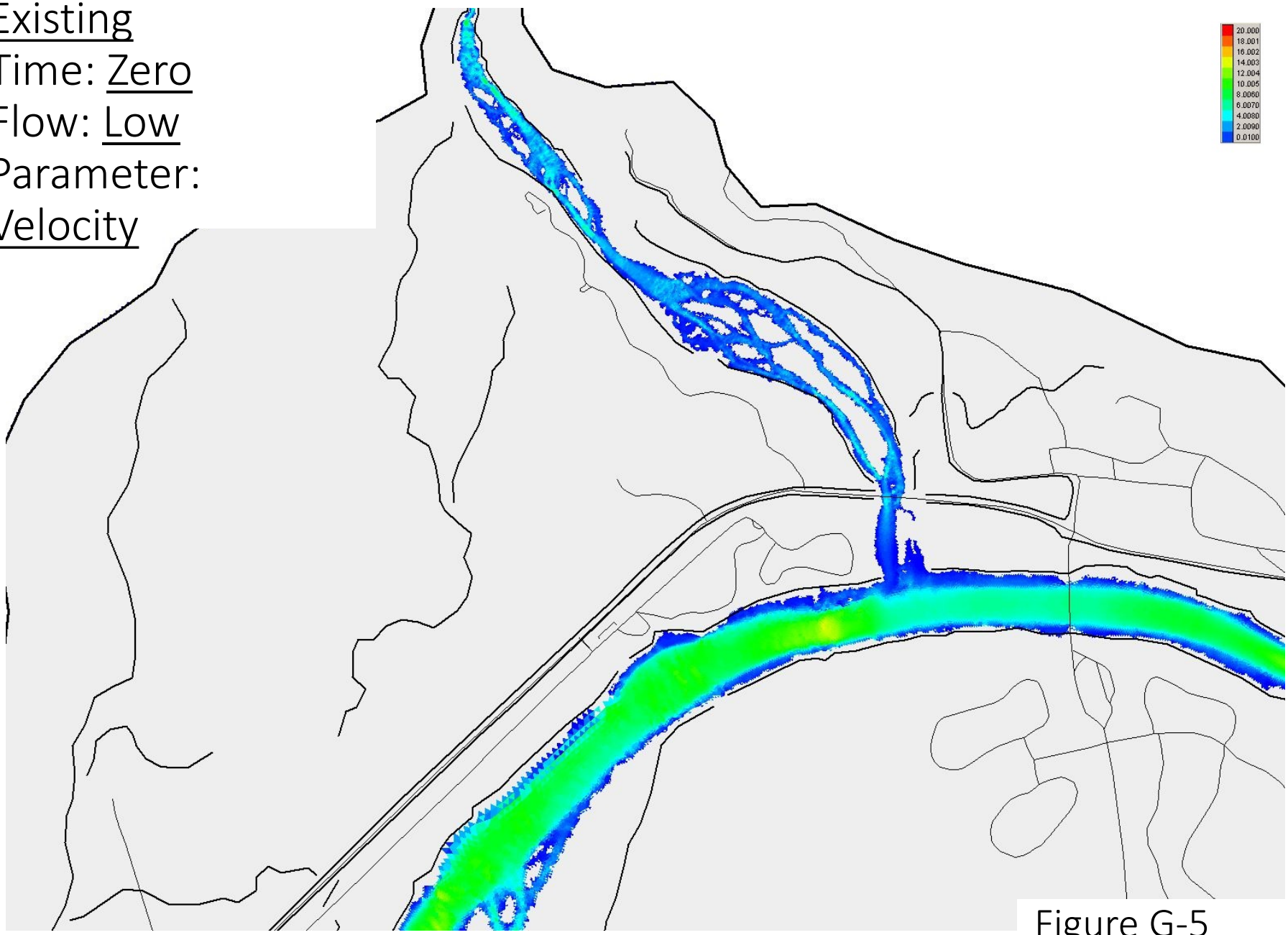

Figure G-5

Alternative:
Existing
Time: Zero
Flow: 2-year
Parameter: Velocity

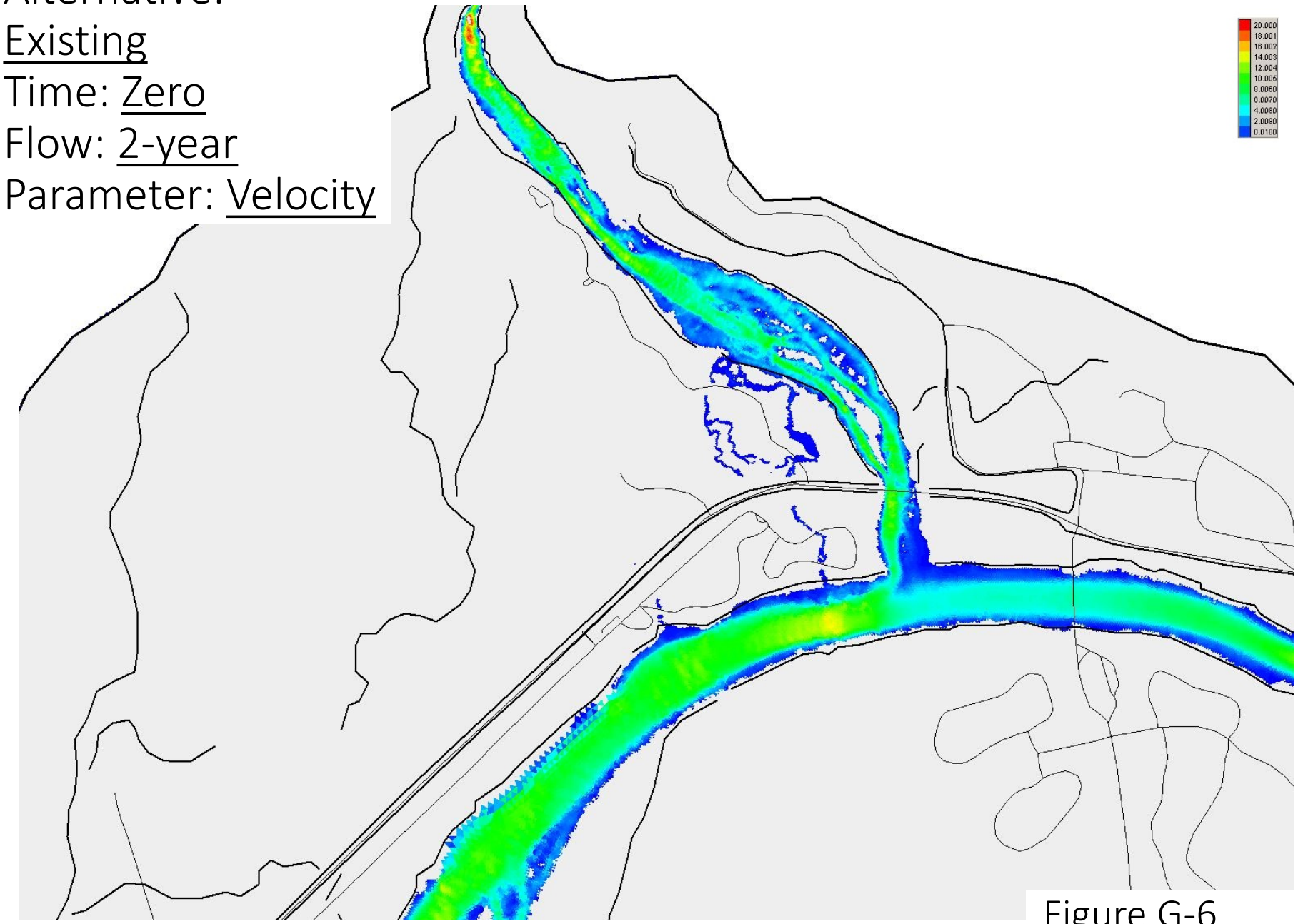

Figure G-6

Alternative:
Existing
Time: Zero
Flow: 100-year
Parameter: Velocity

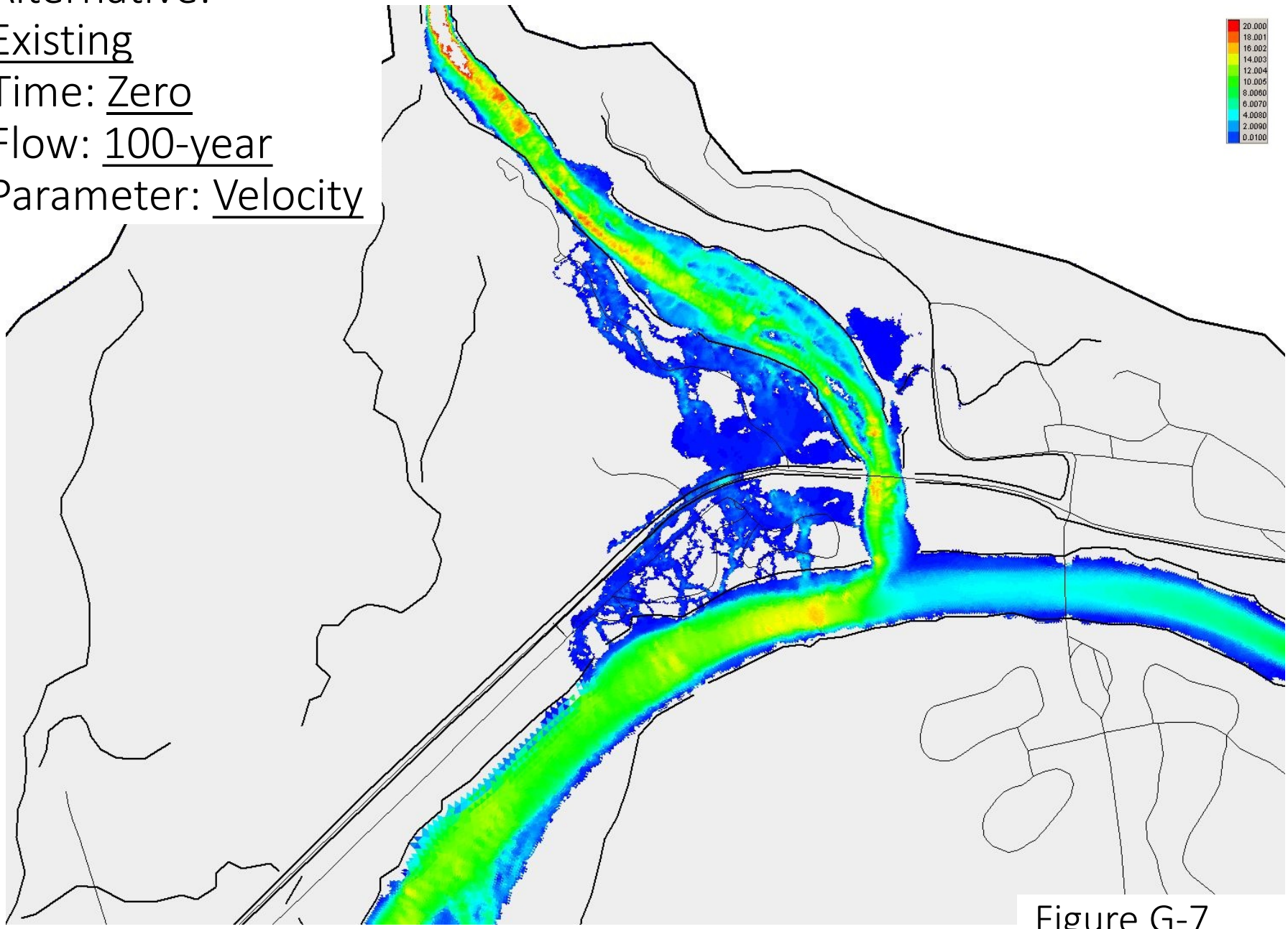

Figure G-7

Alternative:
Existing
Time: Zero
Flow: Bulked
Parameter: Velocity

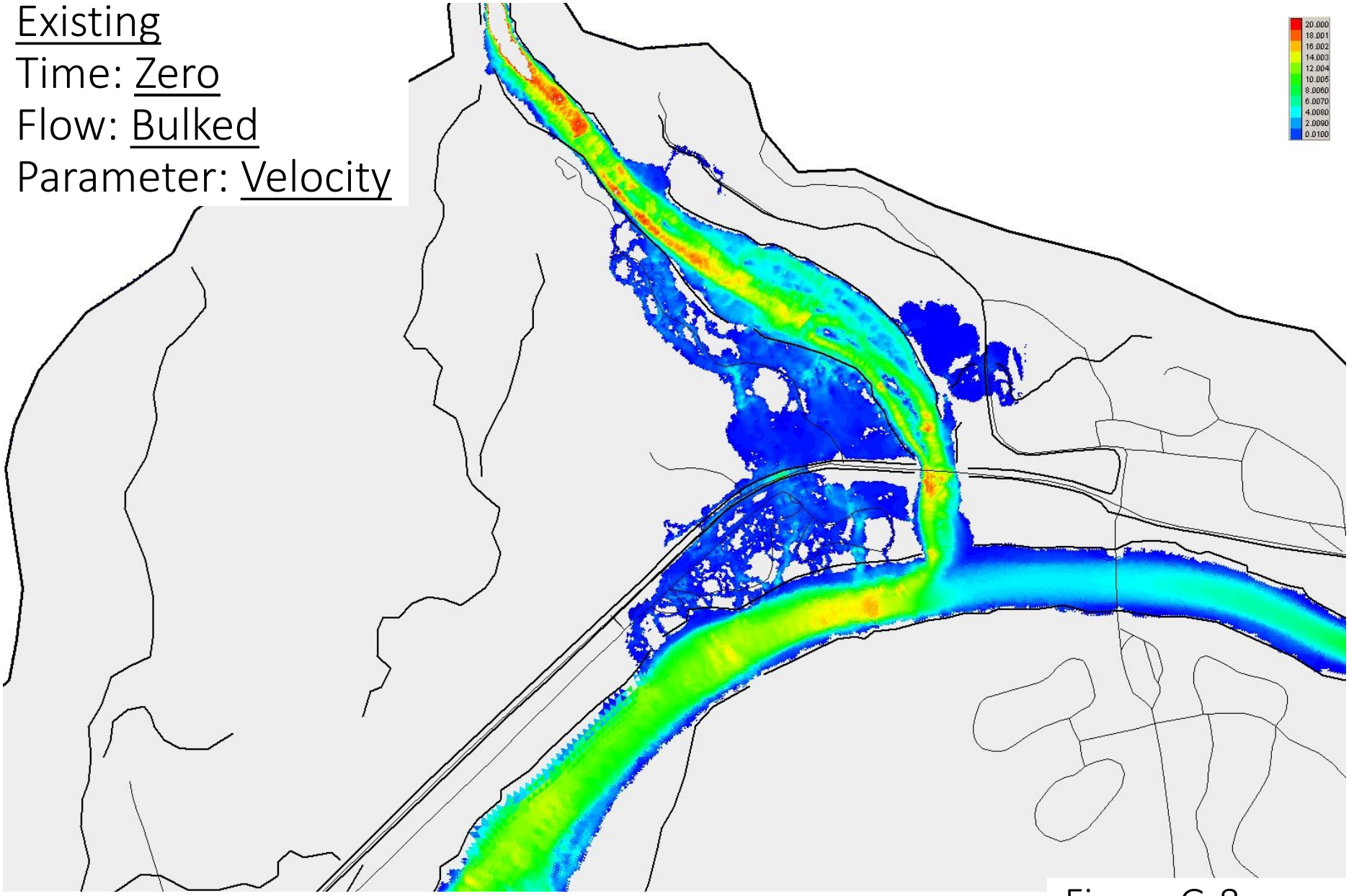

Figure G-8

Alternative: 1 - NA
Time: 5-15 years
Flow: Low
Parameter: Depth

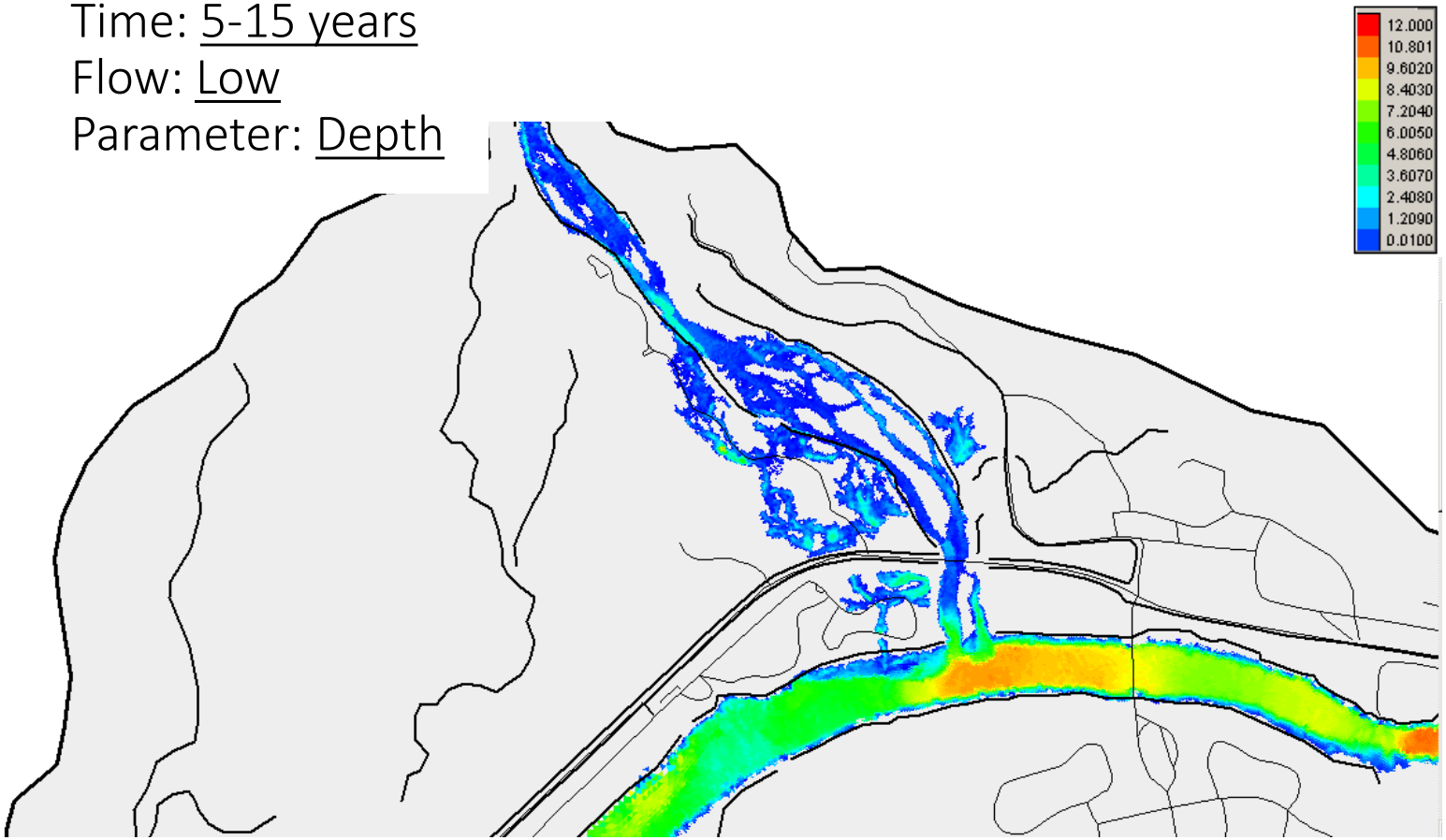

Figure G-9

Alternative: 1 - NA
Time: 5-15 years
Flow: 2-year
Parameter: Depth

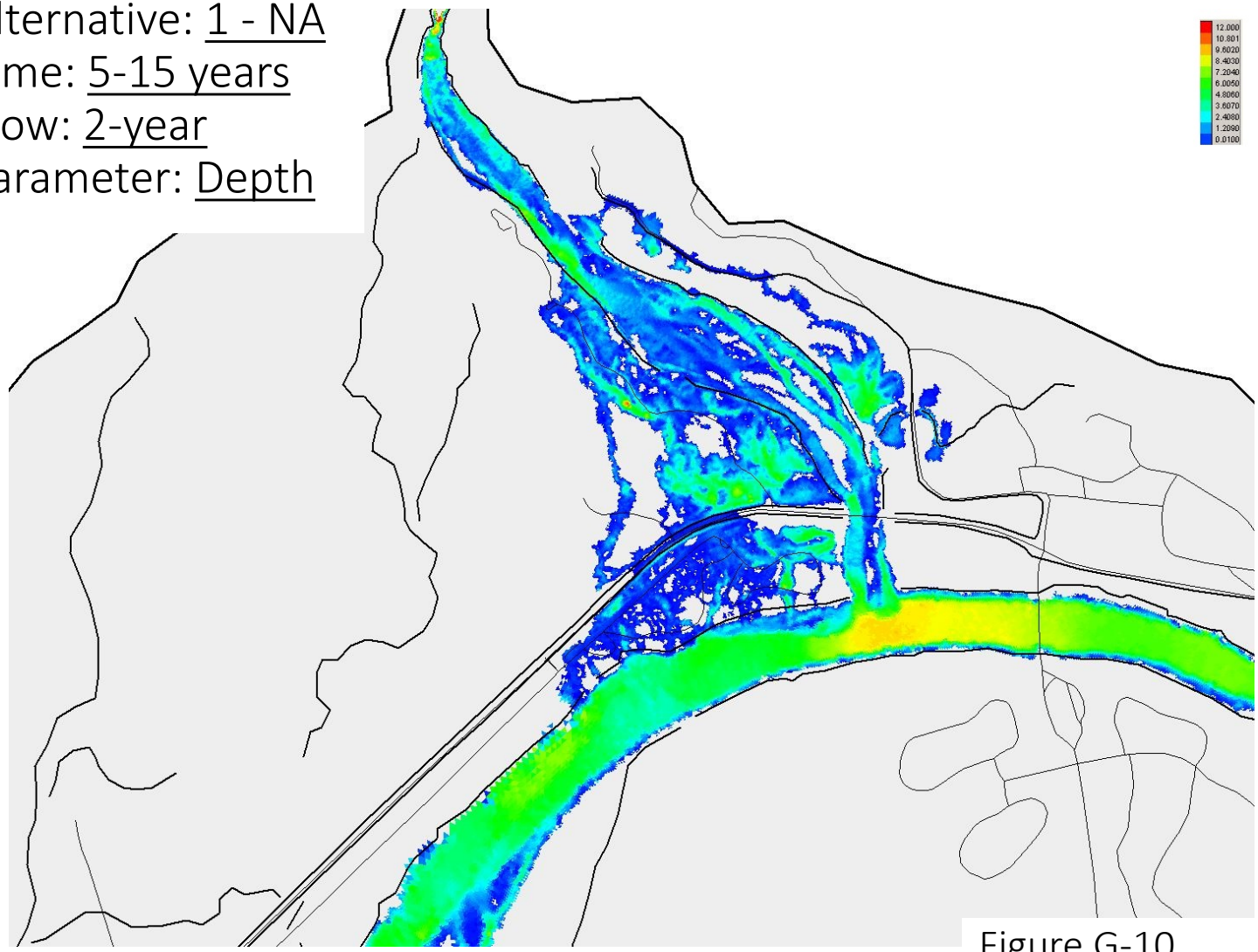

Figure G-10

Alternative: 1 - NA
Time: 5-15 years
Flow: 100-year
Parameter: Depth

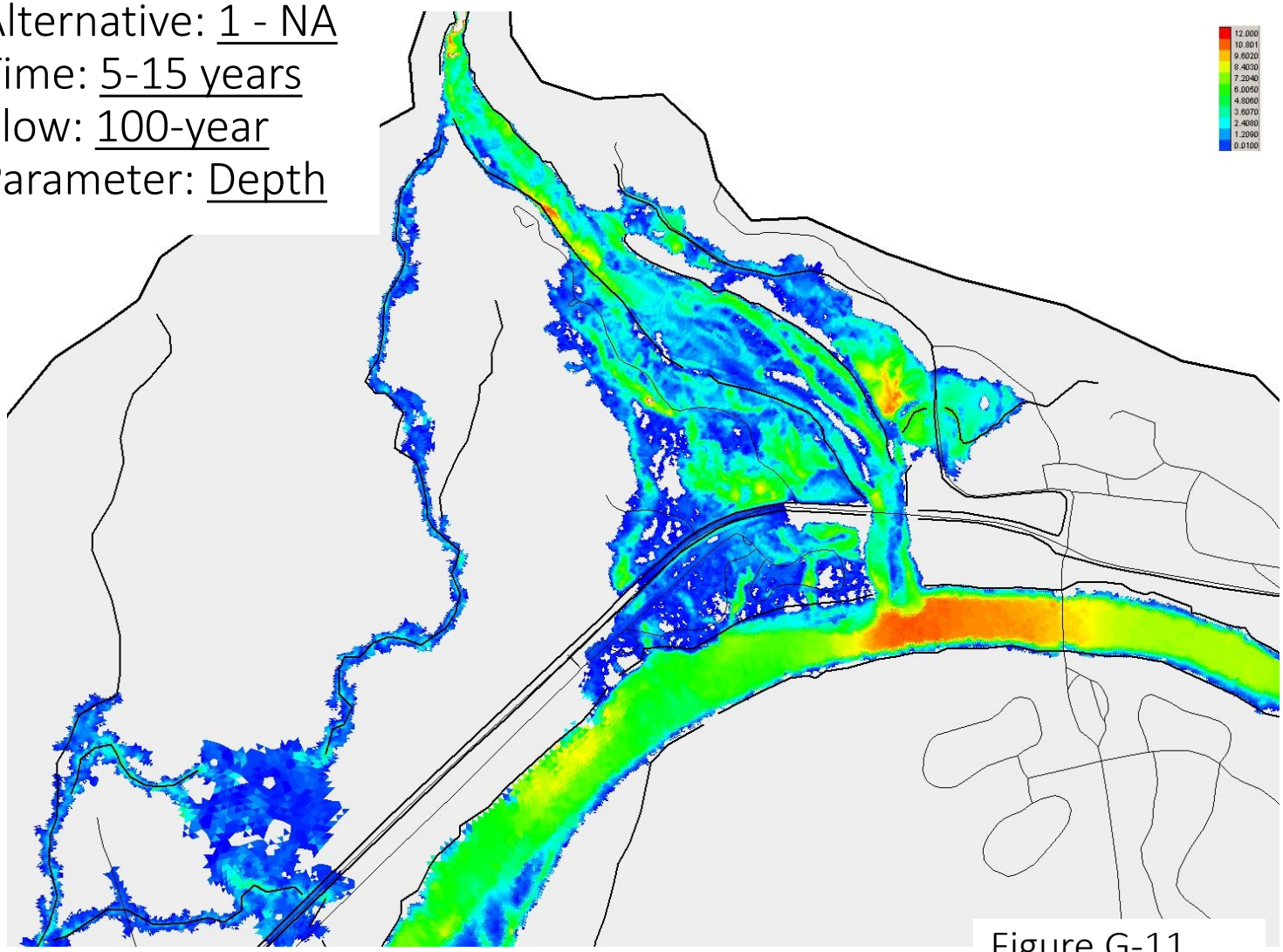

Figure G-11

Alternative: 1 - NA
Time: 5-15 years
Flow: Bulked
Parameter: Depth

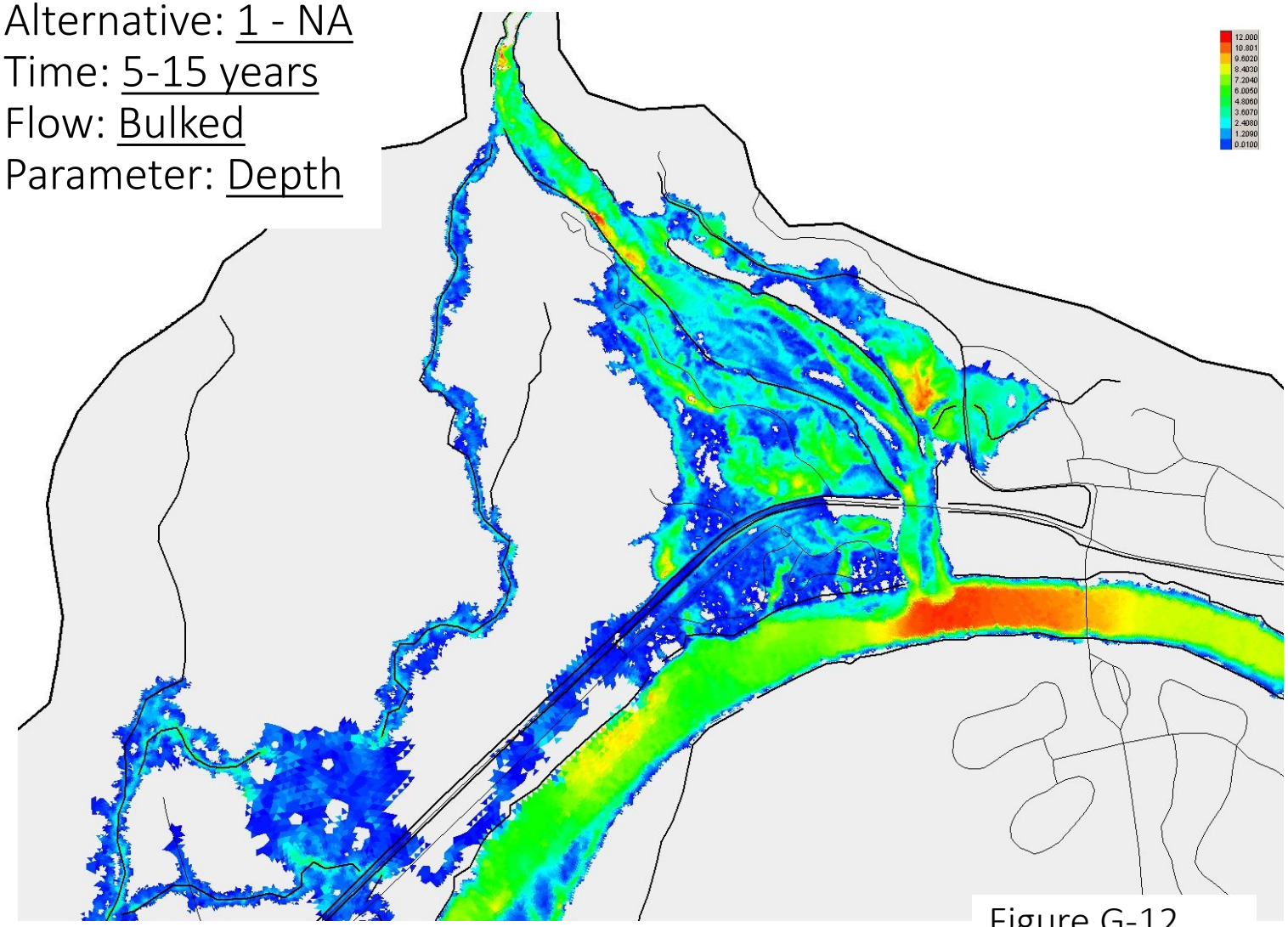

Figure G-12

Alternative: 1 - NA
Time: 5-15 years
Flow: Low
Parameter:
Velocity

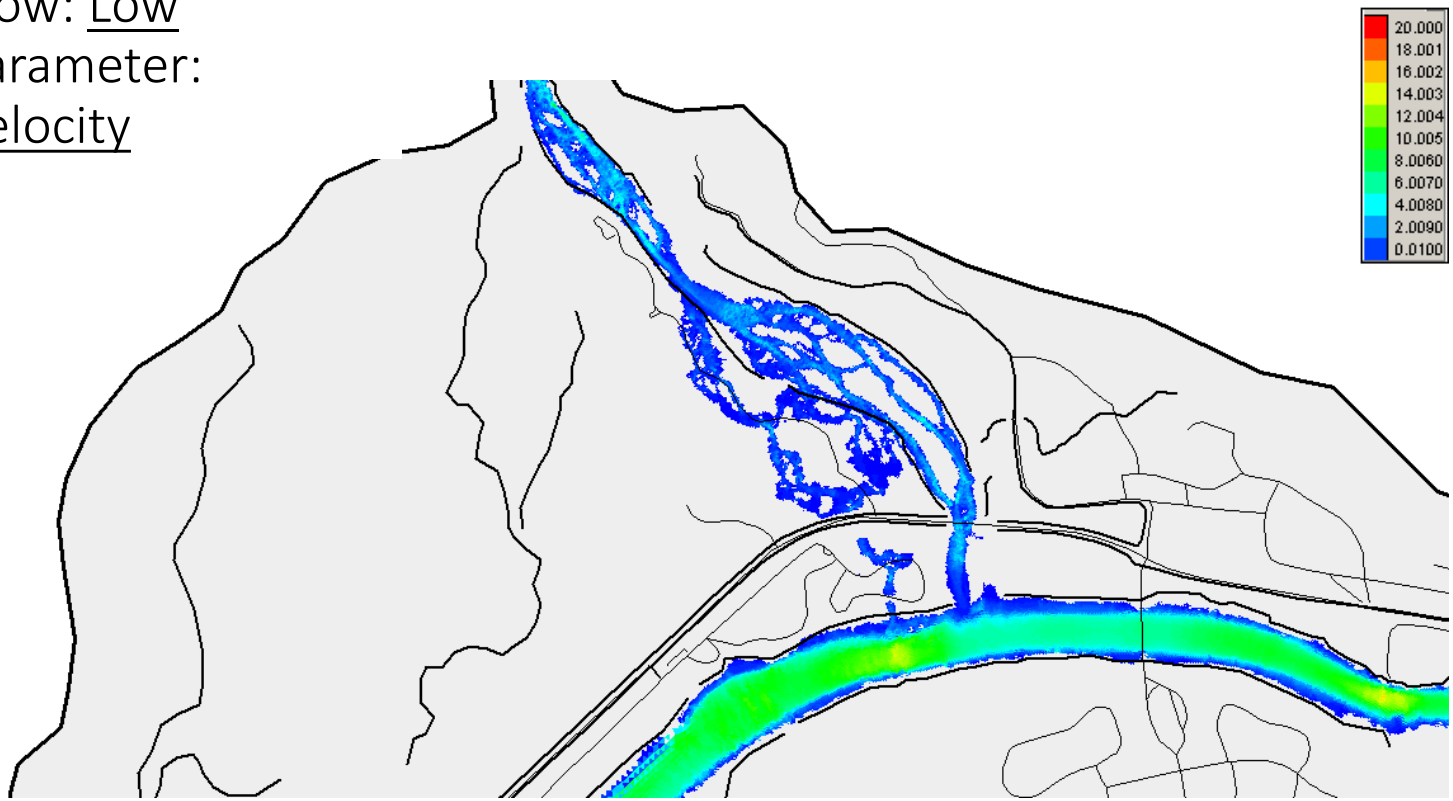

Figure G-13

Alternative: 1 - NA
Time: 5-15 years
Flow: 2-year
Parameter:
Velocity

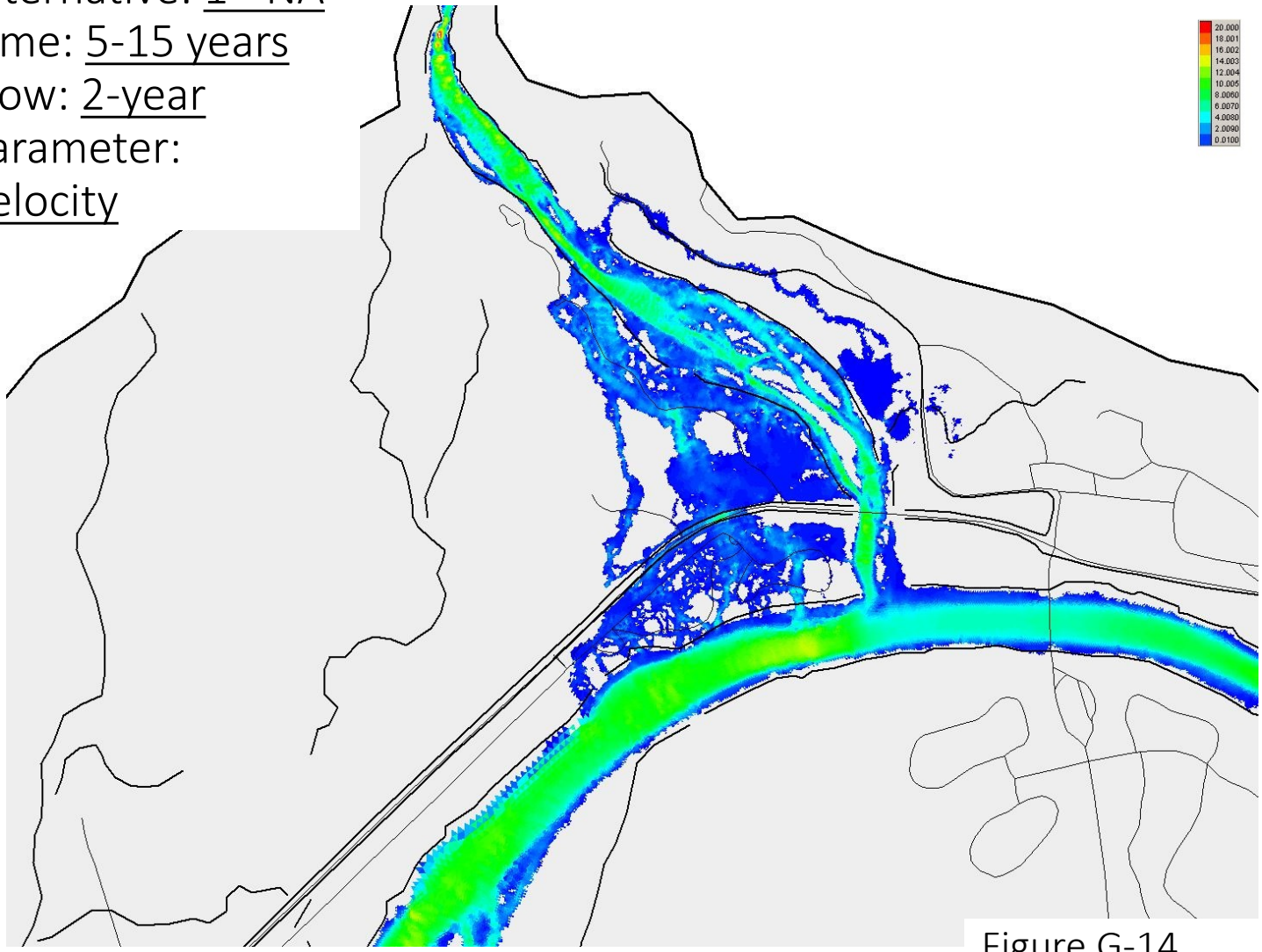

Figure G-14

Alternative: 1 - NA
Time: 5-15 years
Flow: 100-year
Parameter:
Velocity

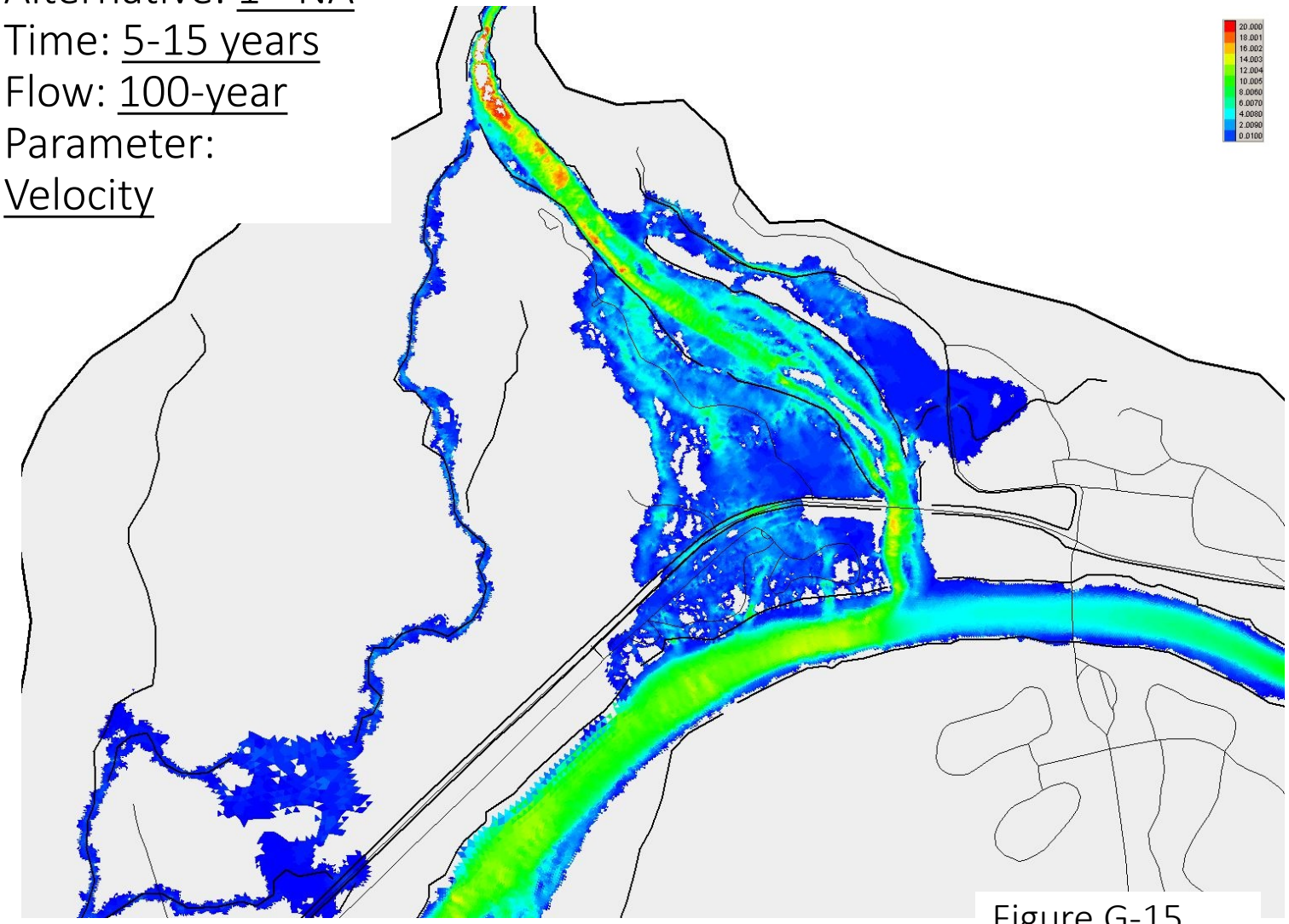

Figure G-15

Alternative: 1 - NA
Time: 5-15 years
Flow: Bulked
Parameter:
Velocity

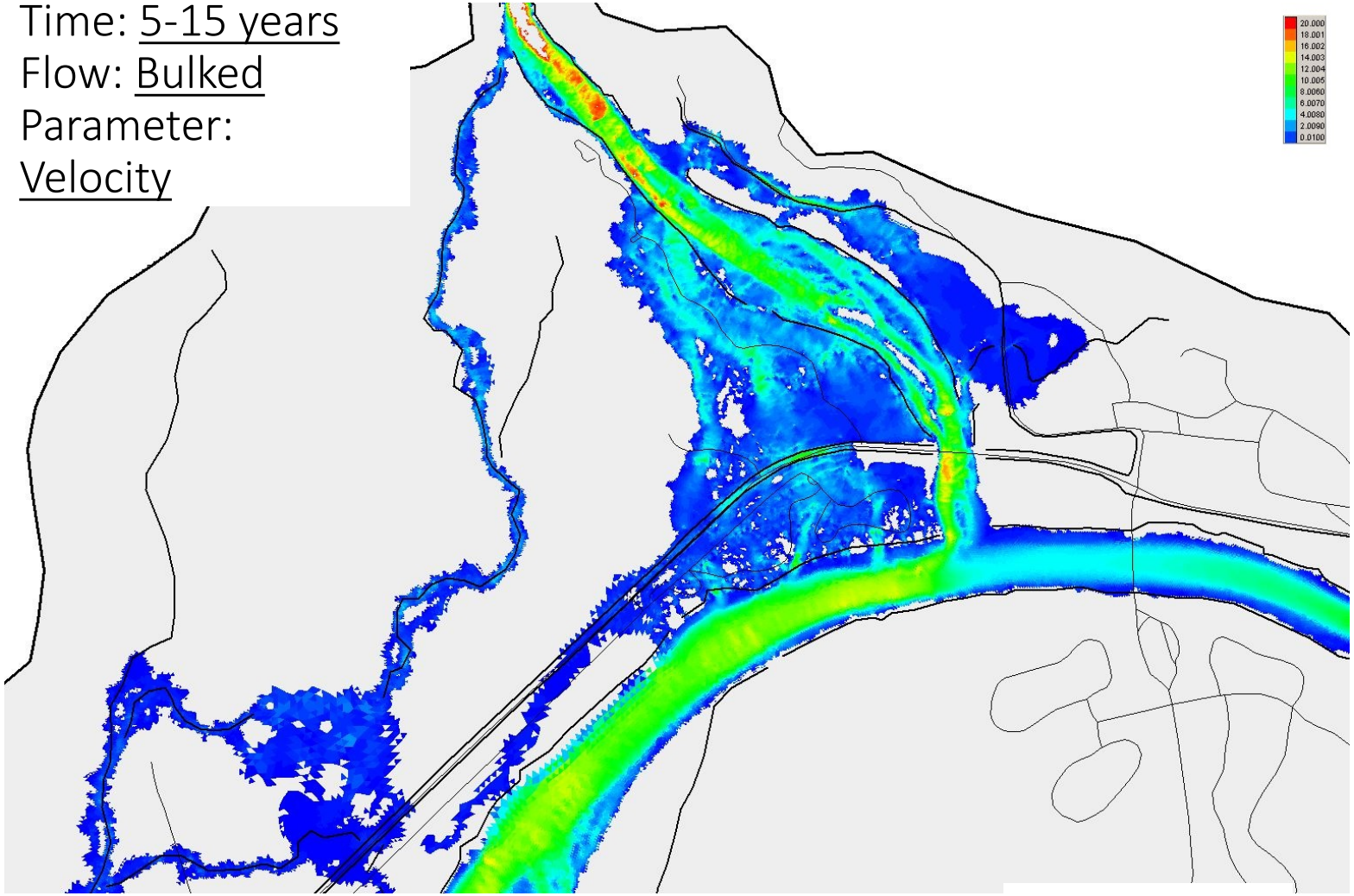

Figure G-16

Alternative: 2
Time: Zero
Flow: Low
Parameter: Depth

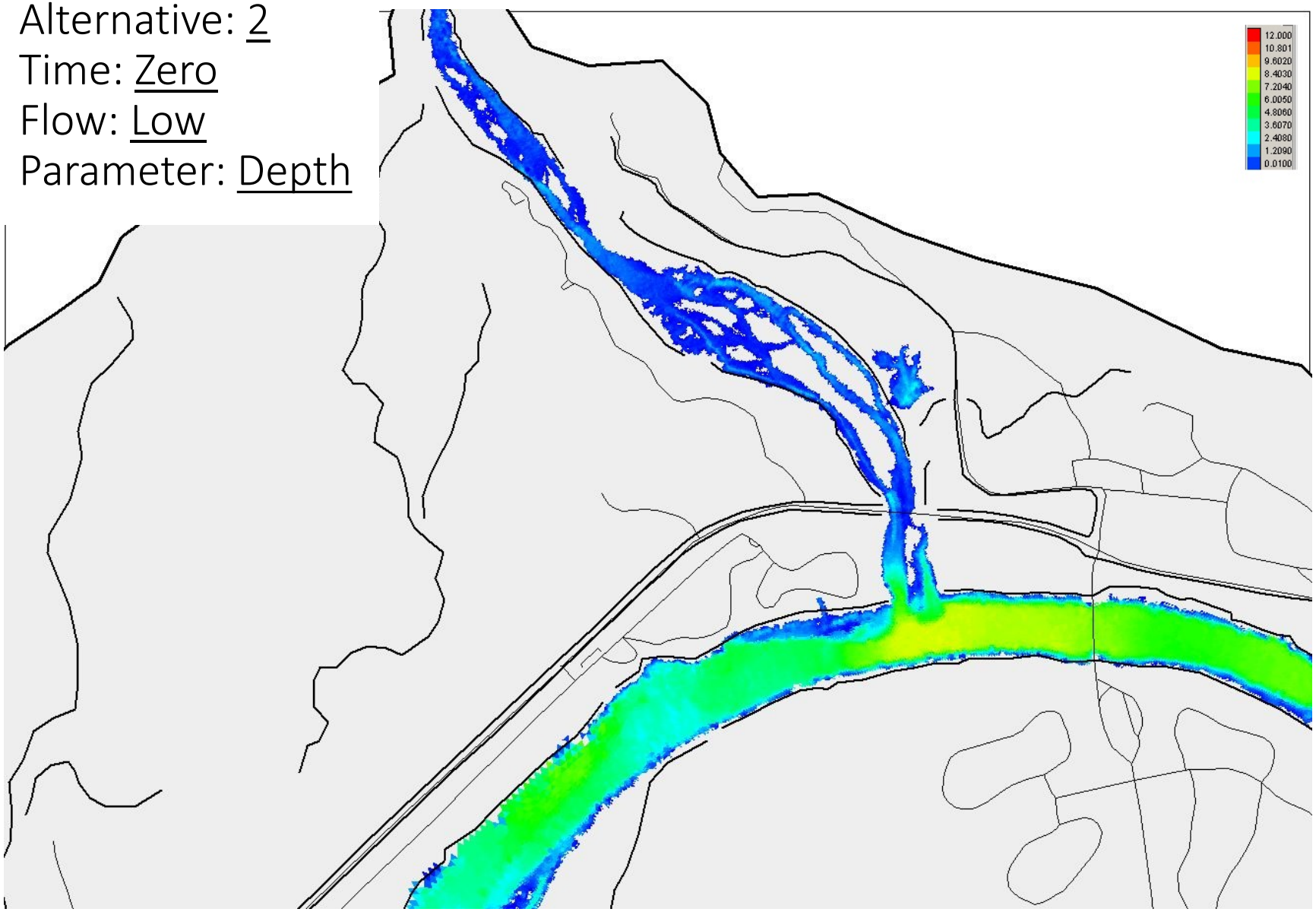

Figure G-17

Alternative: 2
Time: 5-15 years
Flow: Low
Parameter: Depth

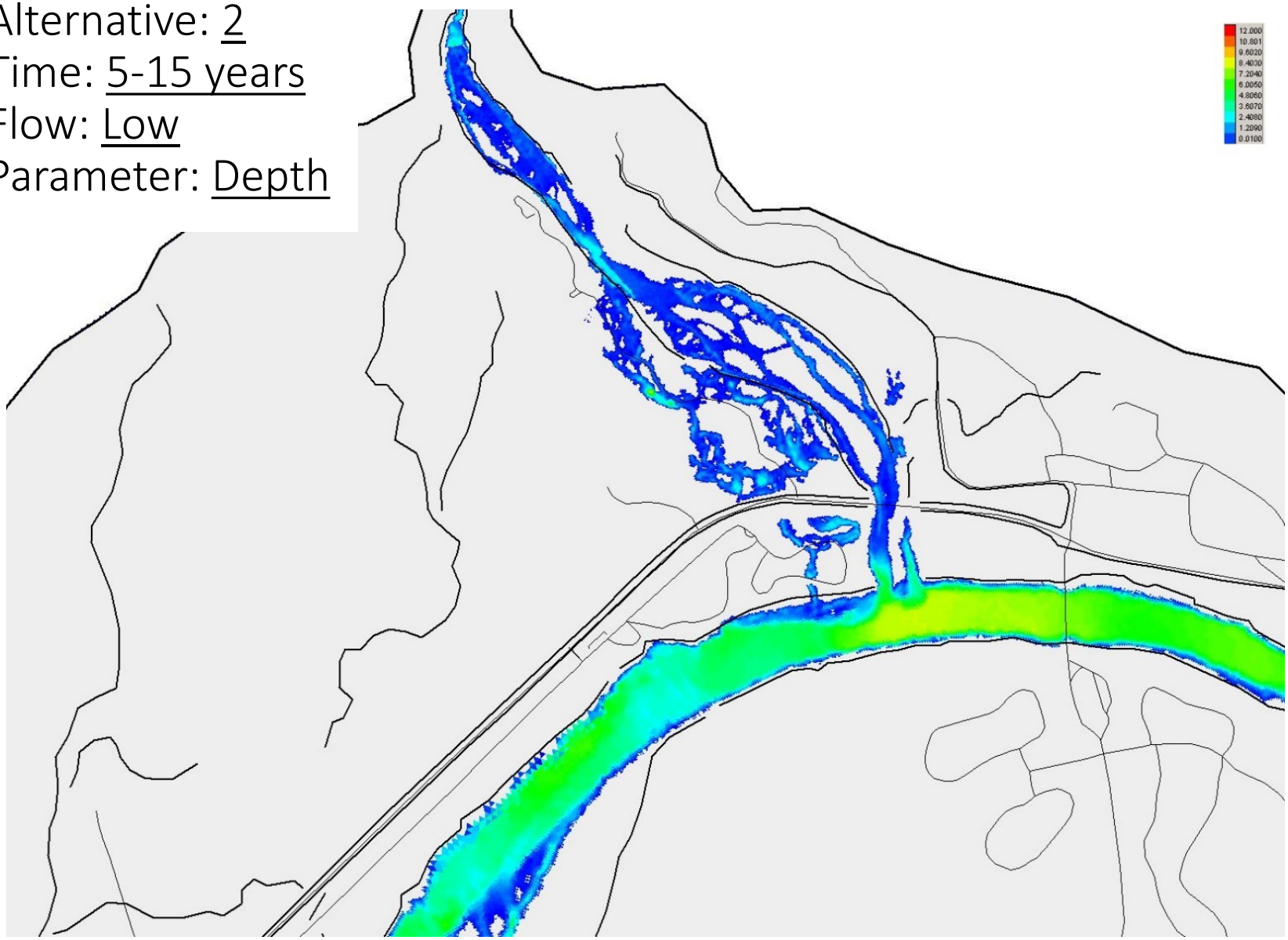

Figure G-18

Alternative: 2
Time: Zero
Flow: 2-year
Parameter: Depth

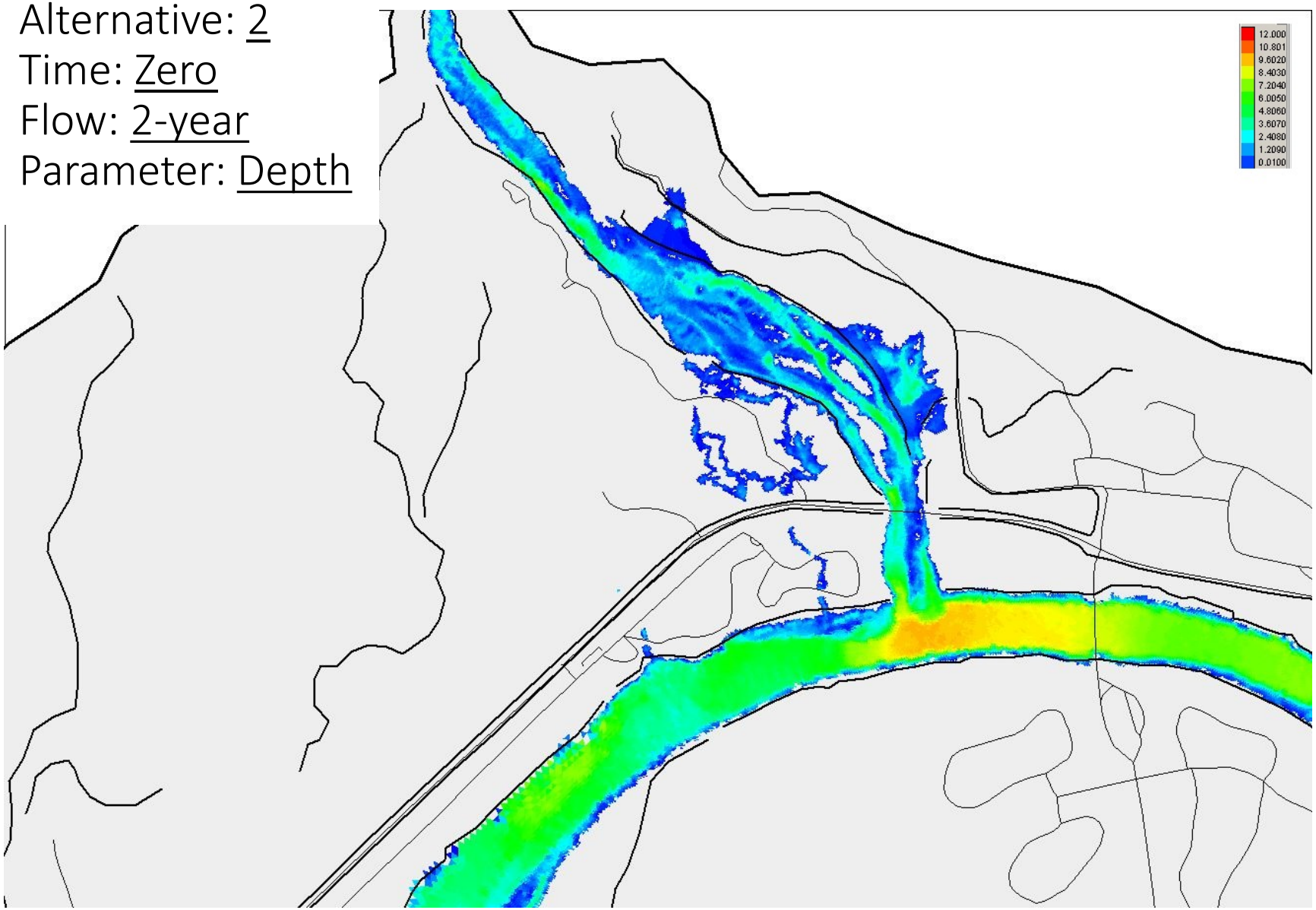

Figure G-19

Alternative: 2
Time: 5-15 years
Flow: 2-year
Parameter: Depth

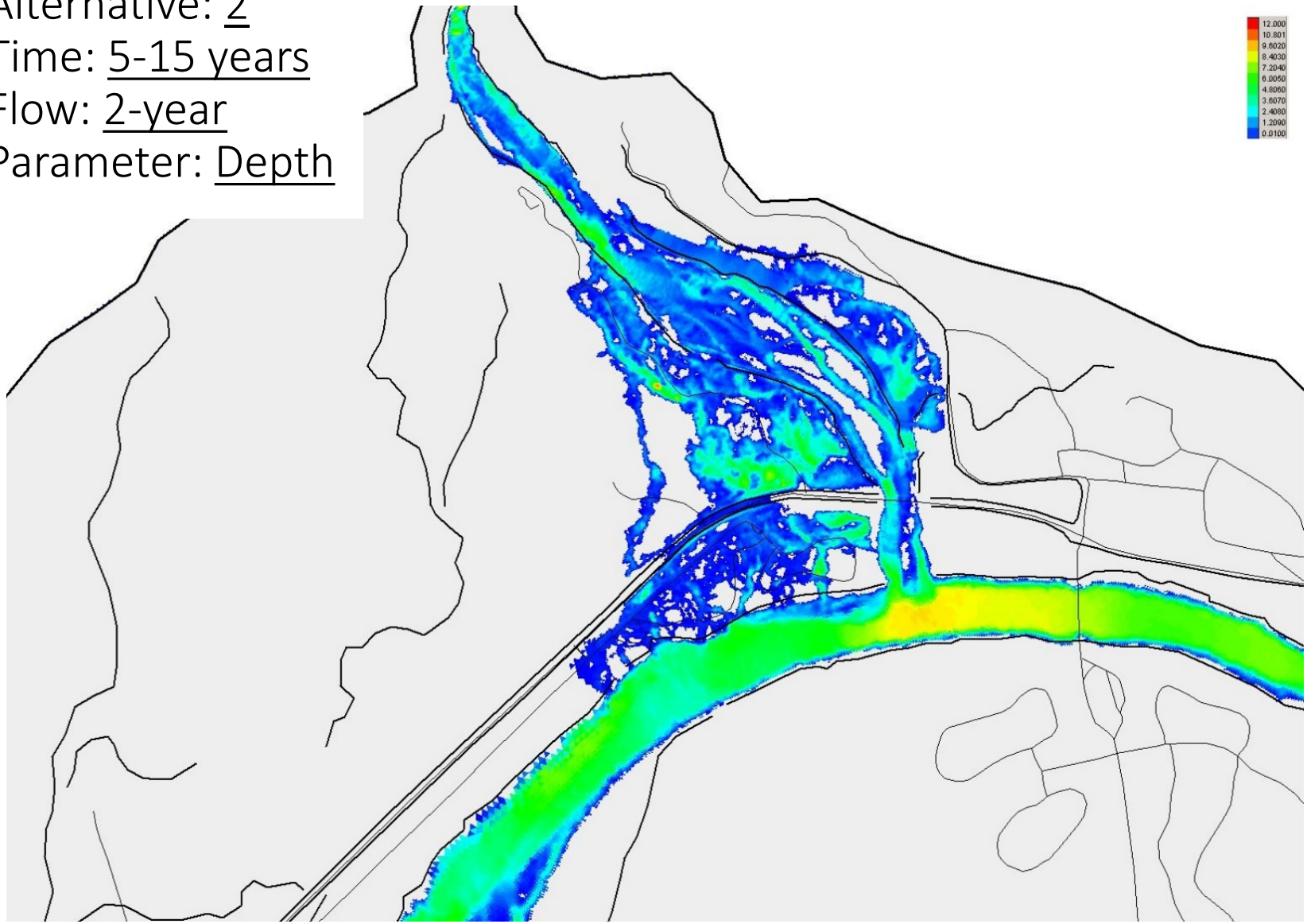

Figure G-20

Alternative: 2
Time: Zero
Flow: 100-year
Parameter: Depth

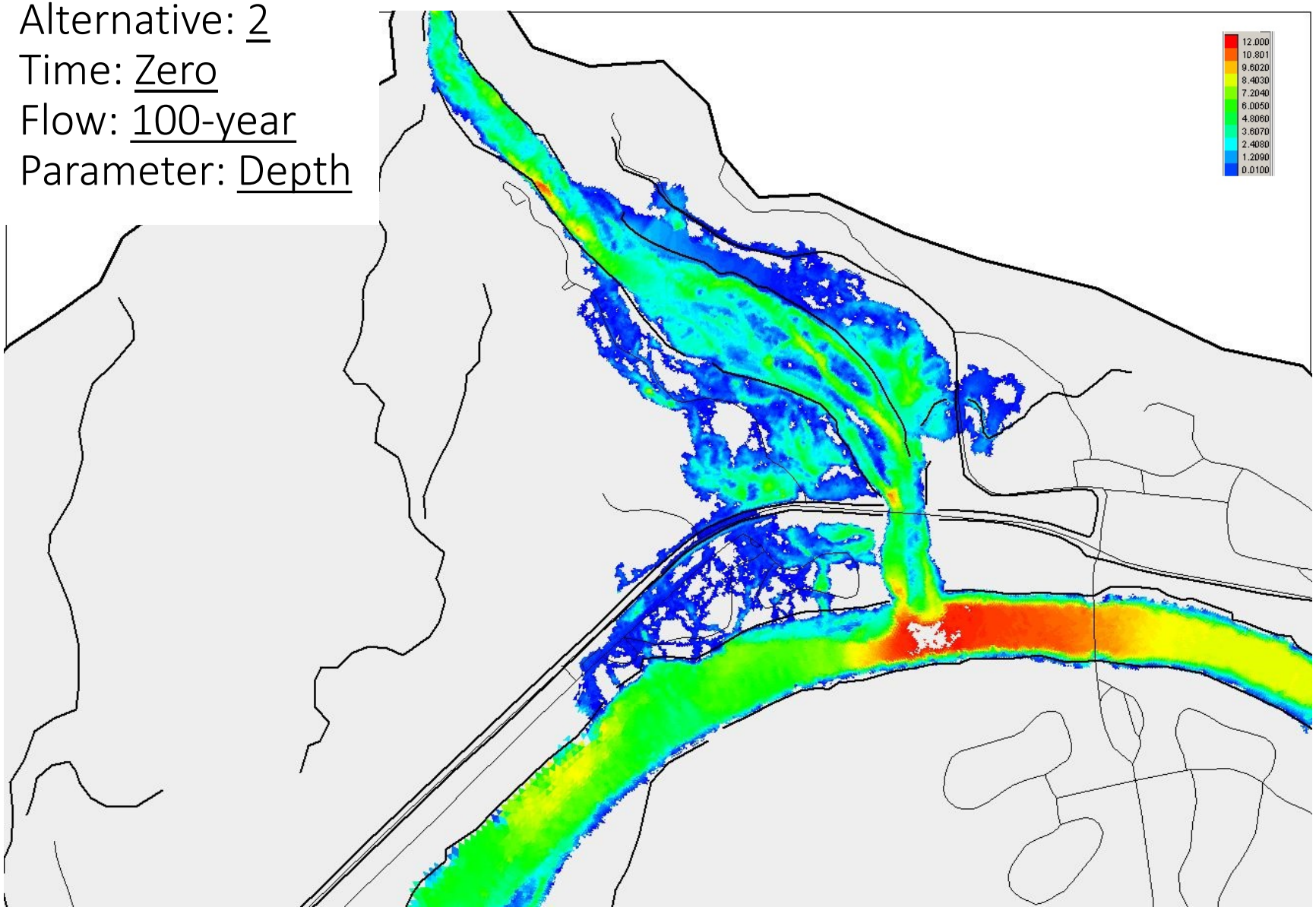

Figure G-21

Alternative: 2
Time: 5-15 years
Flow: 100-year
Parameter: Depth

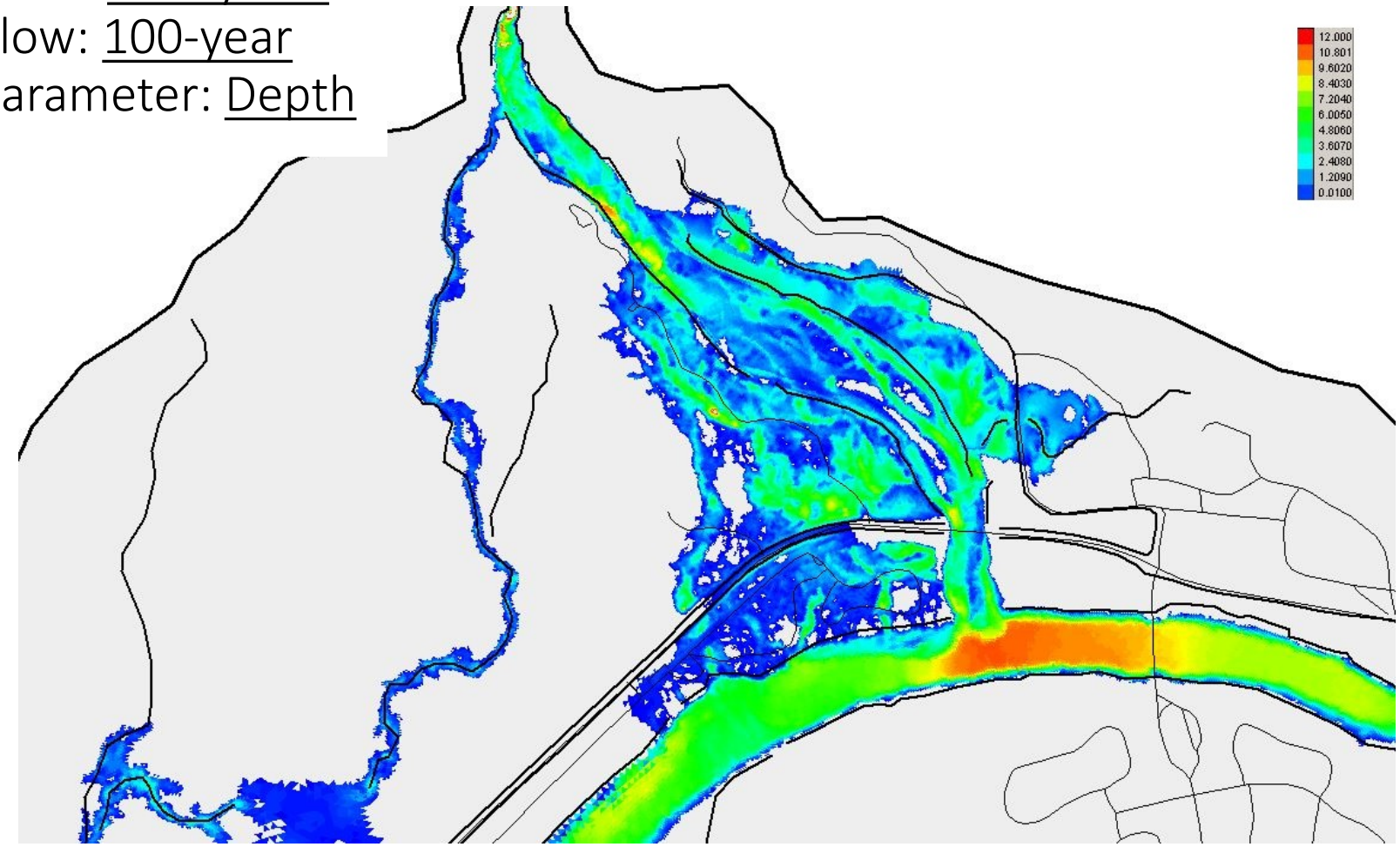

Figure G-22

Alternative: 2
Time: 5-15 years
Flow: Bulked
Parameter: Depth

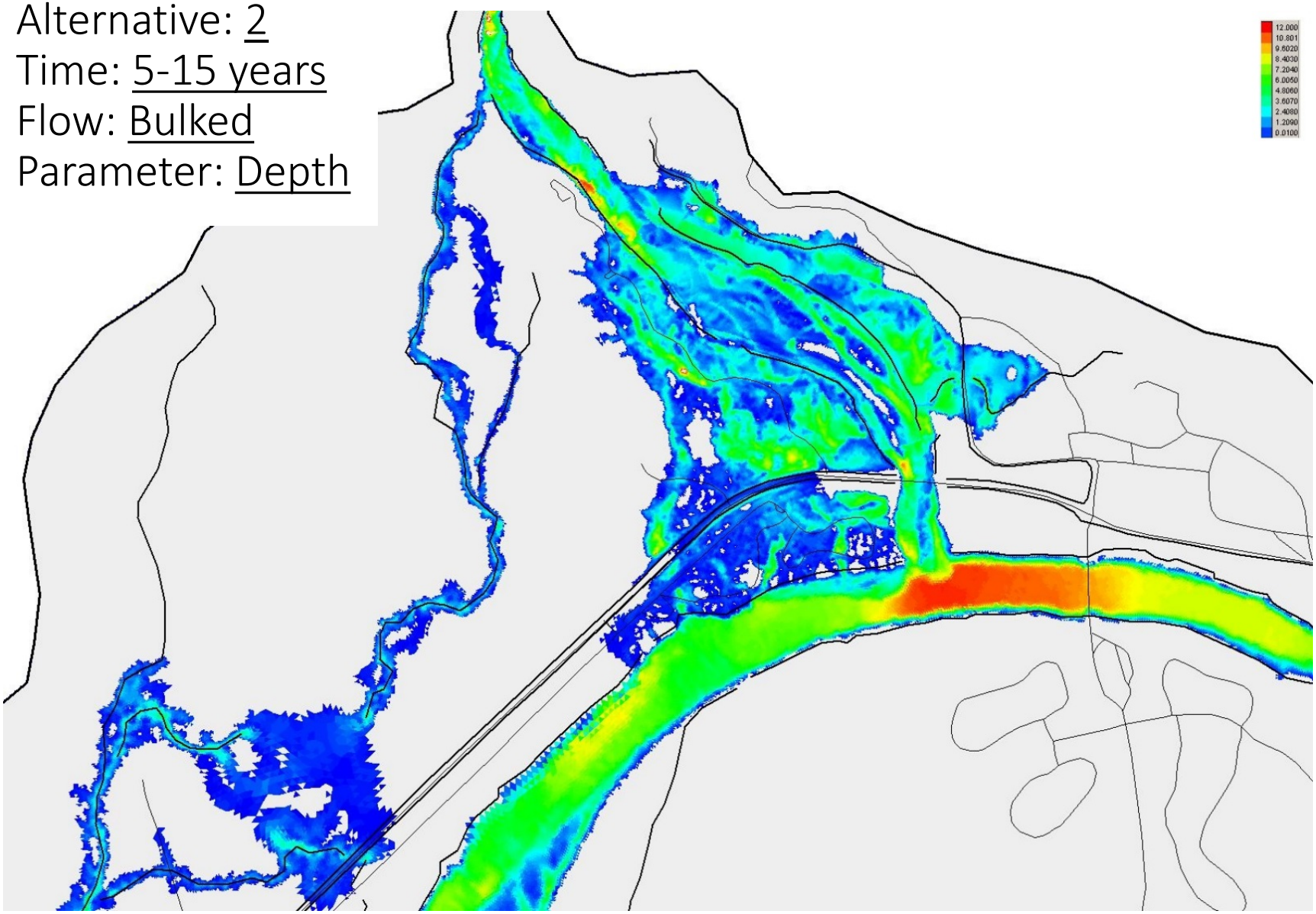

Figure G-23

Alternative: 2
Time: Zero
Flow: Low
Parameter:
Velocity

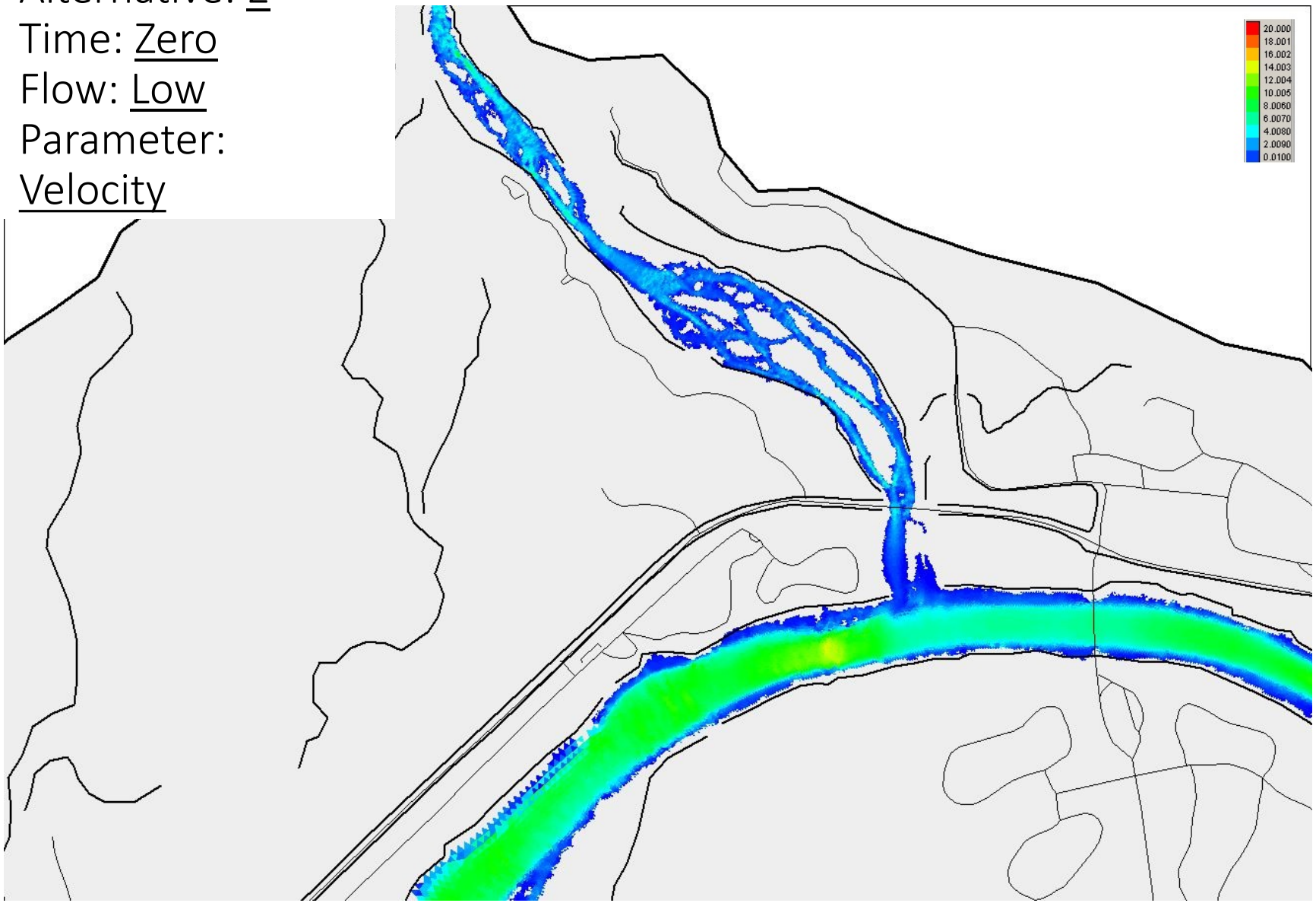

Figure G-24

Alternative: 2
Time: 5-15 years
Flow: Low
Parameter:
Velocity

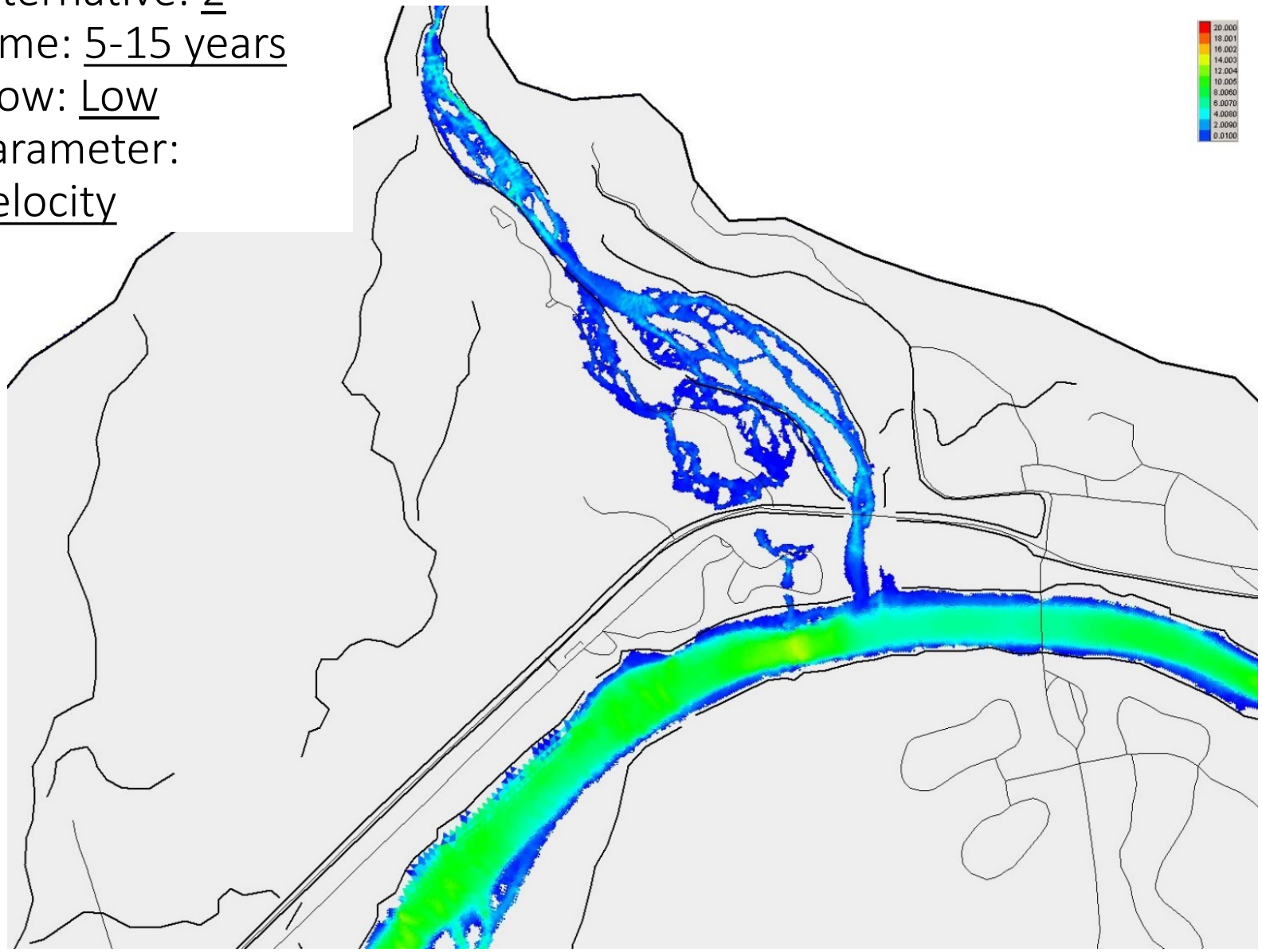

Figure G-25

Alternative: 2
Time: Zero
Flow: 2-year
Parameter:
Velocity

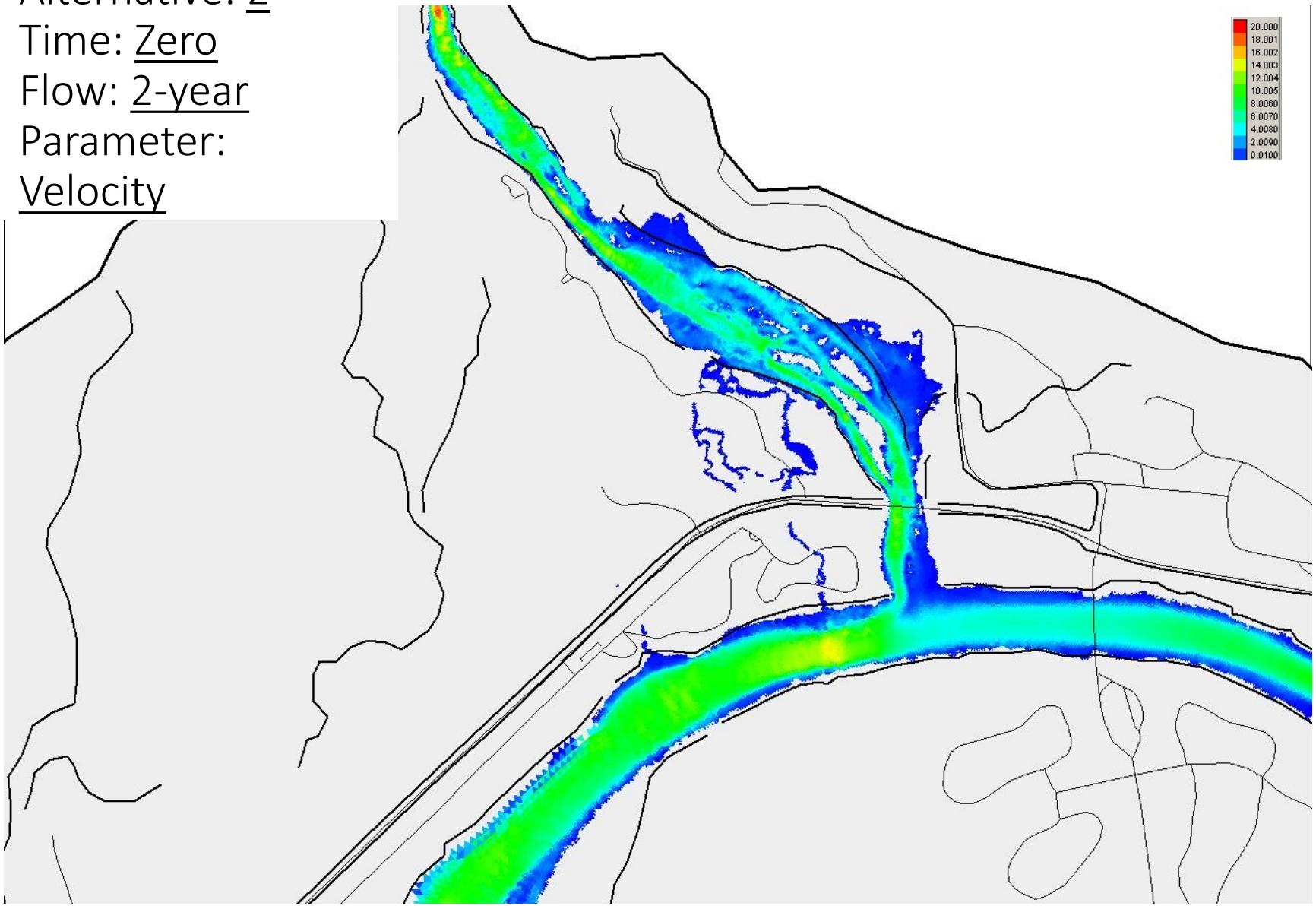

Figure G-26

Alternative: 2
Time: 5-15 years
Flow: 2-year
Parameter: Velocity

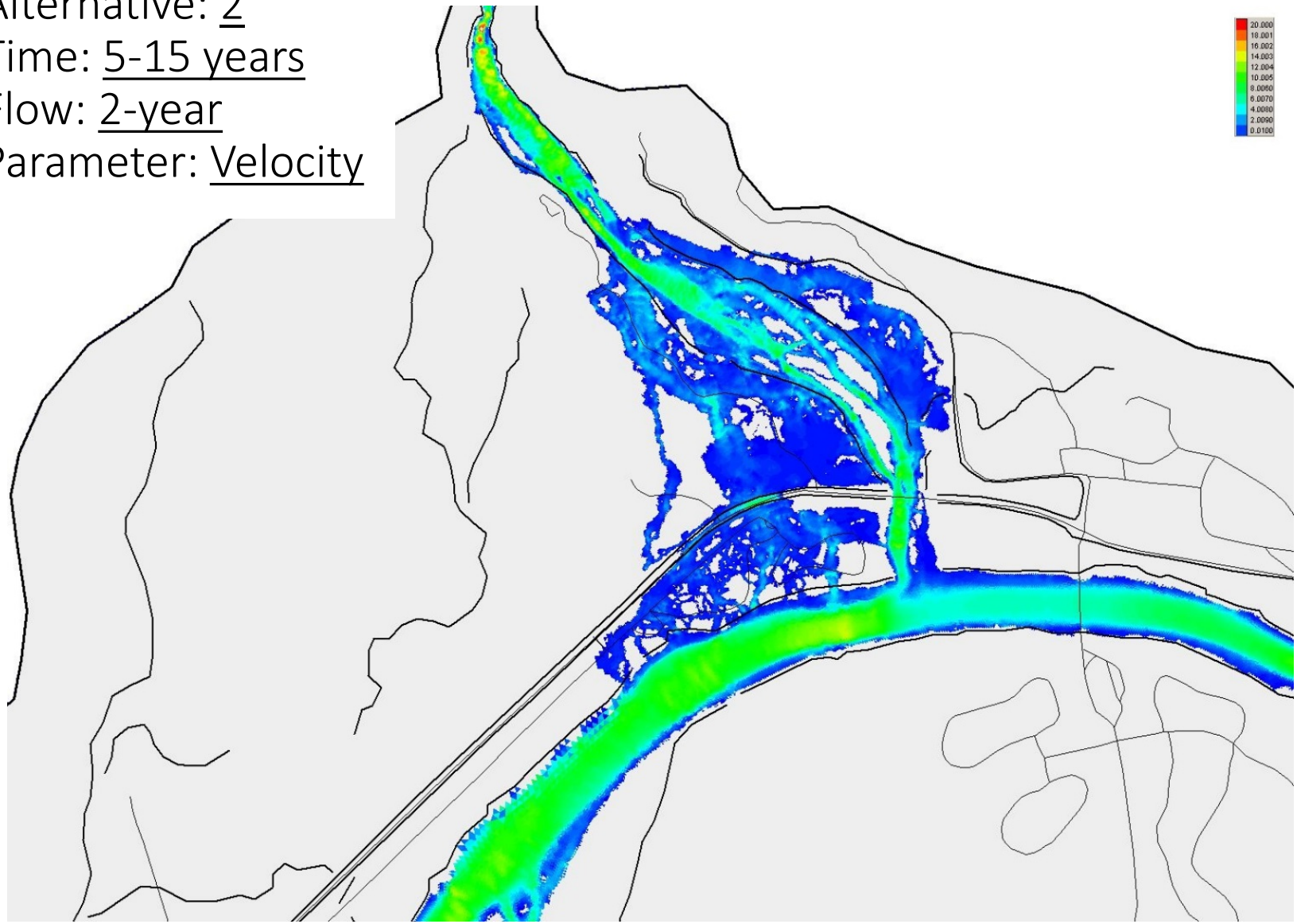

Figure G-27

Alternative: 2
Time: Zero
Flow: 100-year
Parameter: Velocity

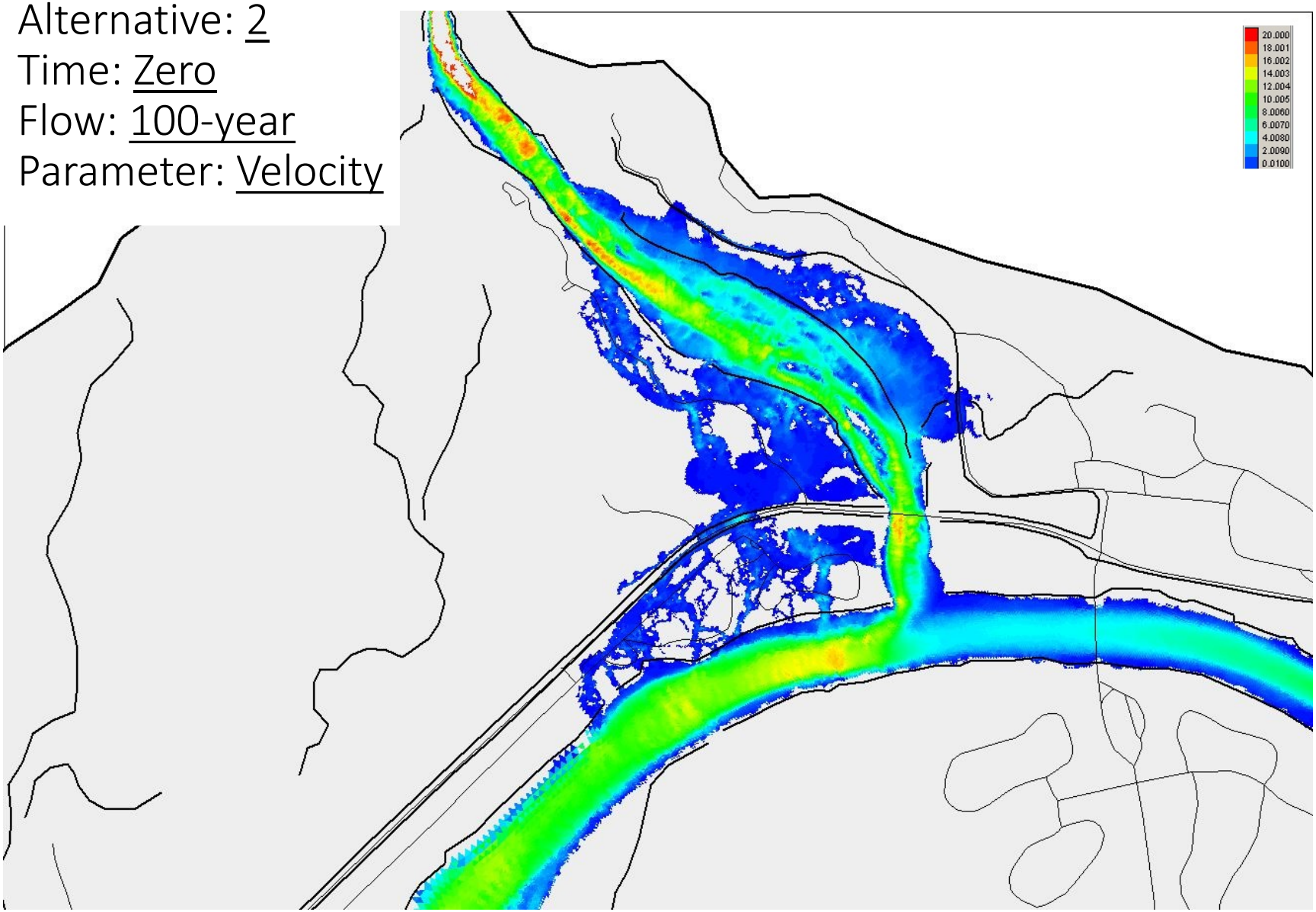

Figure G-28

Alternative: 2
Time: 5-15 years
Flow: 100-year
Parameter:
Velocity

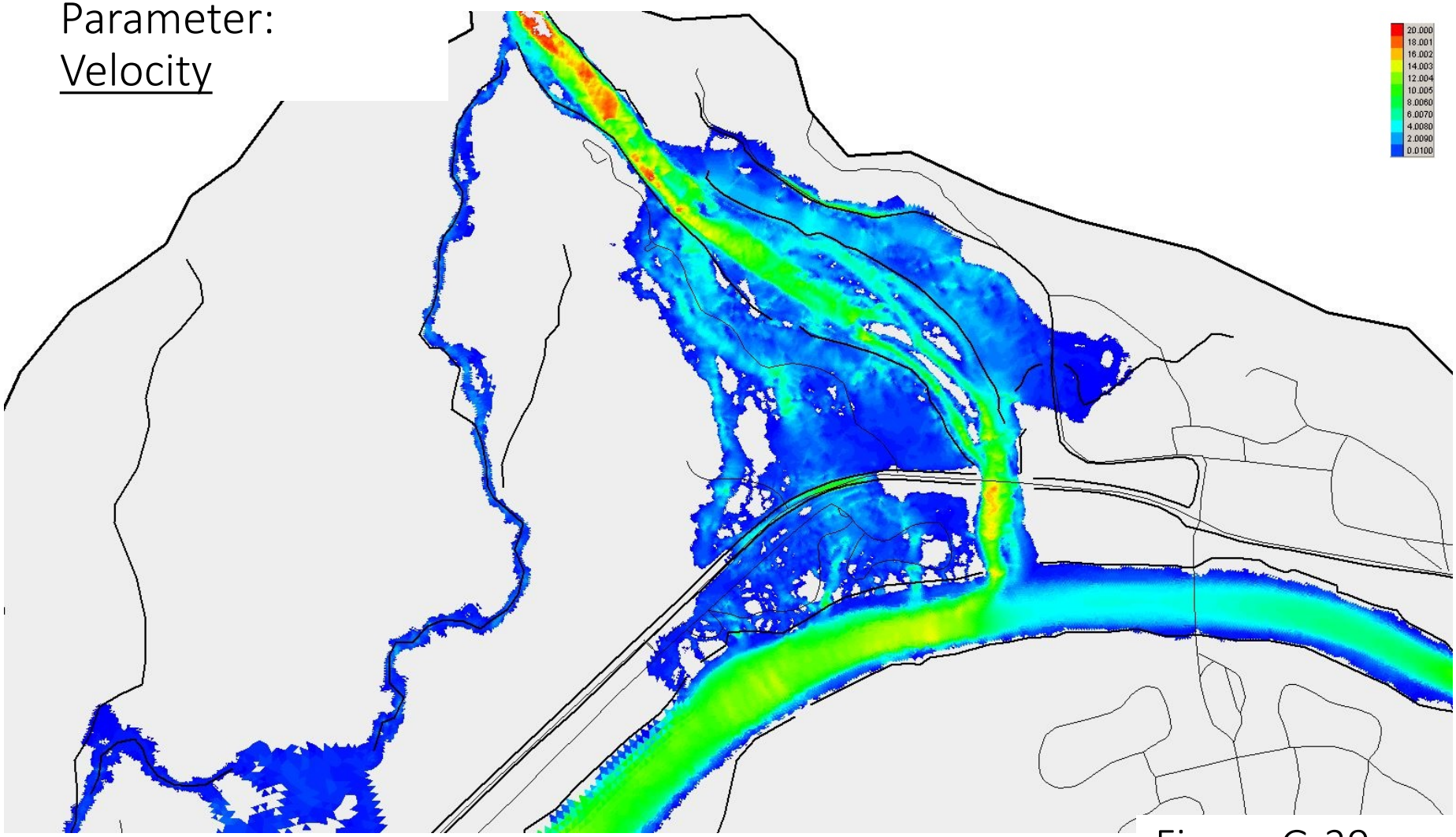

Figure G-29

Alternative: 2
Time: 5-15 years
Flow: Bulked
Parameter: Velocity

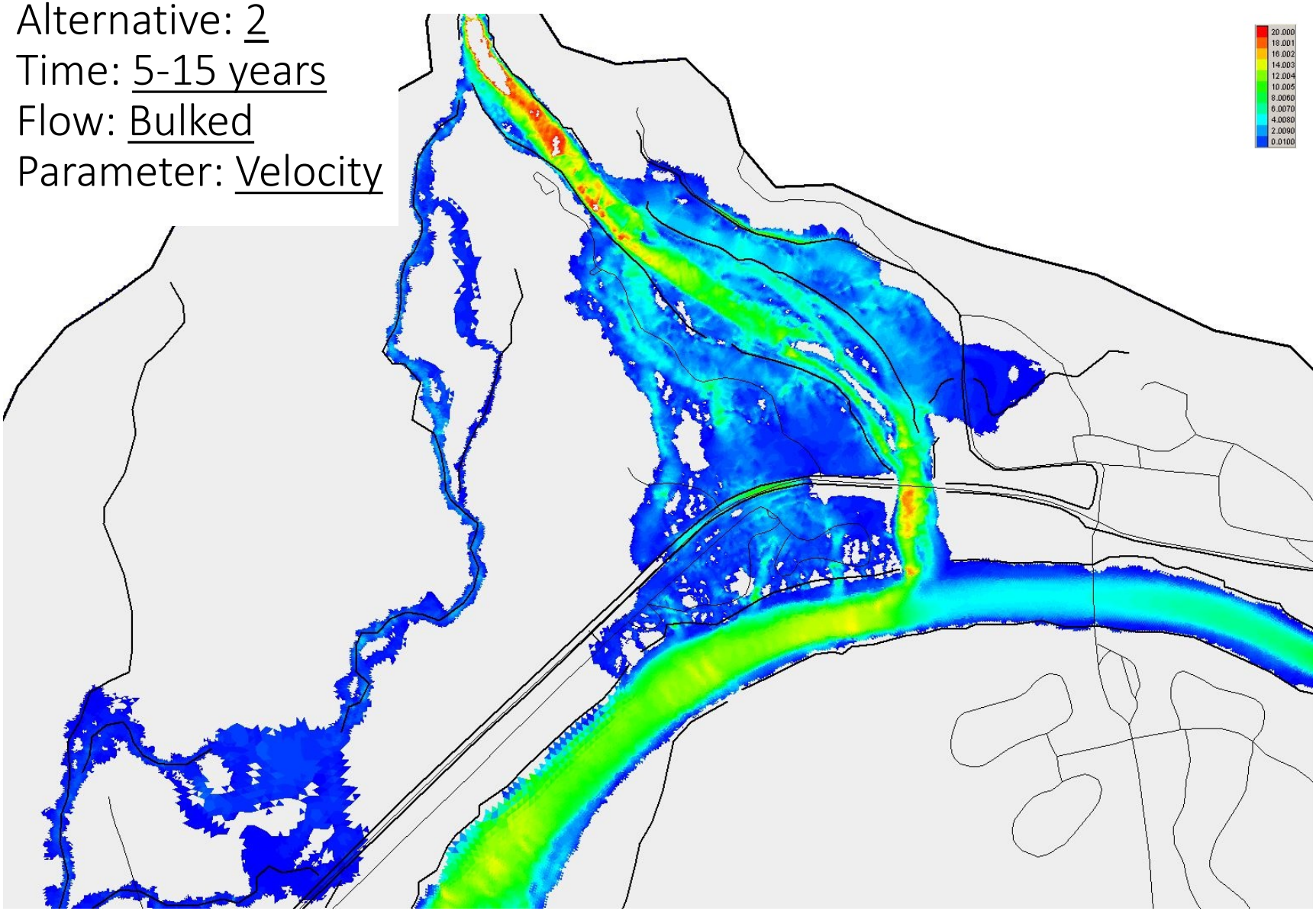

Figure G-30

Alternative: 3
Time: Zero
Flow: Low
Parameter: Depth

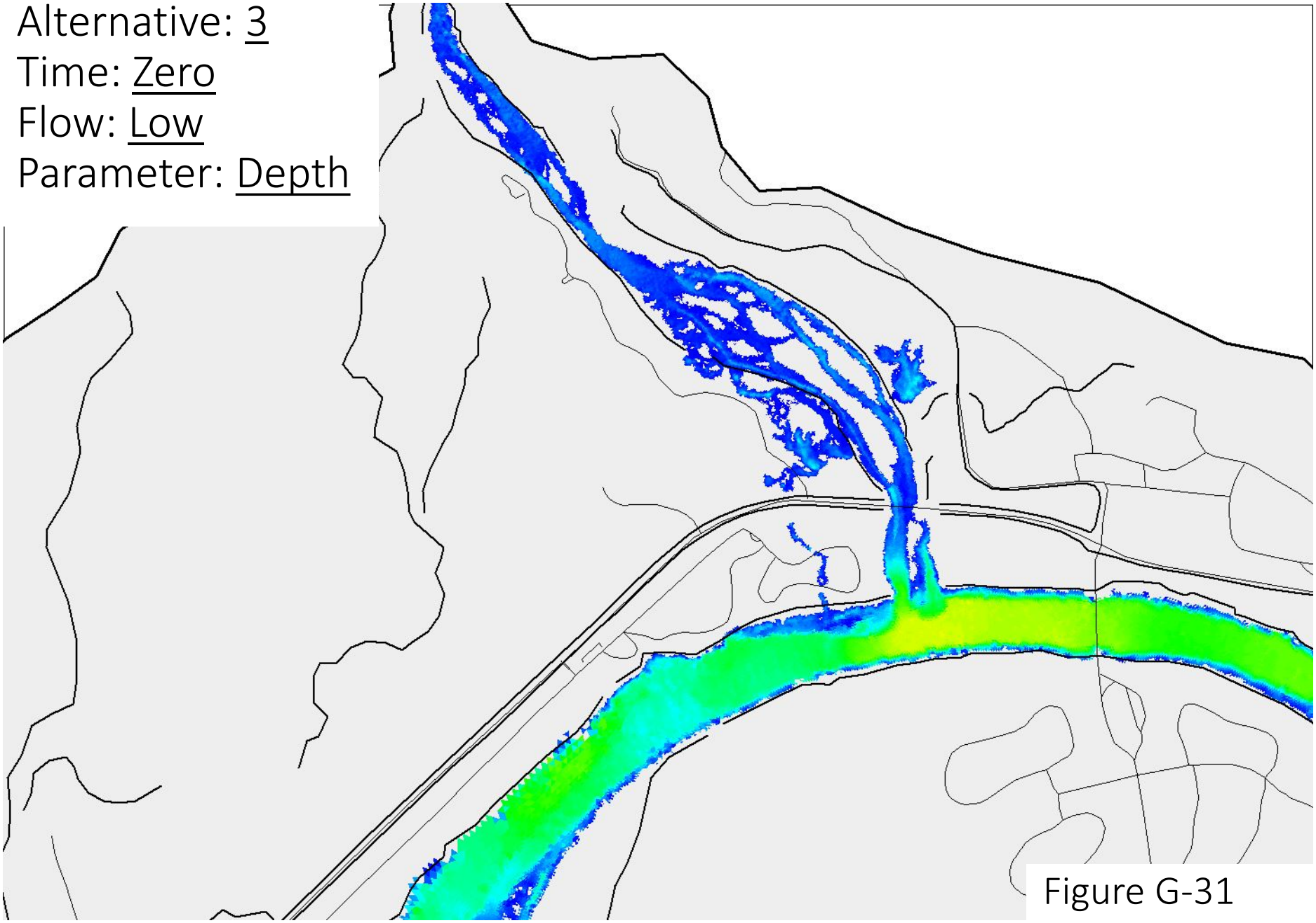

Figure G-31

Alternative: 3
Time: 5-15 years
Flow: Low
Parameter: Depth

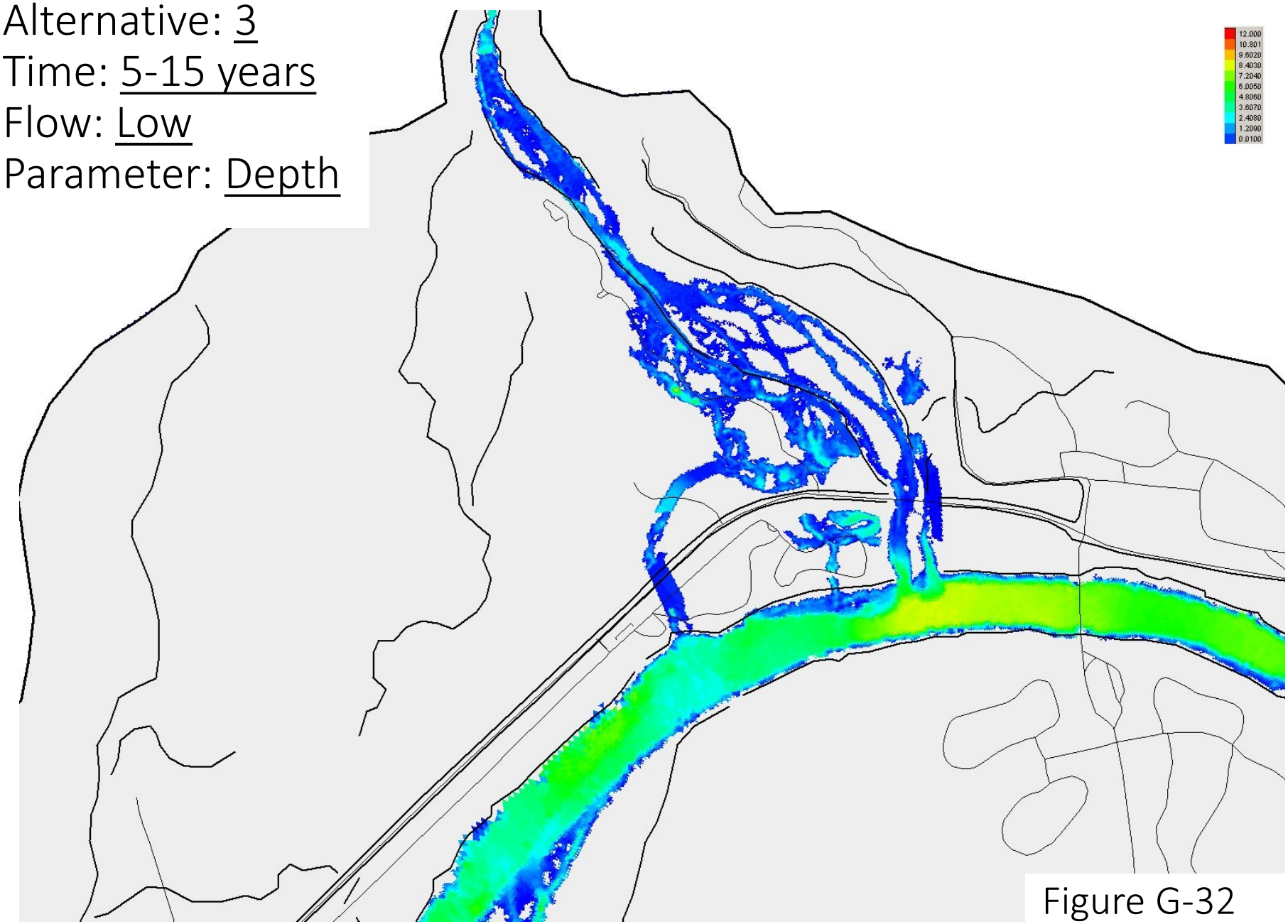

Figure G-32

Alternative: 3
Time: Zero
Flow: 2-year
Parameter: Depth

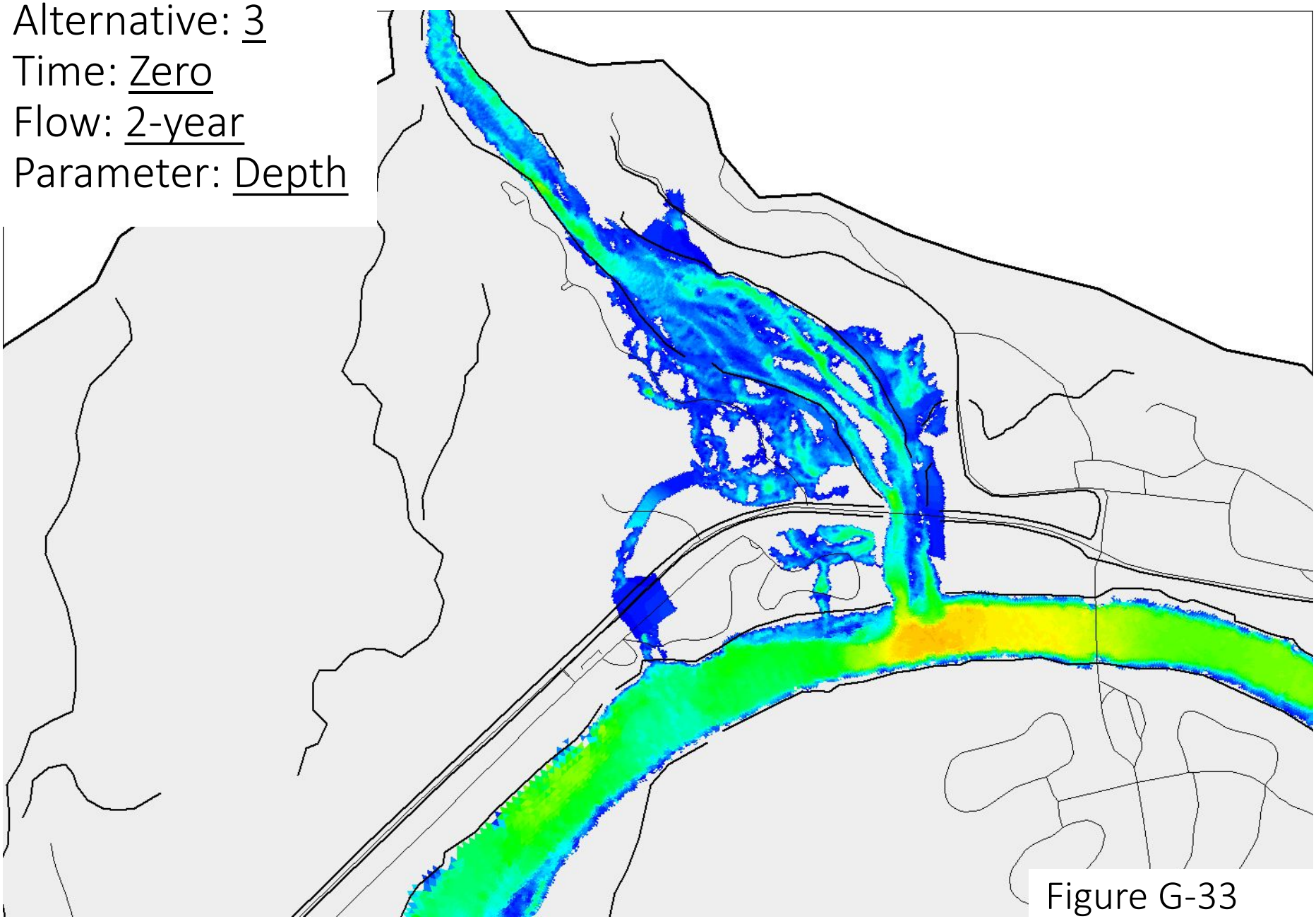

Figure G-33

Alternative: 3
Time: 5-15 years
Flow: 2-year
Parameter: Depth

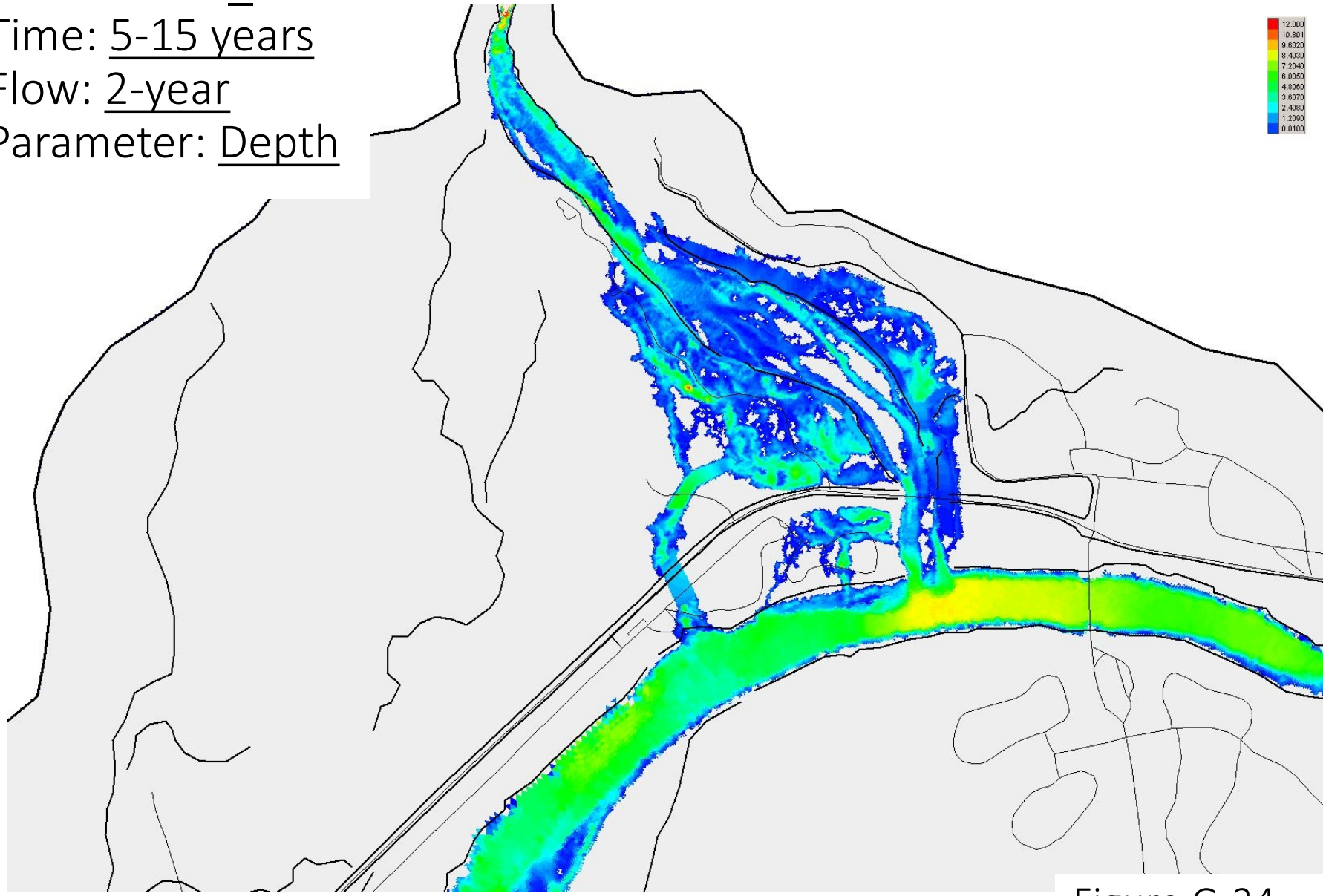

Figure G-34

Alternative: 3
Time: Zero
Flow: 100-year
Parameter: Depth

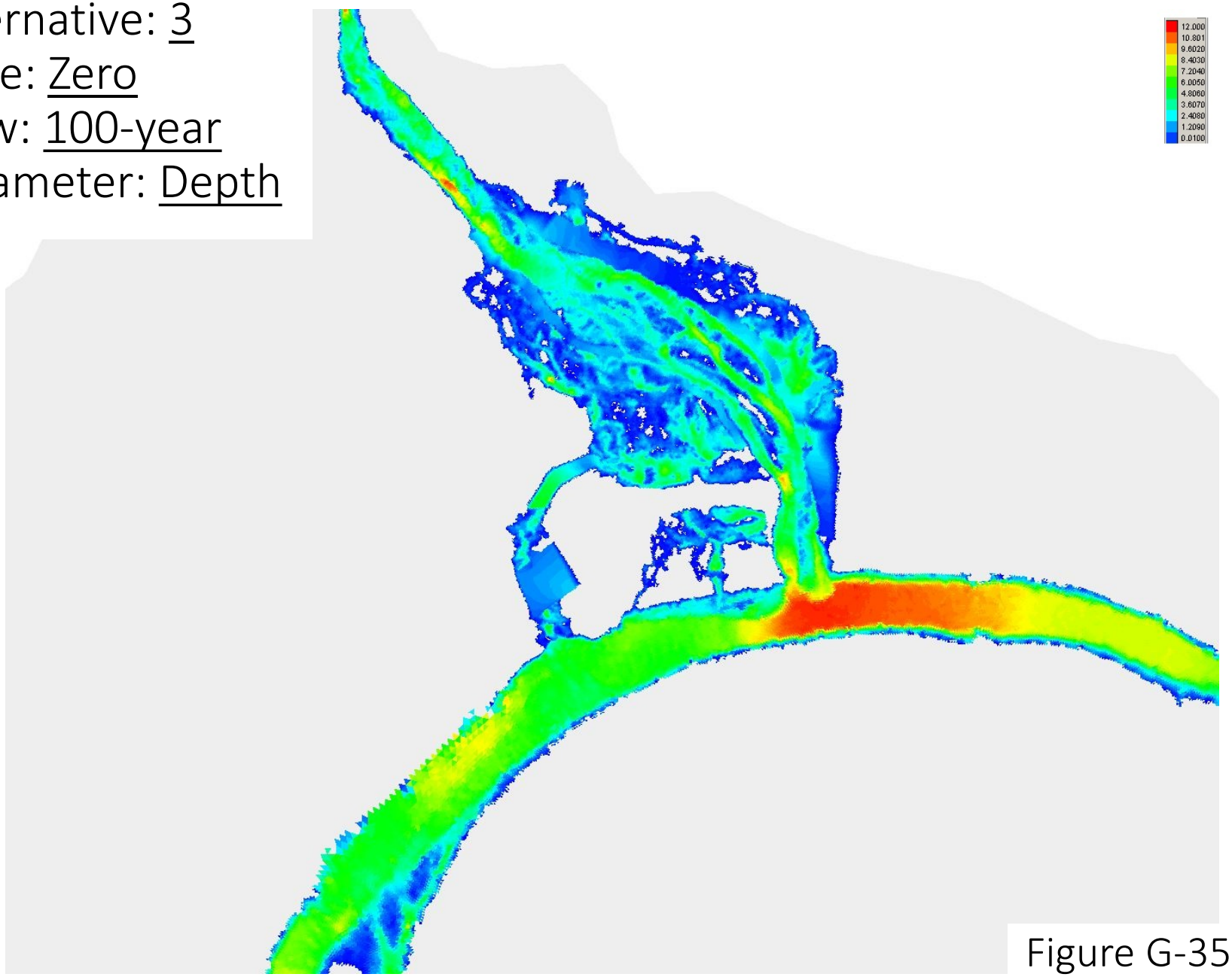

Figure G-35

Alternative: 3
Time: 5-15 years
Flow: 100-year
Parameter: Depth

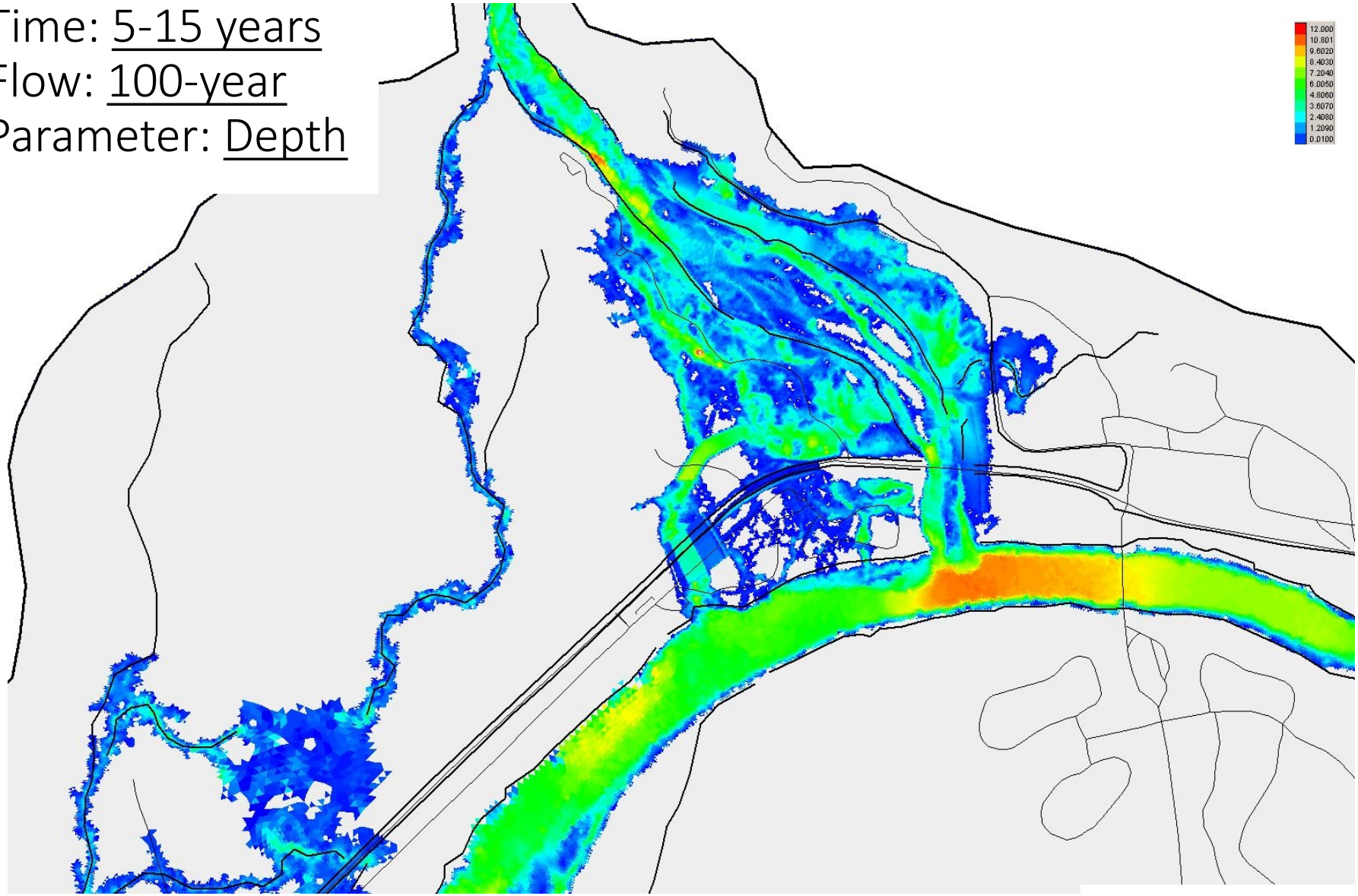

Figure G-36

Alternative: 3
Time: 5-15 years
Flow: Bulked
Parameter: Depth

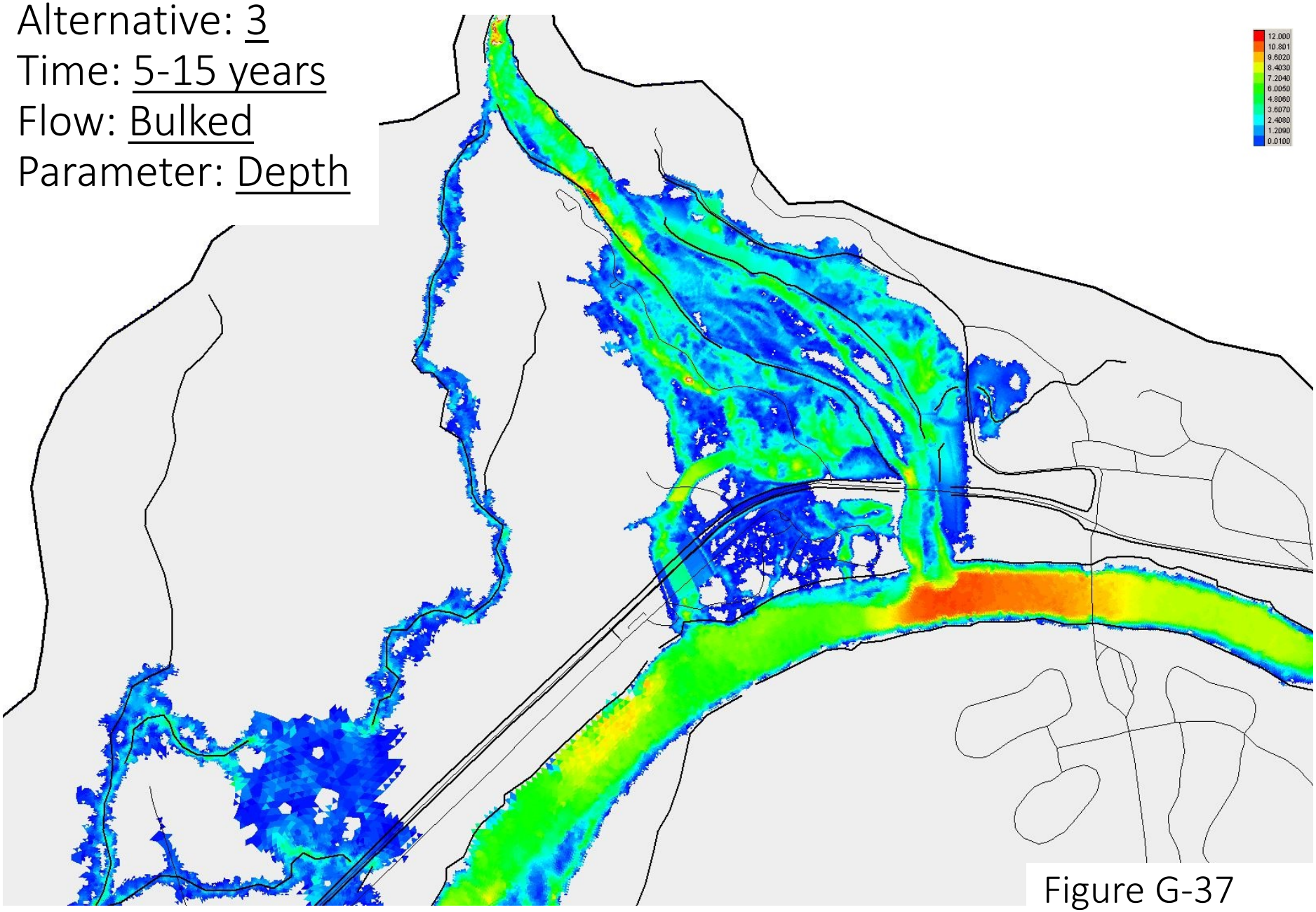

Figure G-37

Alternative: 3
Time: Zero
Flow: Low
Parameter:
Velocity

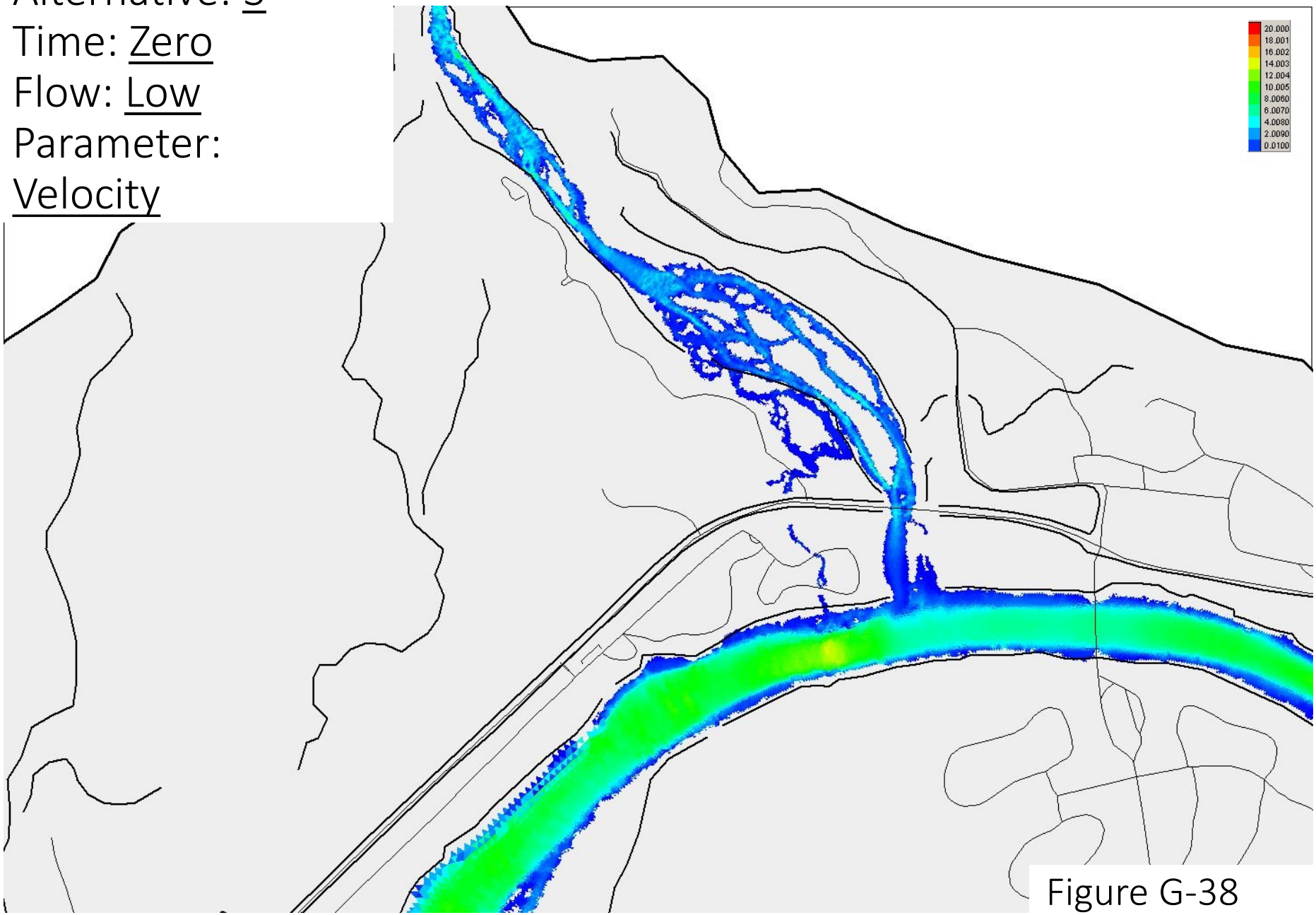

Figure G-38

Alternative: 3
Time: 5-15 years
Flow: Low
Parameter:
Velocity

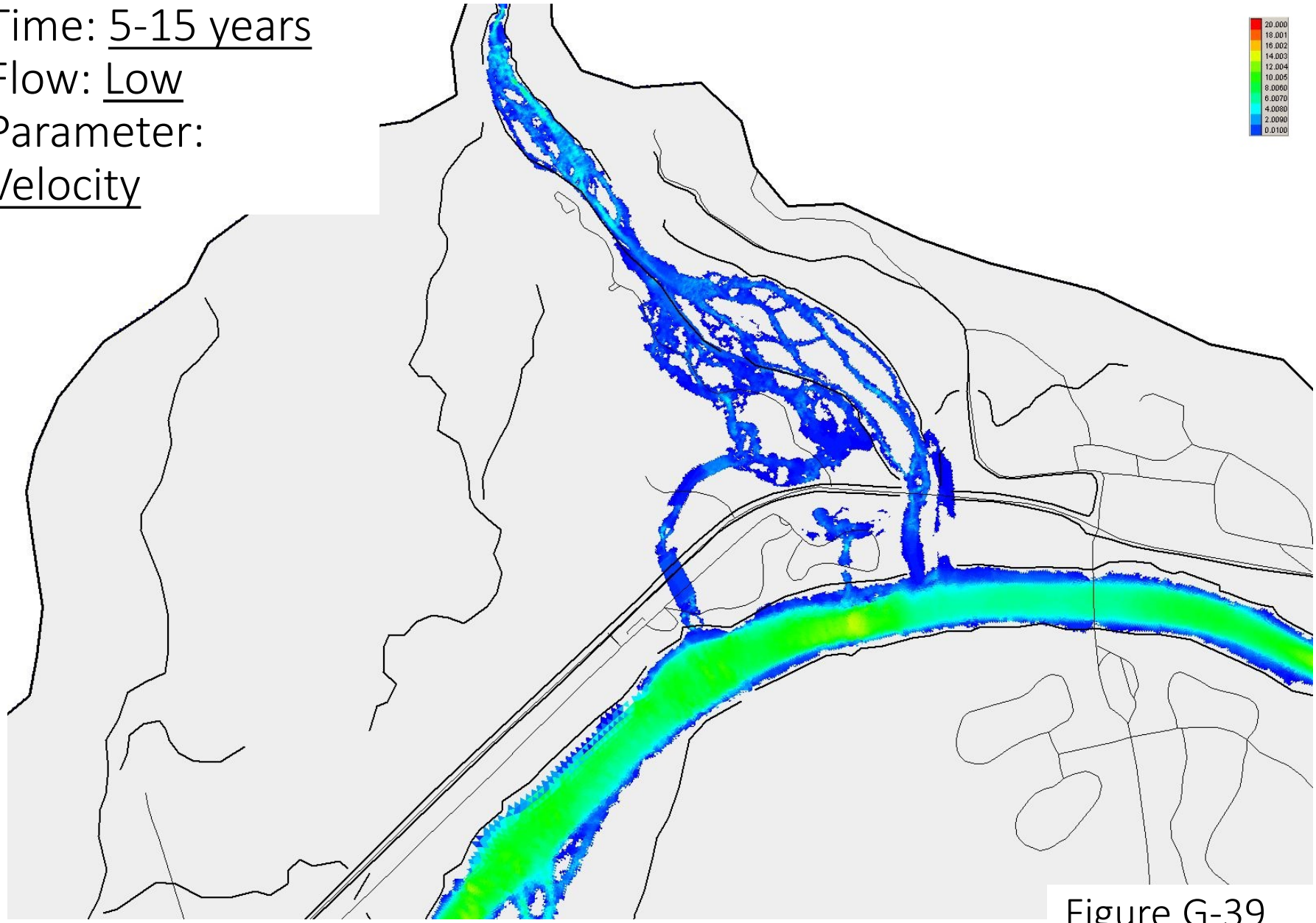

Figure G-39

Alternative: 3
Time: Zero
Flow: 2-year
Parameter: Velocity

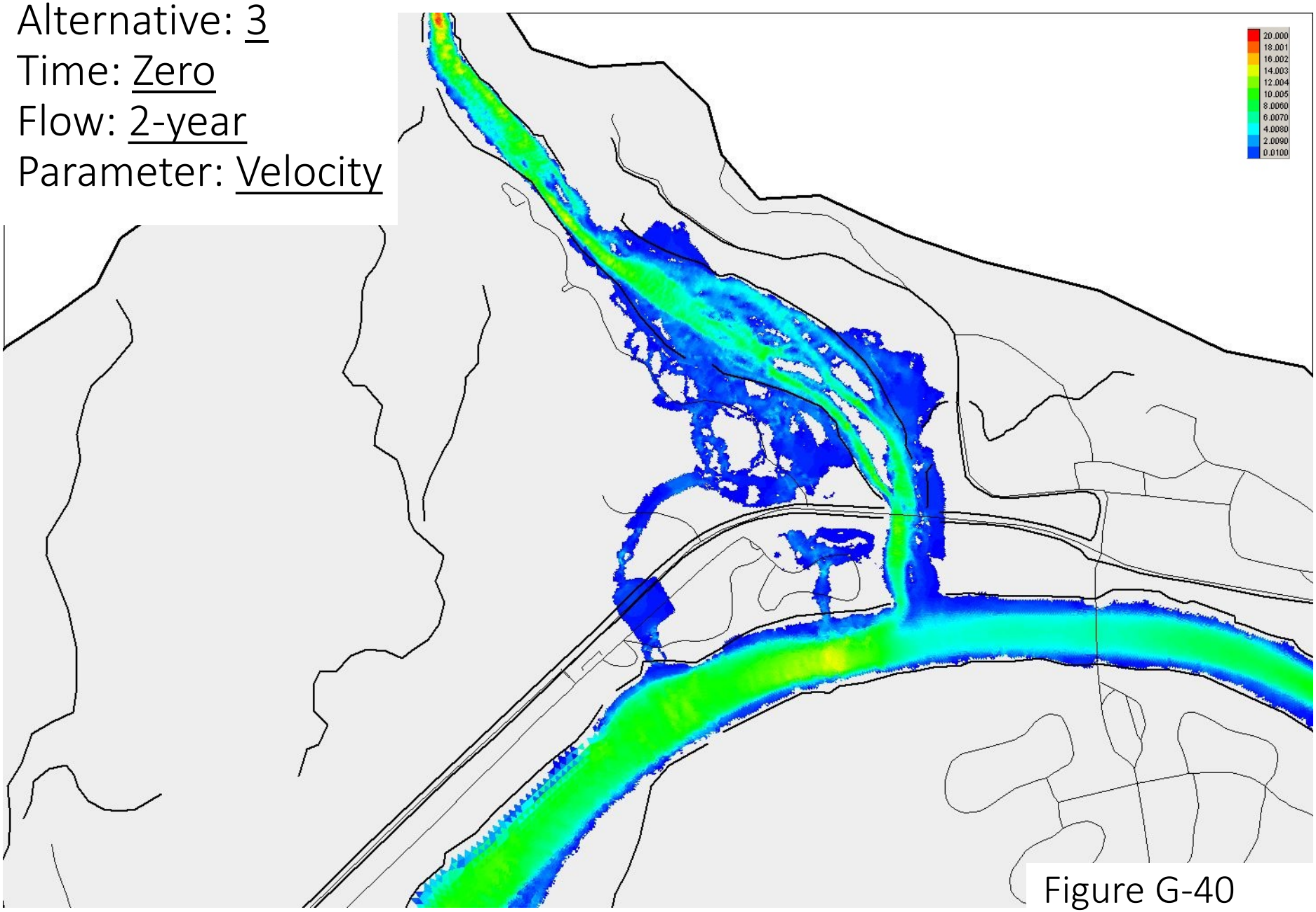

Figure G-40

Alternative: 3
Time: 5-15 years
Flow: 2-year
Parameter: Velocity

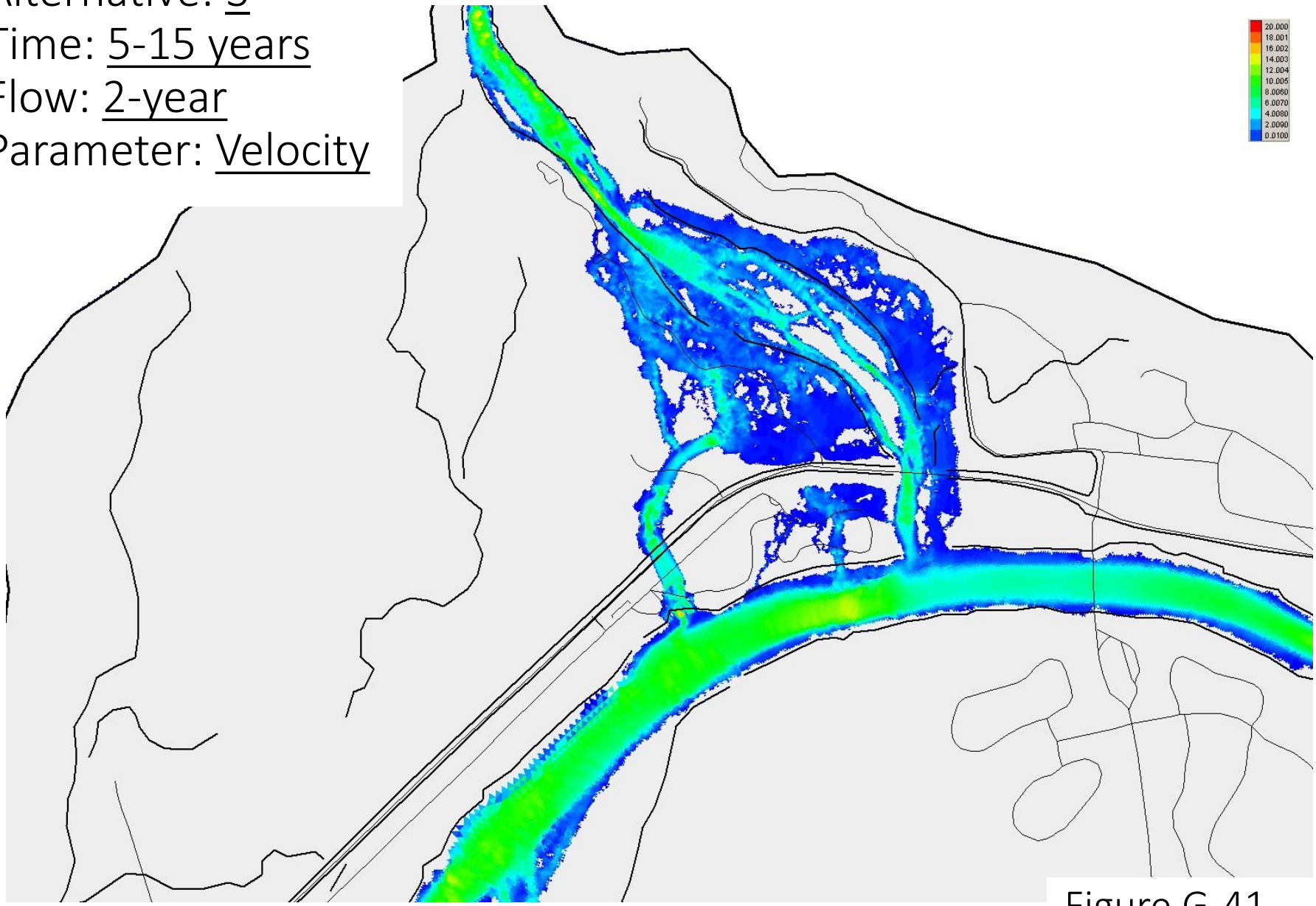

Figure G-41

Alternative: 3
Time: Zero
Flow: 100-year
Parameter: Velocity

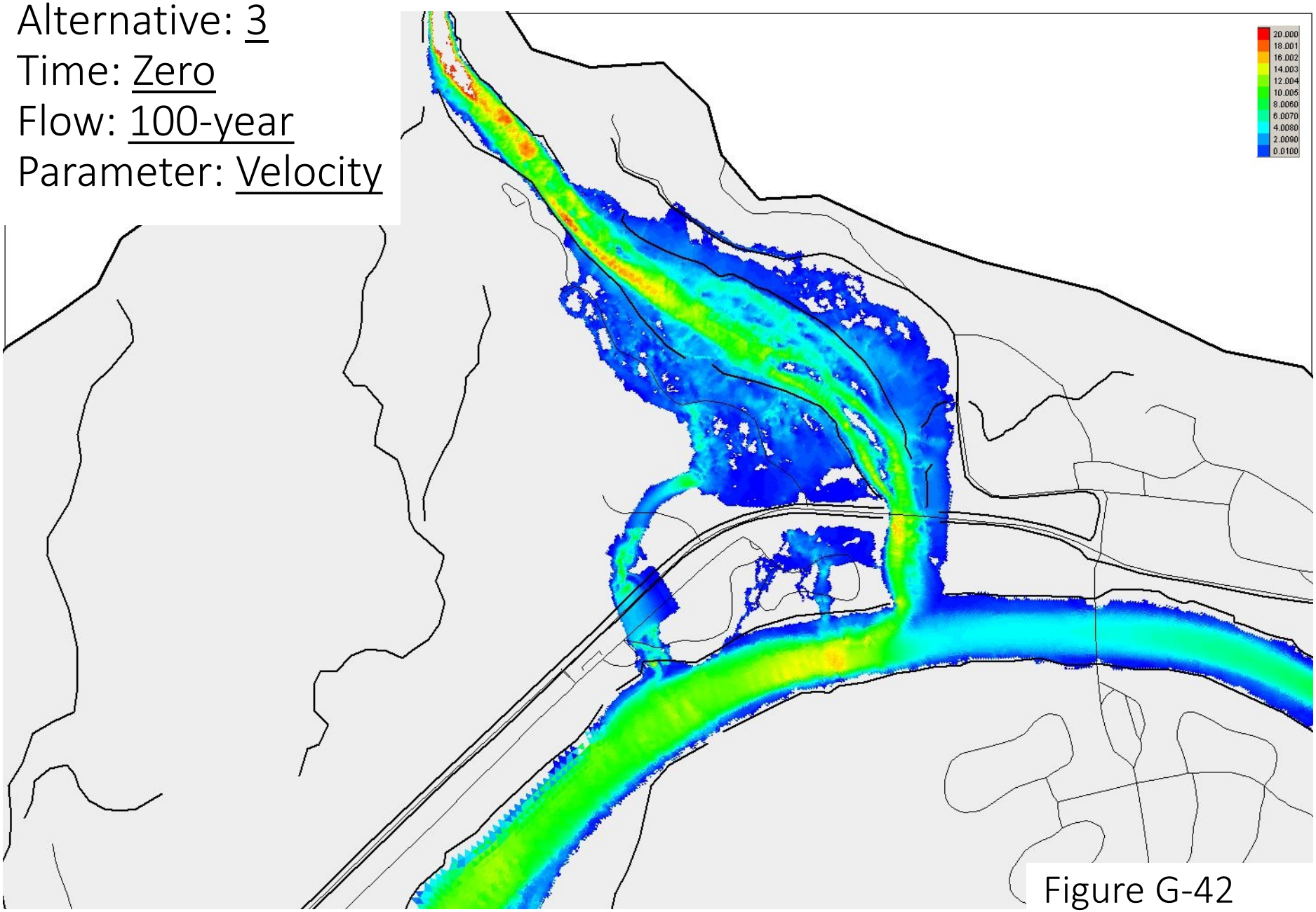

Figure G-42

Alternative: 3
Time: 5-15 years
Flow: 100-year
Parameter:
Velocity

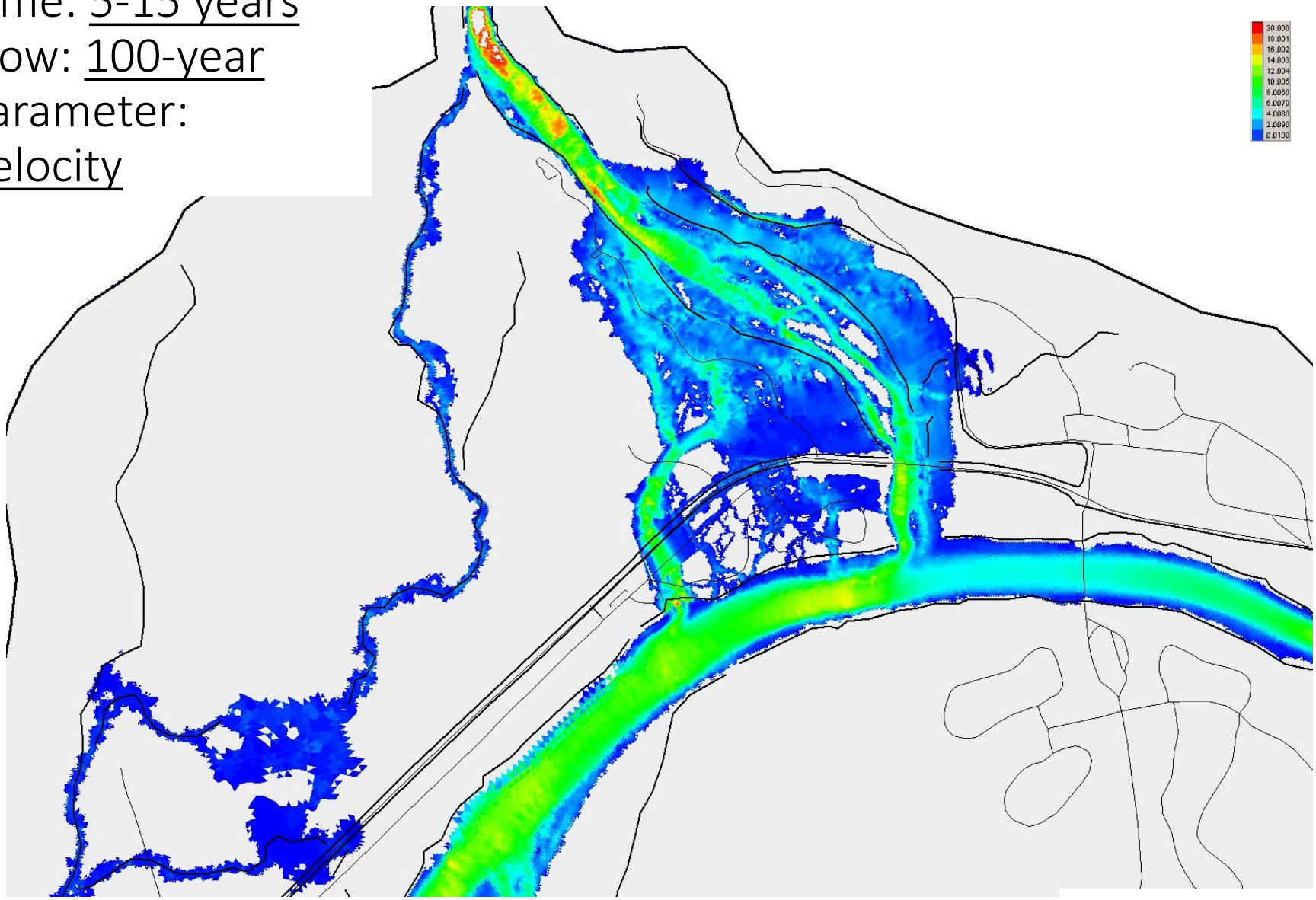

Figure G-43

Alternative: 3
Time: 5-15 years
Flow: Bulked
Parameter: Velocity

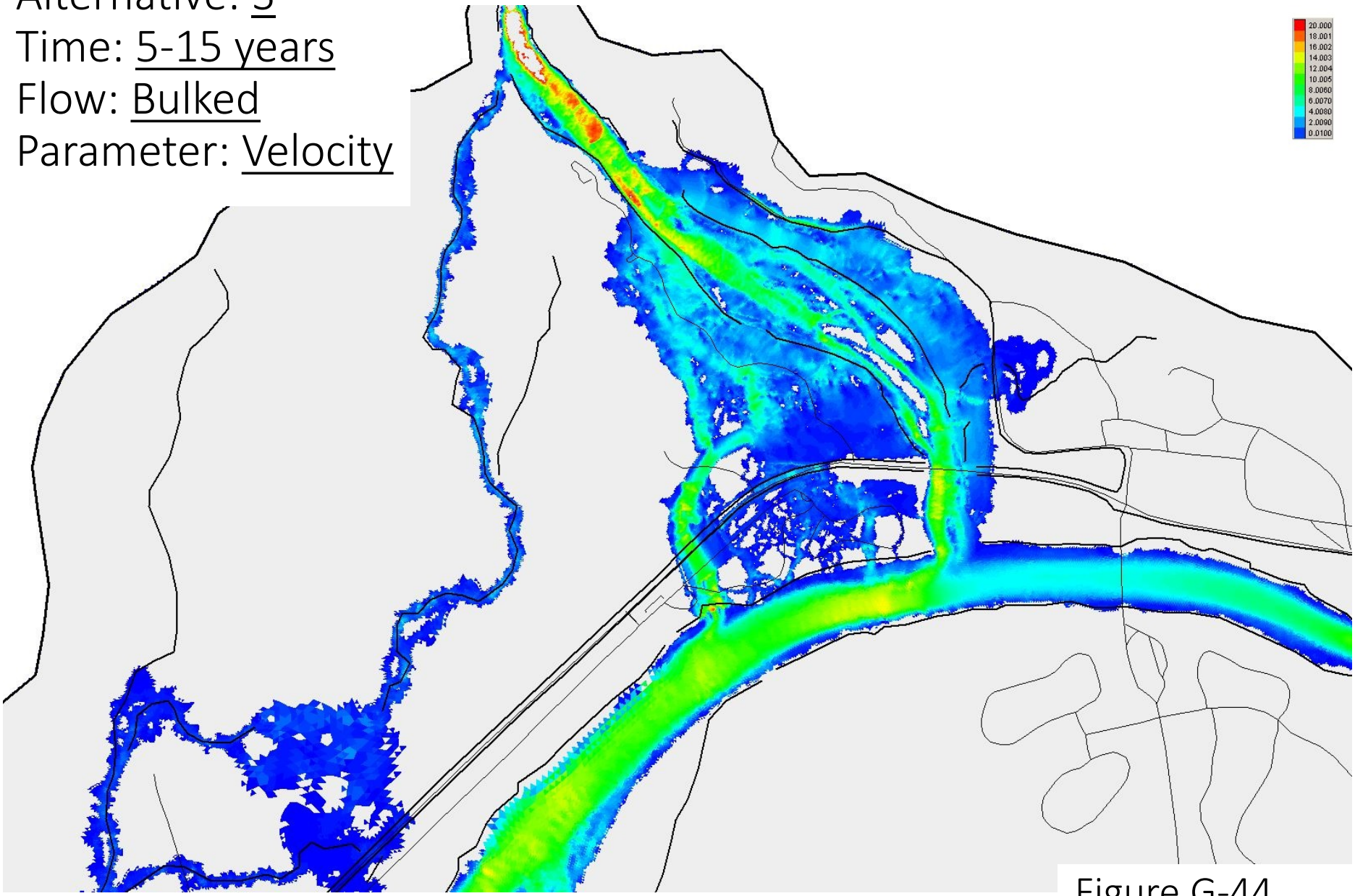

Figure G-44

Alternative: 4
Time: Zero
Flow: Low
Parameter: Depth

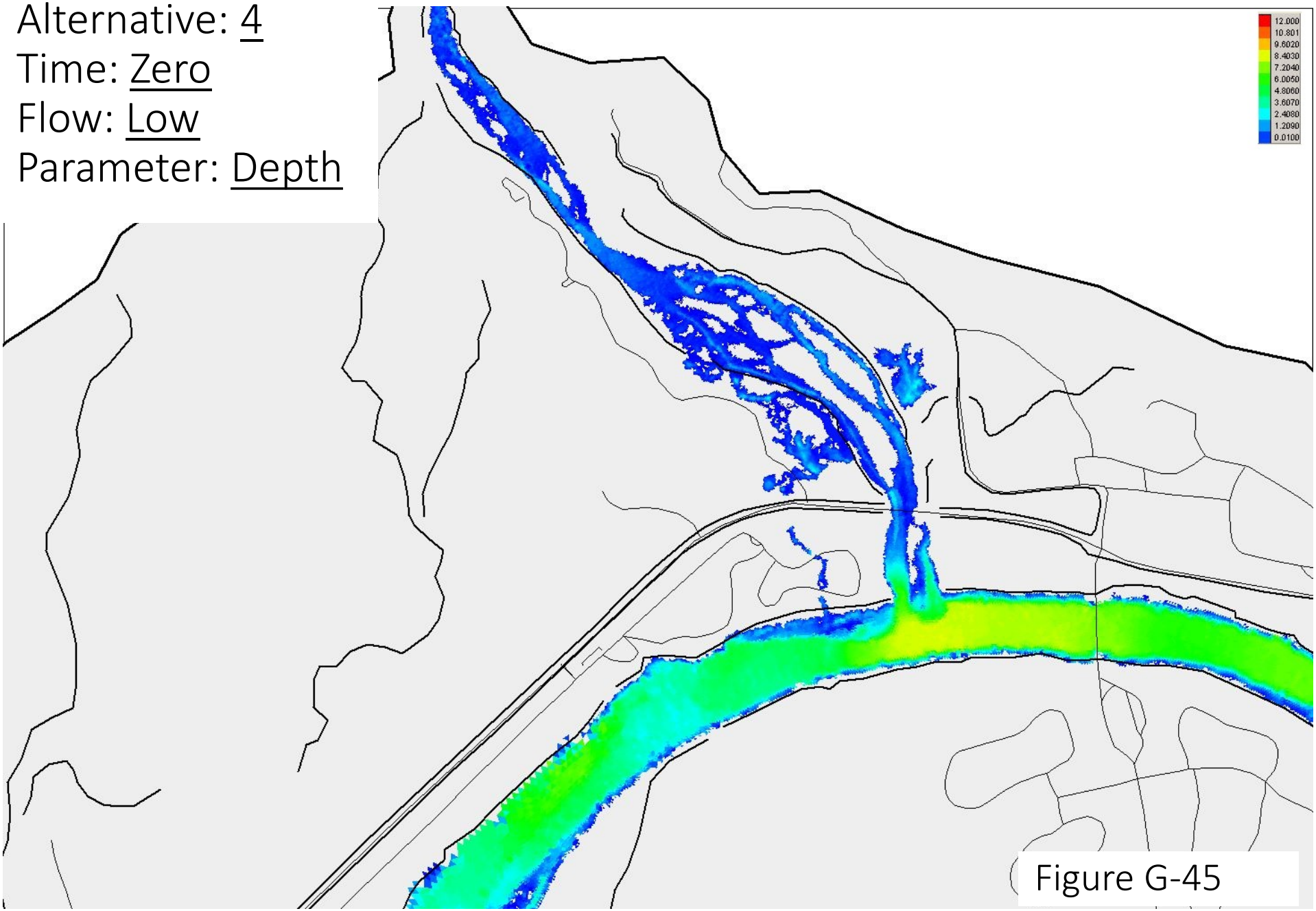

Figure G-45

Alternative: 4
Time: 5-15 years
Flow: Low
Parameter: Depth

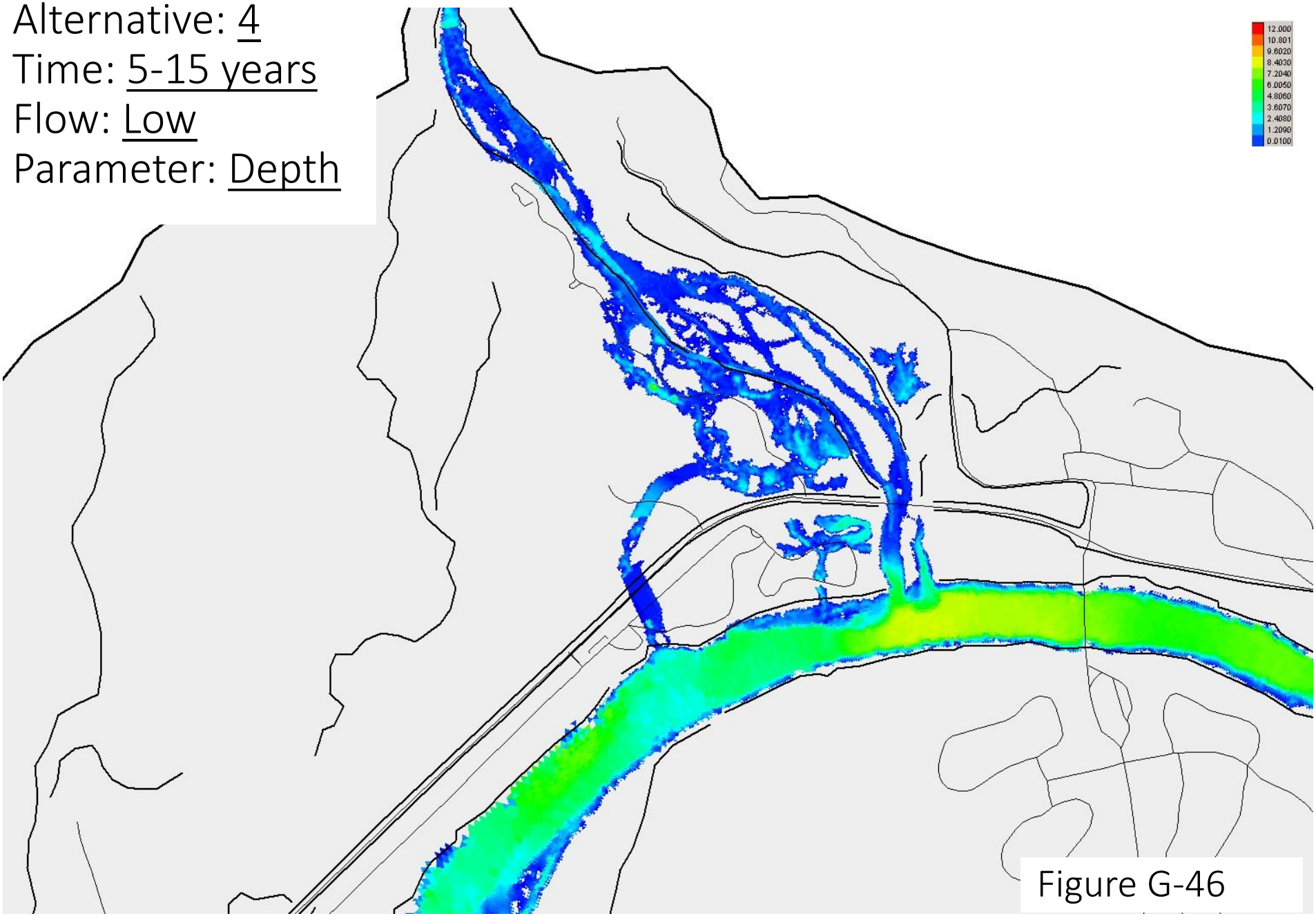

Figure G-46

Alternative: 4
Time: Zero
Flow: 2-year
Parameter: Depth

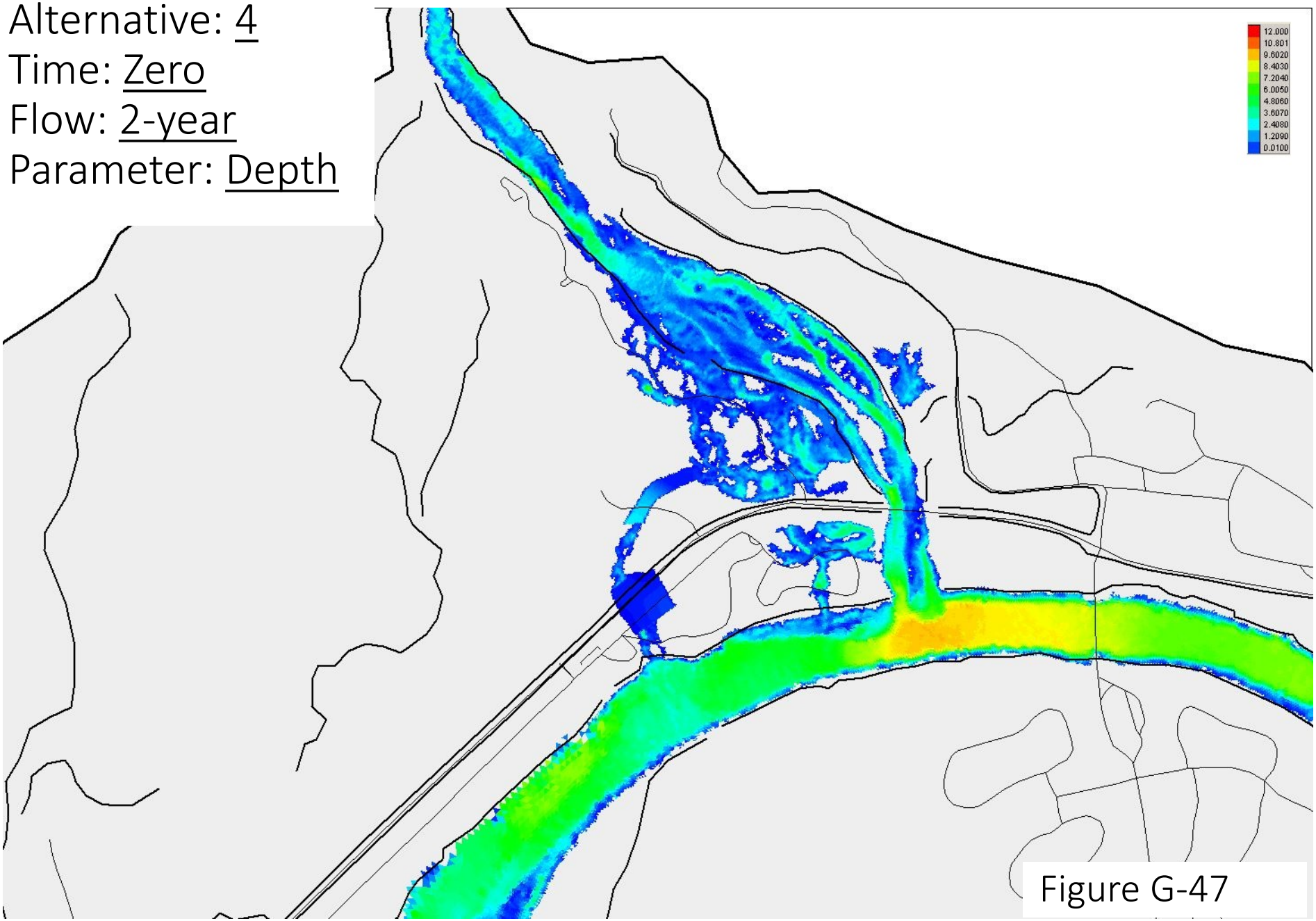

Figure G-47

Alternative: 4
Time: 5-15 years
Flow: 2-year
Parameter: Depth

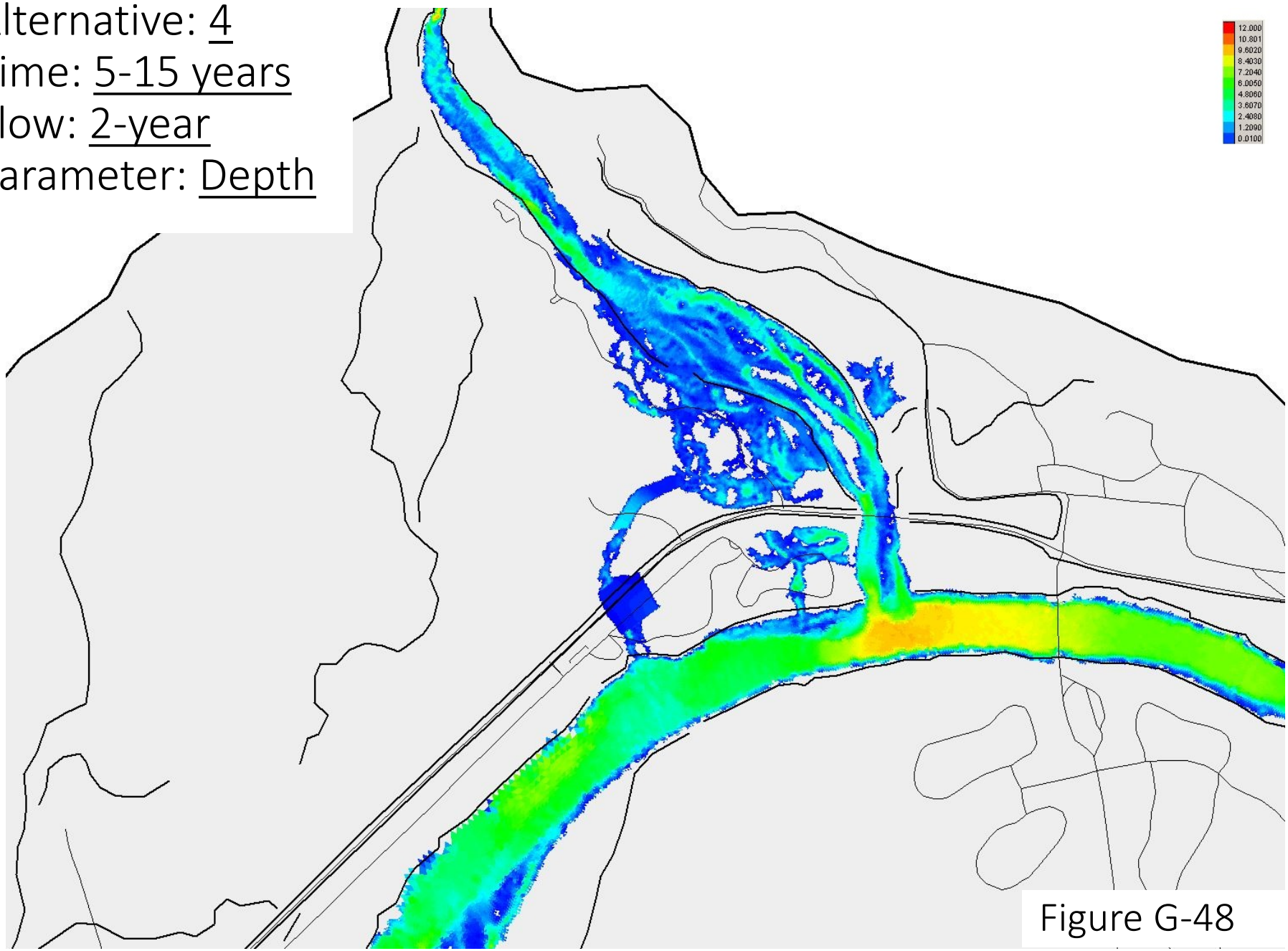

Figure G-48

Alternative: 4
Time: Zero
Flow: 100-year
Parameter: Depth

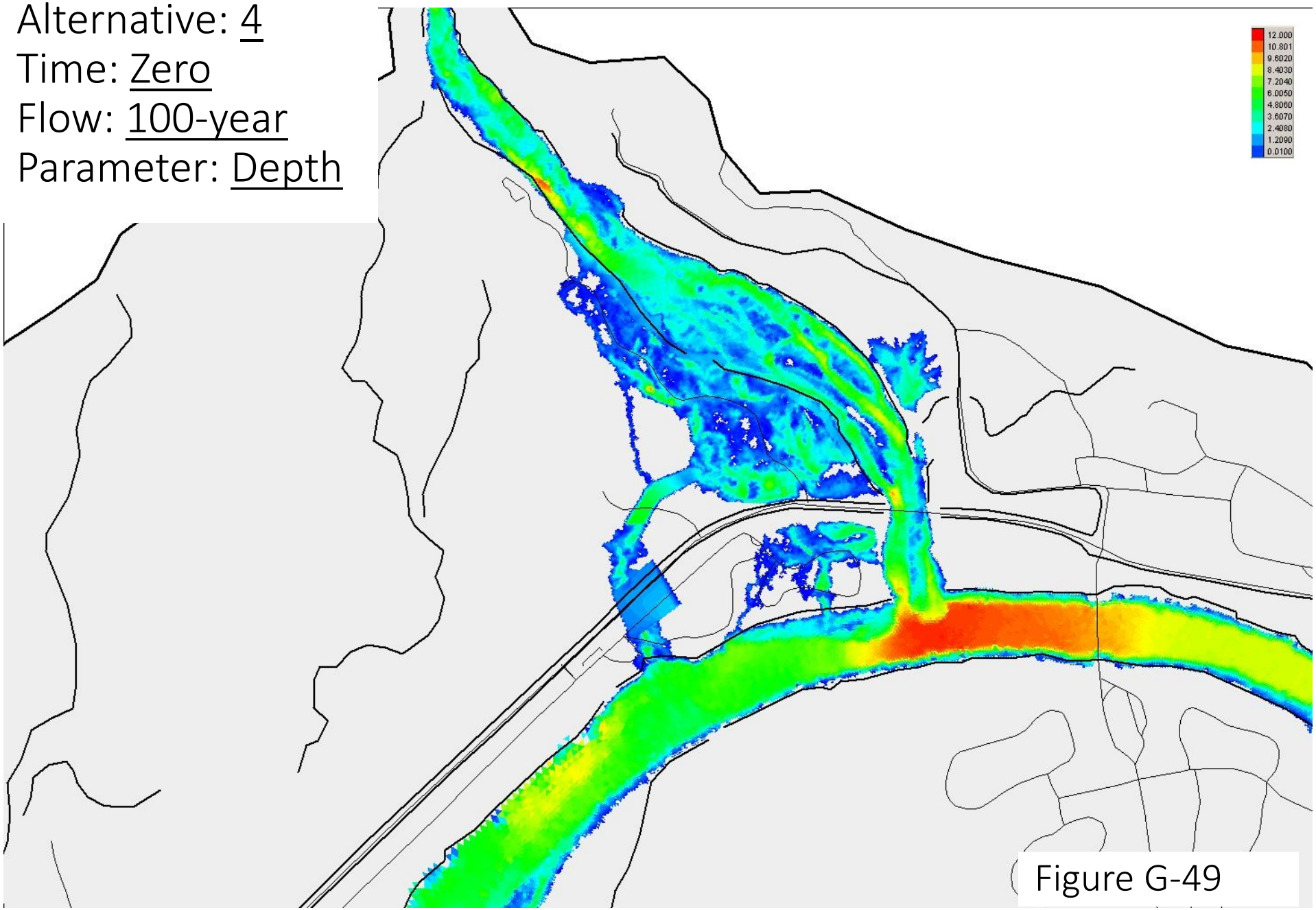

Figure G-49

Alternative: 4
Time: 5-15 years
Flow: 100-year
Parameter: Depth

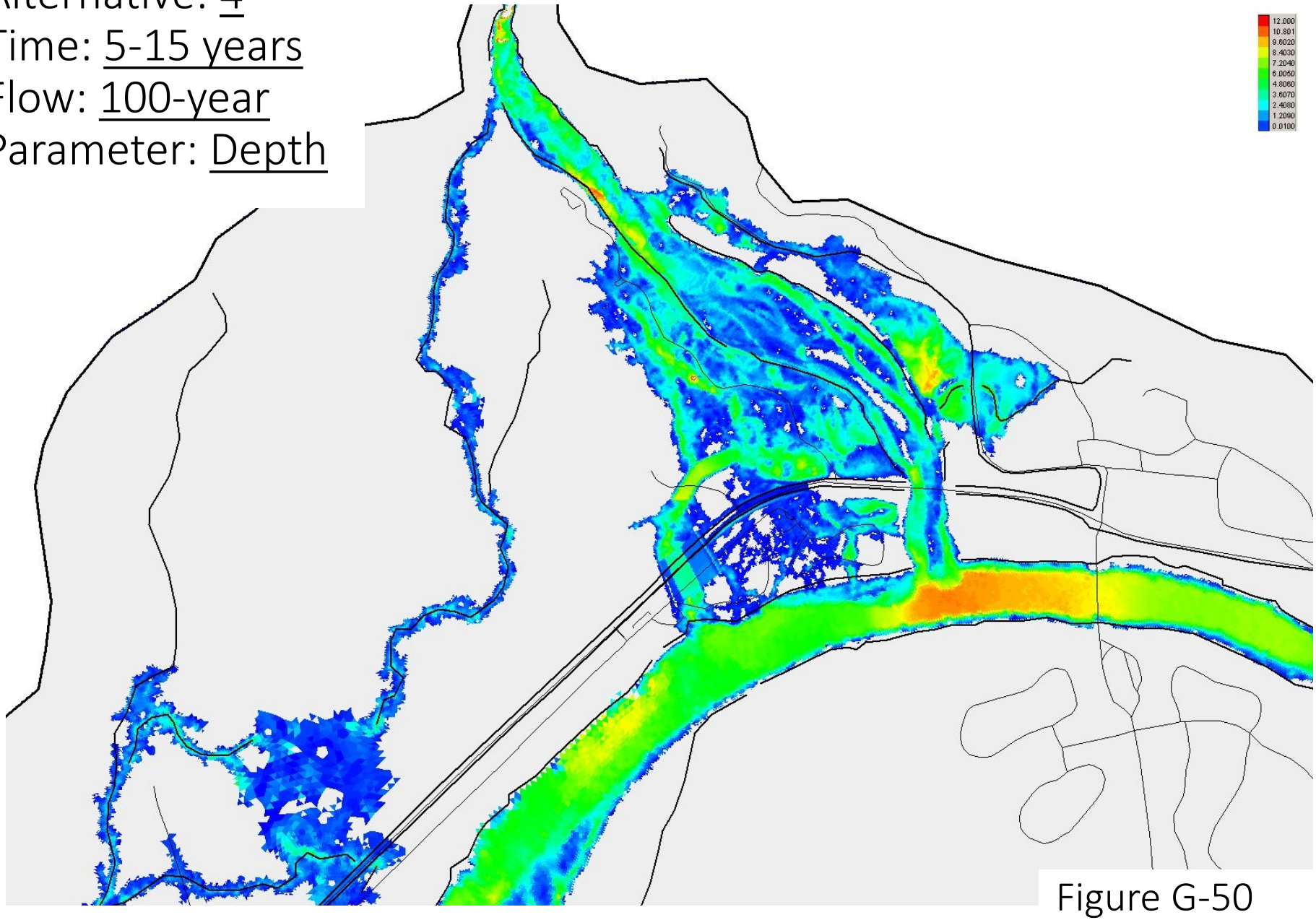

Figure G-50

Alternative: 4
Time: 5-15 years
Flow: Bulked
Parameter: Depth

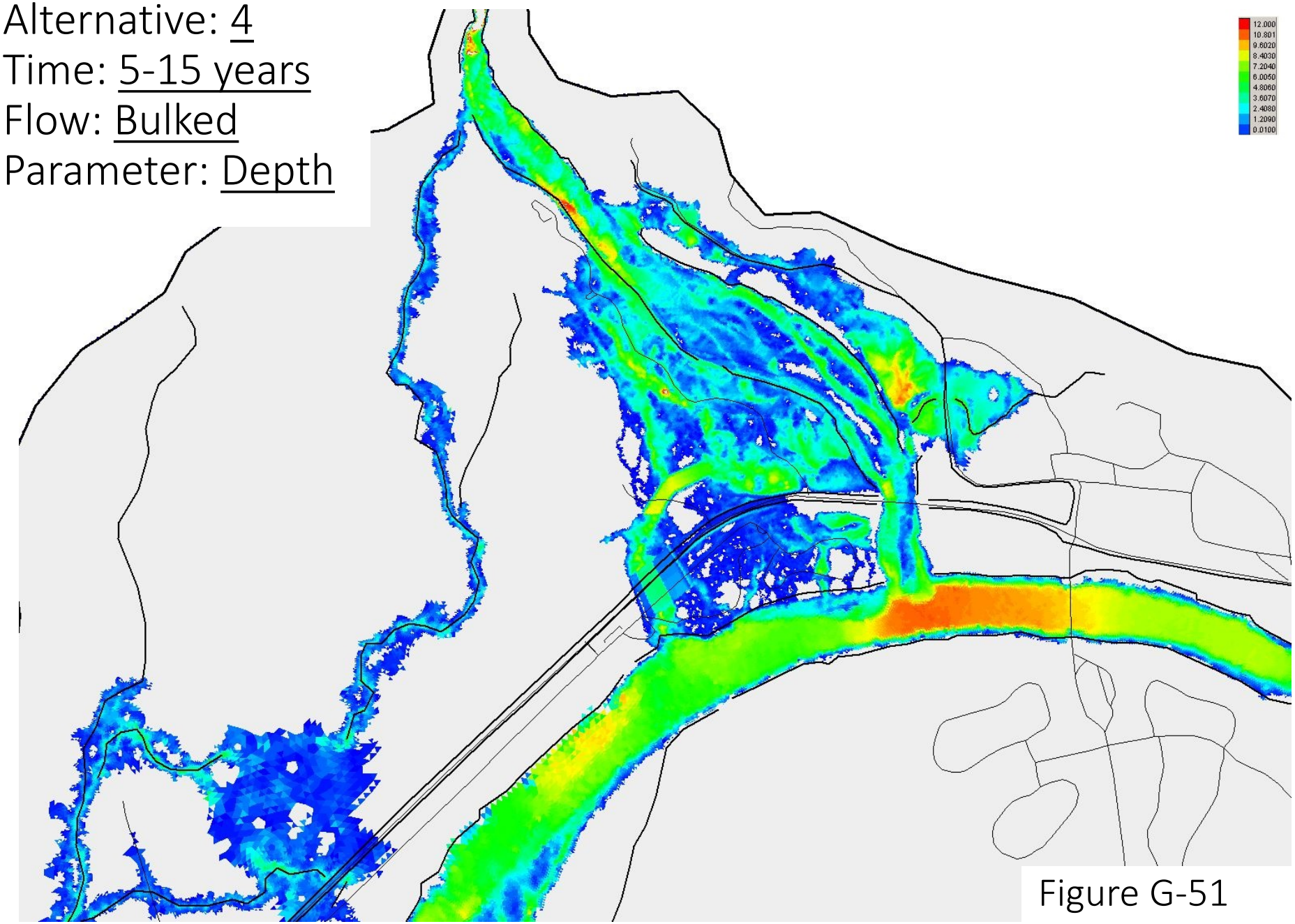

Figure G-51

Alternative: 4
Time: Zero
Flow: Low
Parameter: Velocity

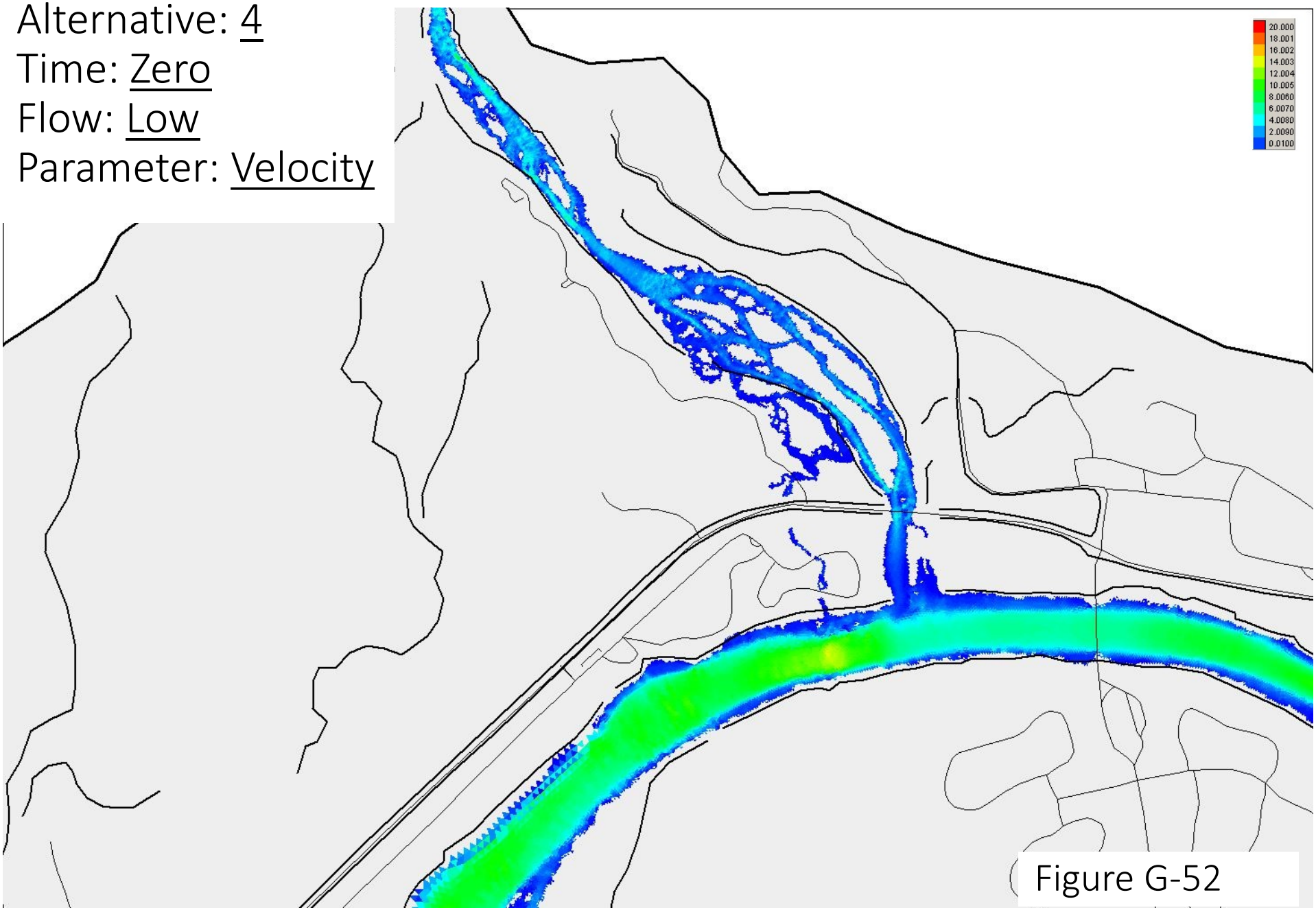

Figure G-52

Alternative: 4
Time: 5-15 years
Flow: Low
Parameter: Velocity

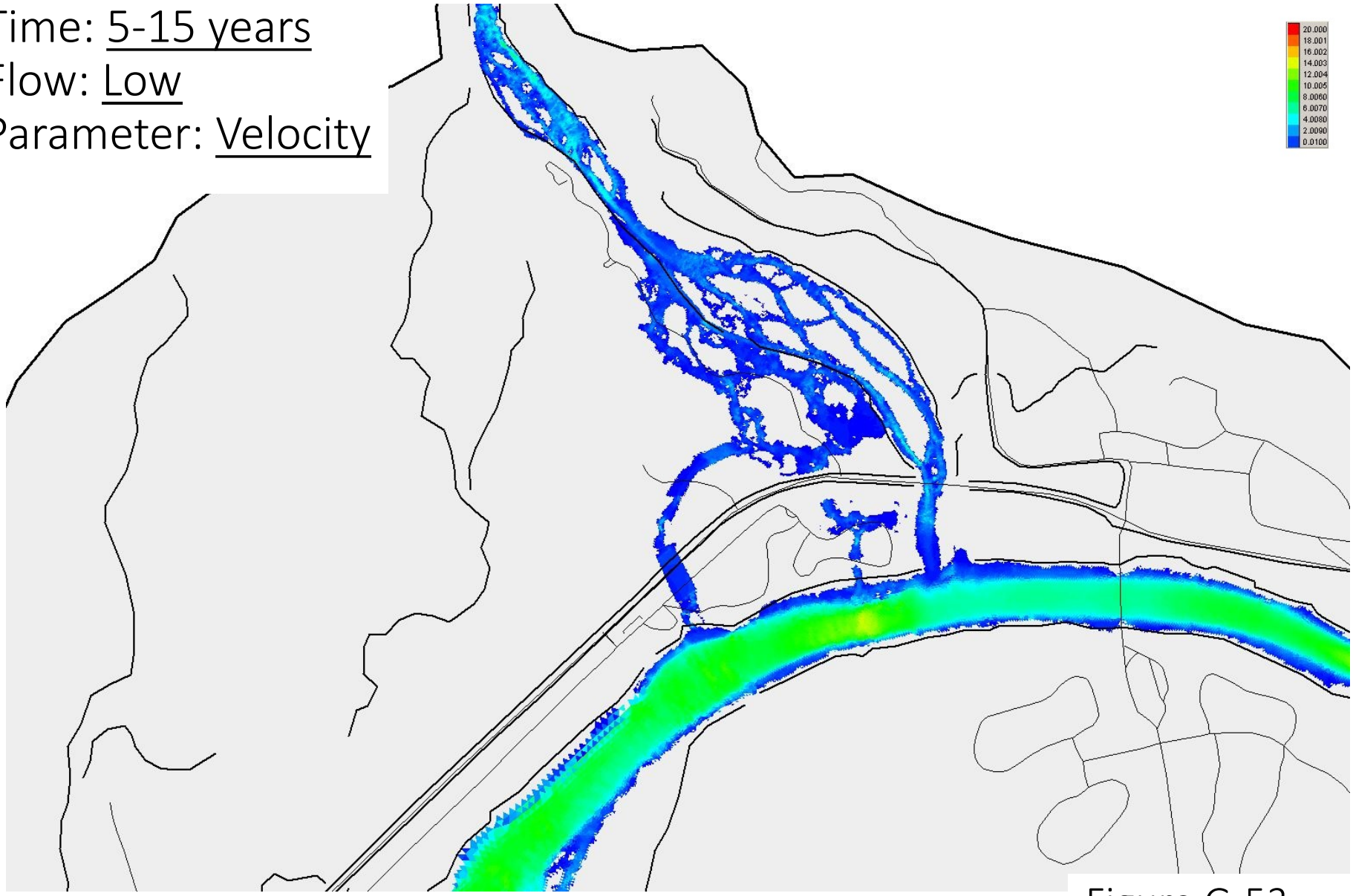

Figure G-53

Alternative: 4
Time: Zero
Flow: 2-year
Parameter: Velocity

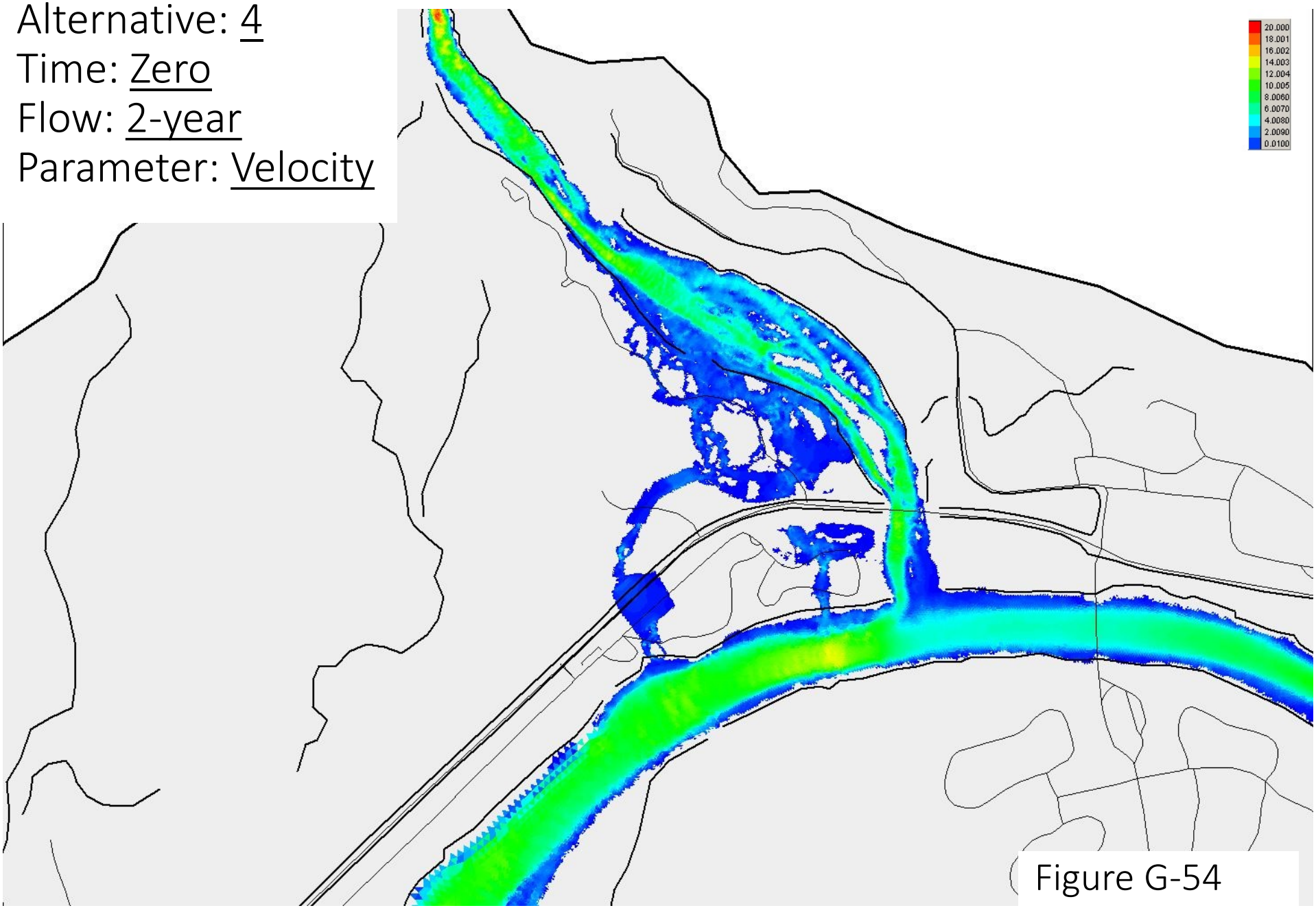

Figure G-54

Alternative: 4
Time: 5-15 years
Flow: 2-year
Parameter: Velocity

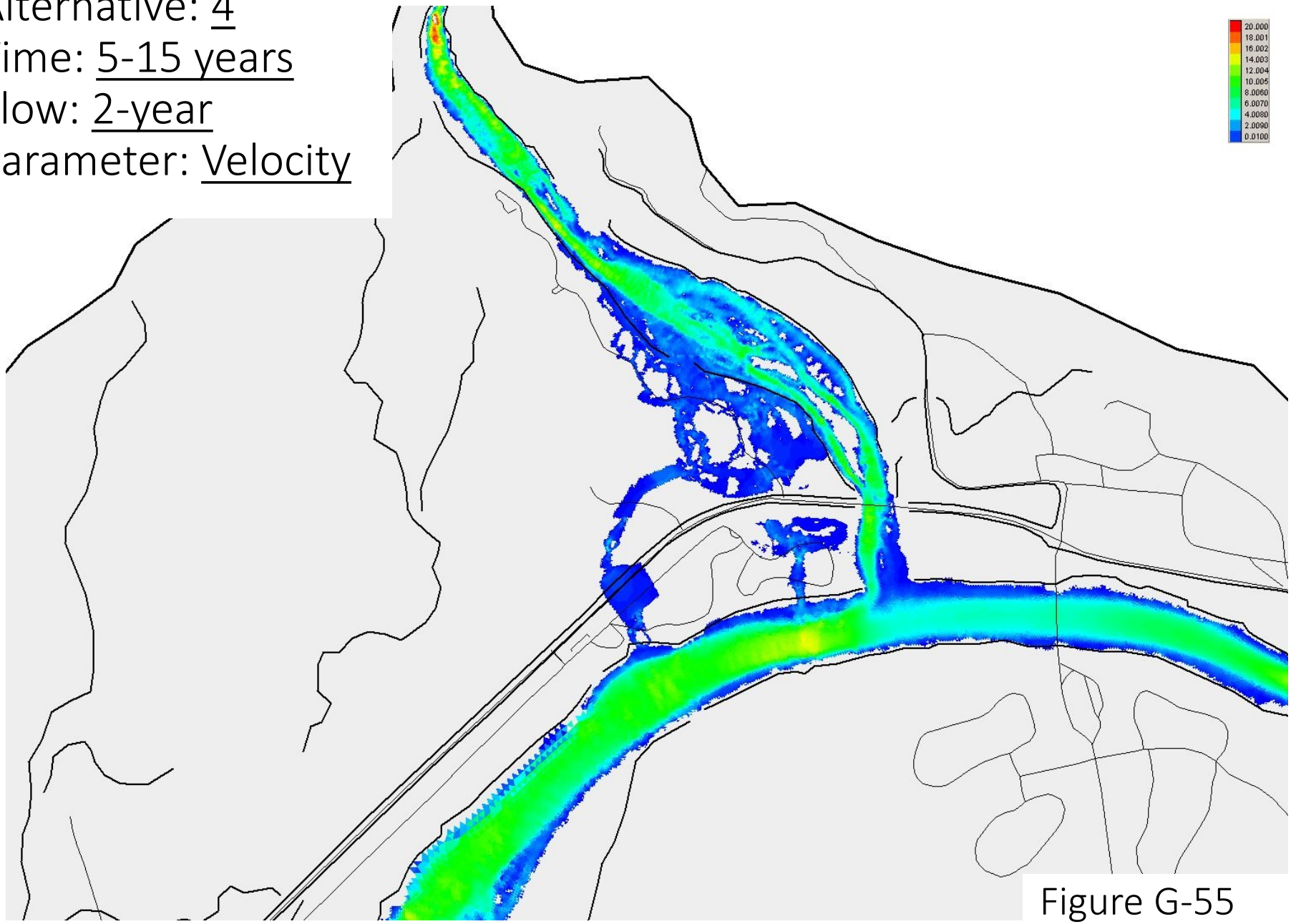

Figure G-55

Alternative: 4
Time: Zero
Flow: 100-year
Parameter: Velocity

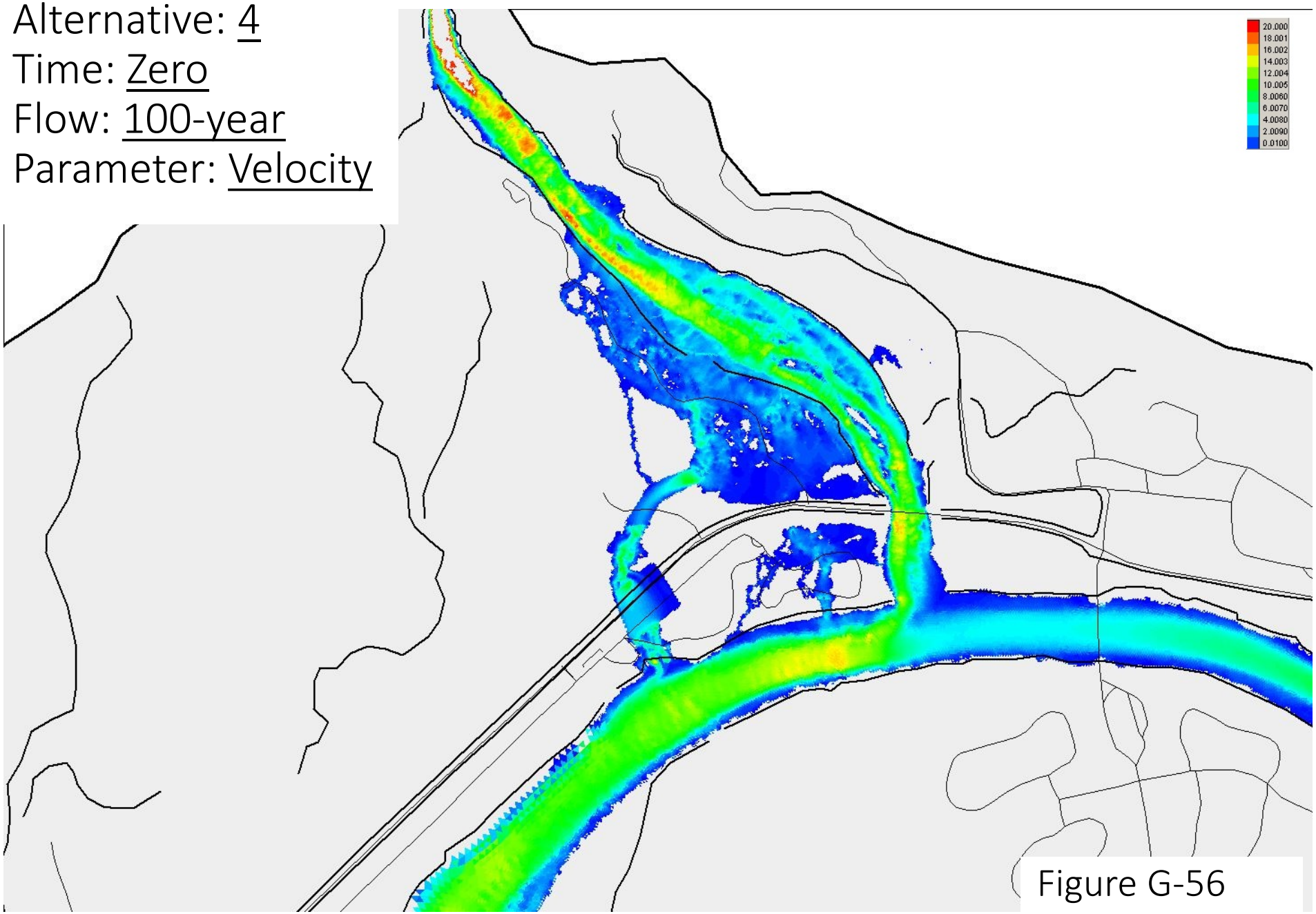

Figure G-56

Alternative: 4
Time: 5-15 years
Flow: 100-year
Parameter: Velocity

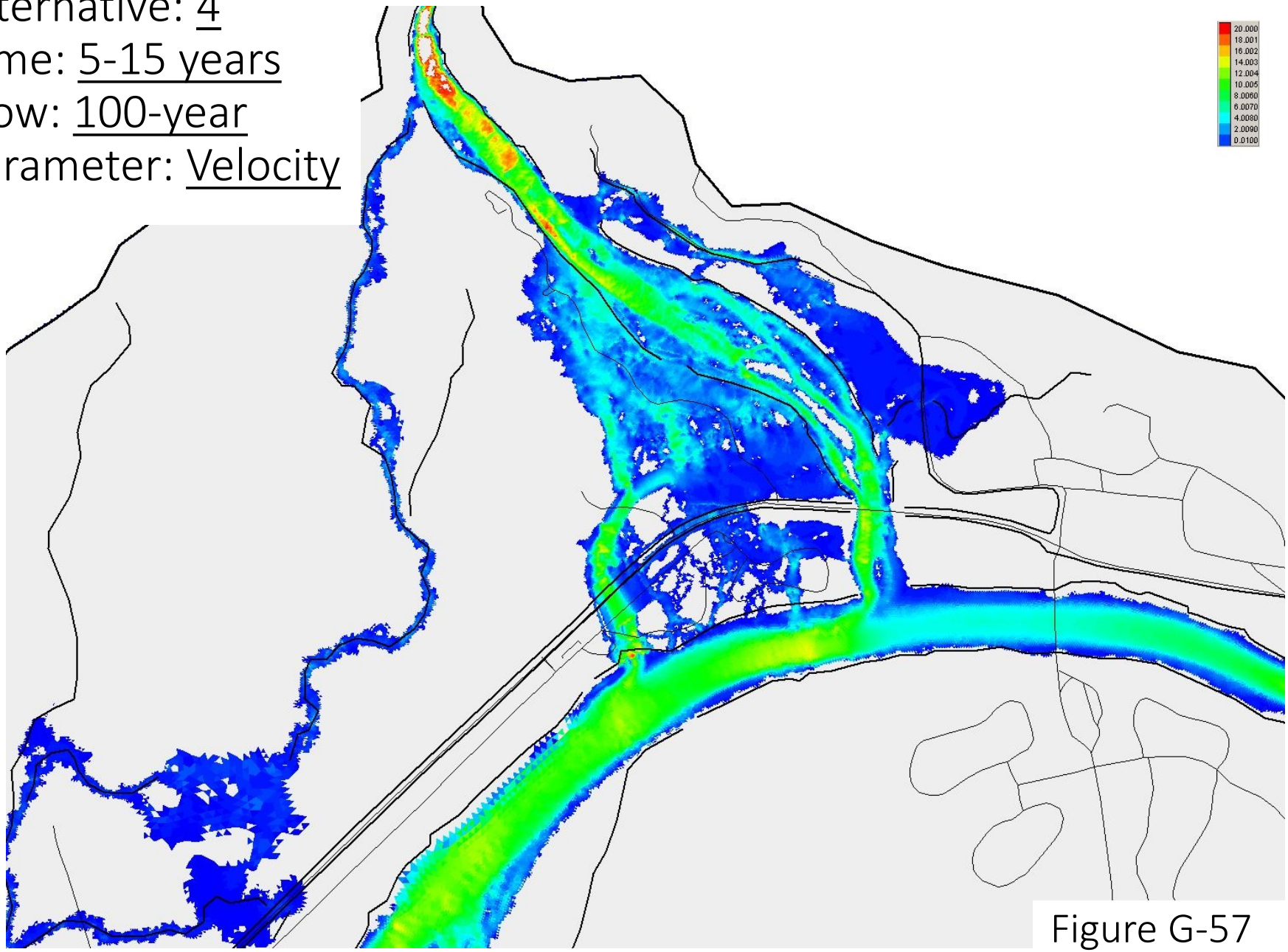

Figure G-57

Alternative: 4
Time: 5-15 years
Flow: Bulked
Parameter: Velocity

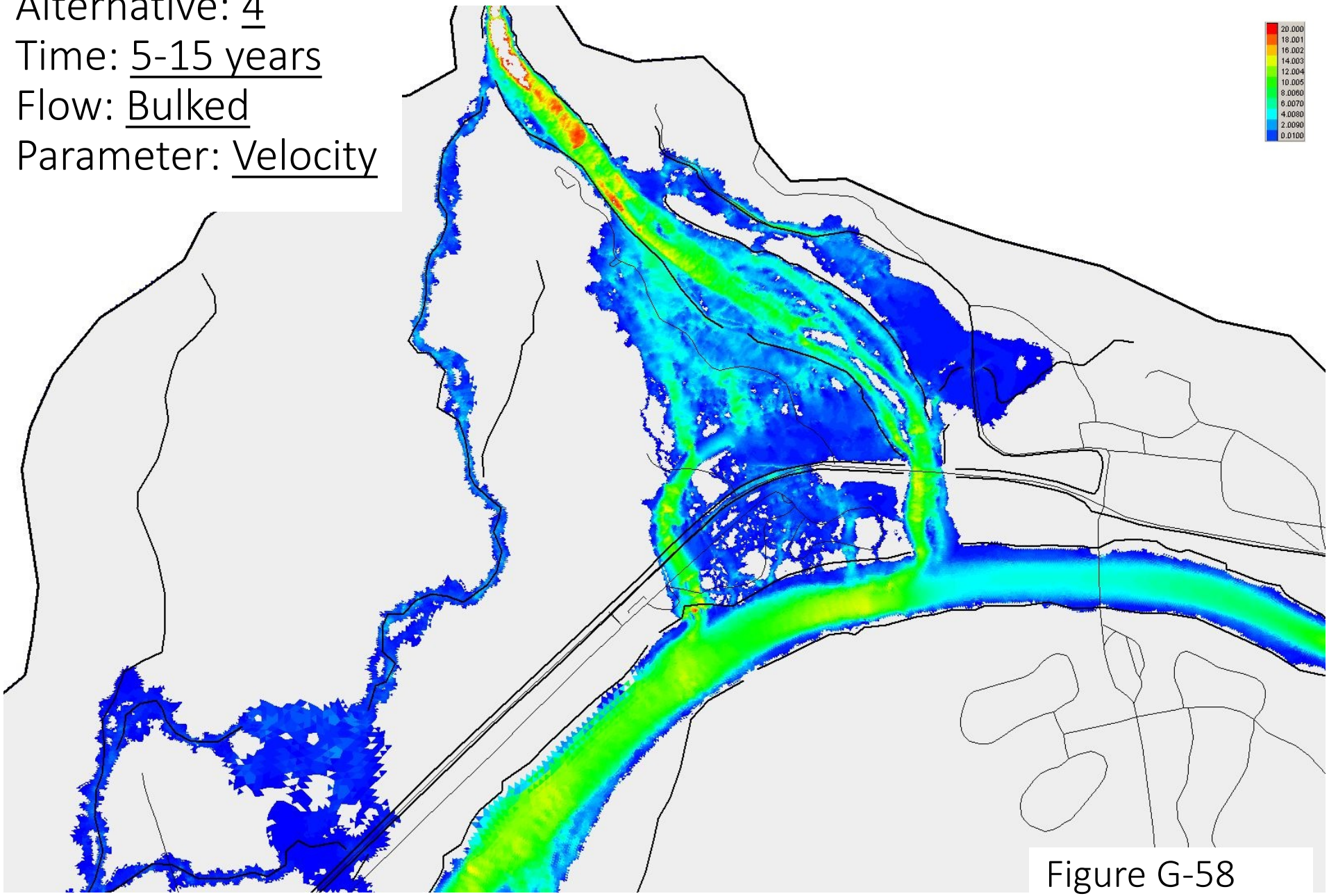

Figure G-58

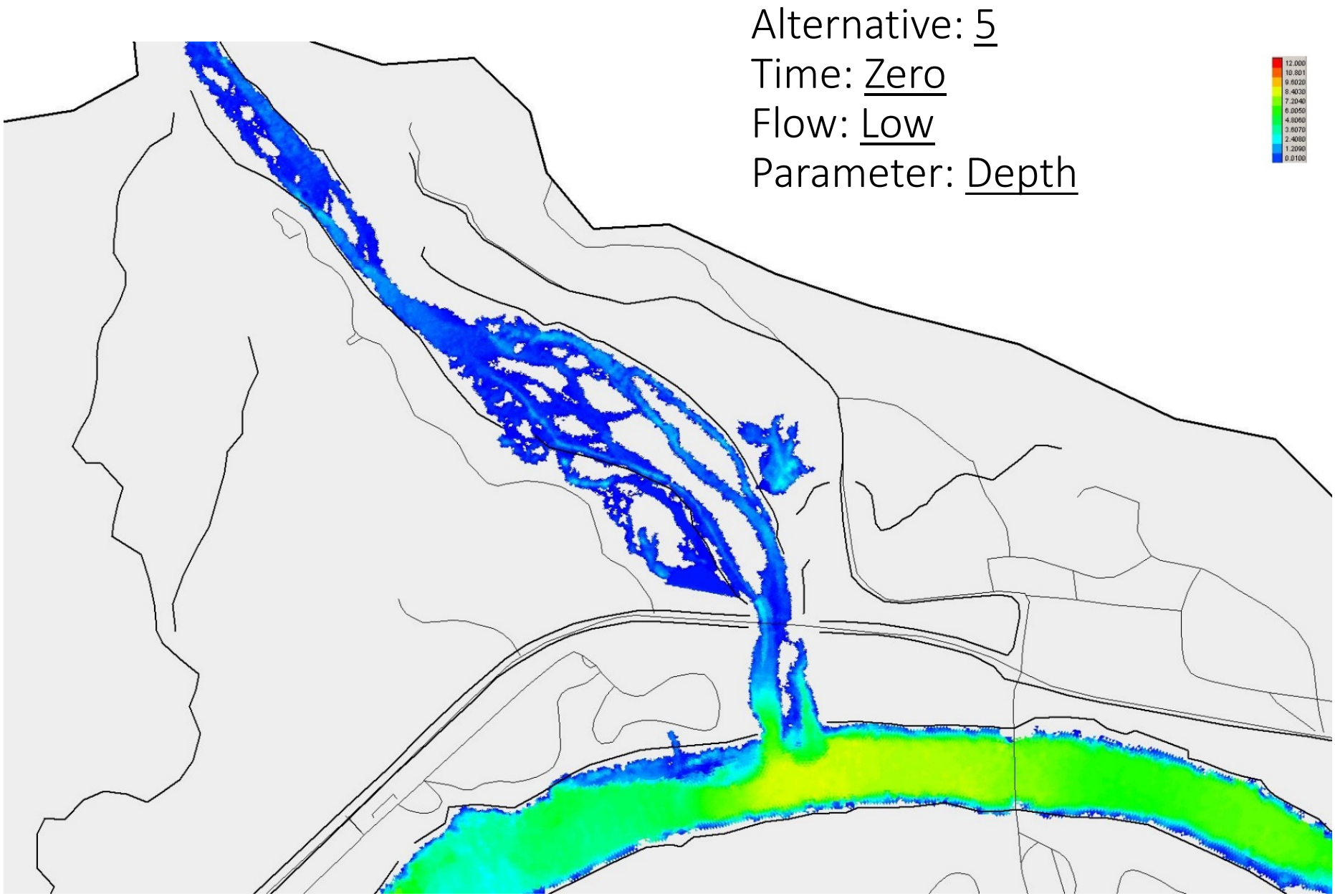
Alternative: 5
Time: Zero
Flow: Low
Parameter: Depth
12.000
10.801
9.6020
8.4030
7.2040
6.0050
4.8060
3.6070
2.4080
1.2090
0.0100

Figure G-59

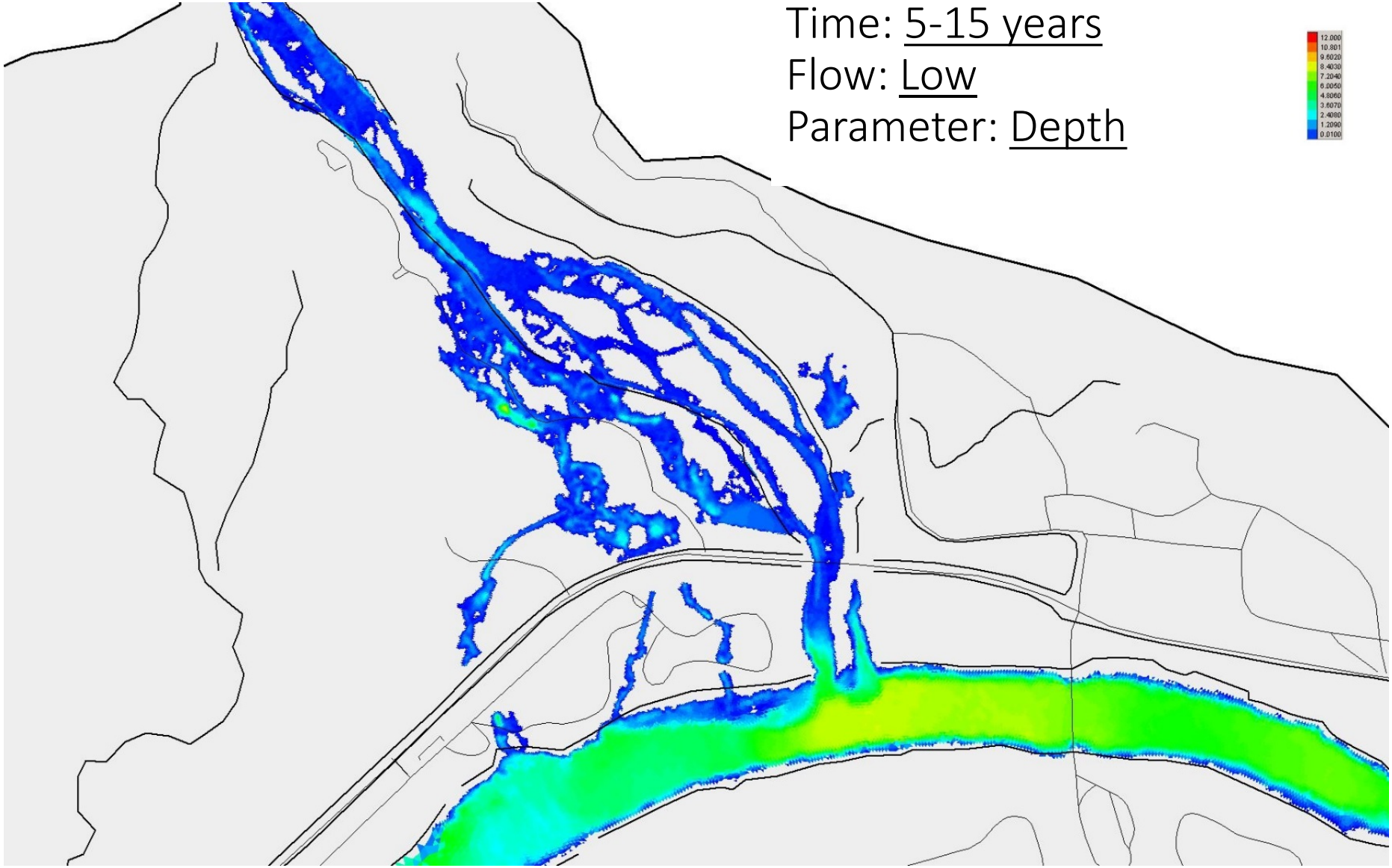
Alternative: 5
Time: 5-15 years
Flow: Low
Parameter: Depth
12.000
10.801
9.6020
8.4030
7.2040
6.0050
4.8060
3.6070
2.4080
1.2090
0.0100

Figure G-60

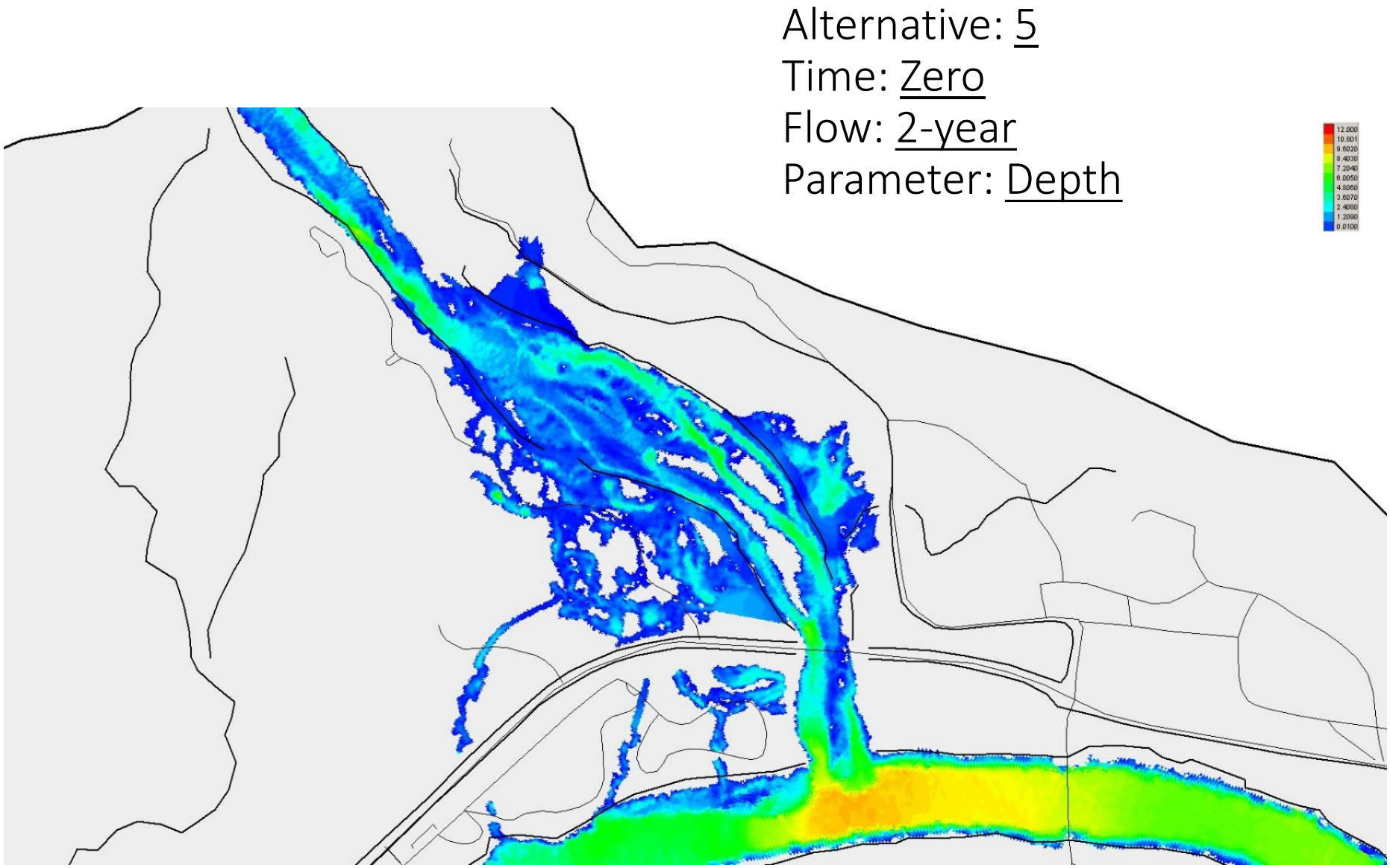
Alternative: 5
Time: Zero
Flow: 2-year
Parameter: Depth
12.000
10.801
9.6020
8.4030
7.2040
6.0050
4.8060
3.6070
2.4080
1.2090
0.0100

Figure G-61

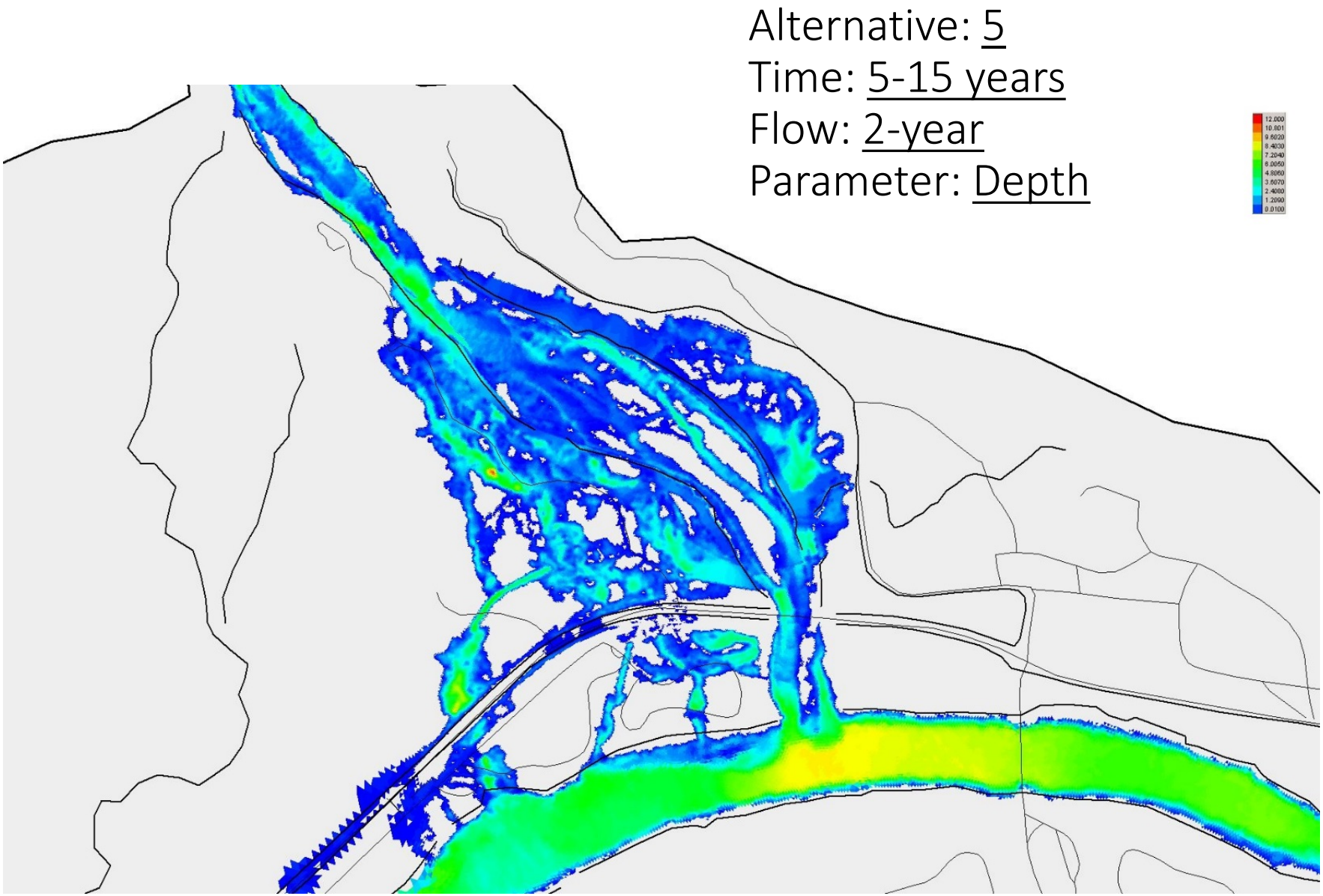
Alternative: 5
Time: 5-15 years
Flow: 2-year
Parameter: Depth
12.000
10.801
9.6020
8.4030
7.2040
6.0050
4.8060
3.6070
2.4080
1.2090
0.0100

Figure G-62

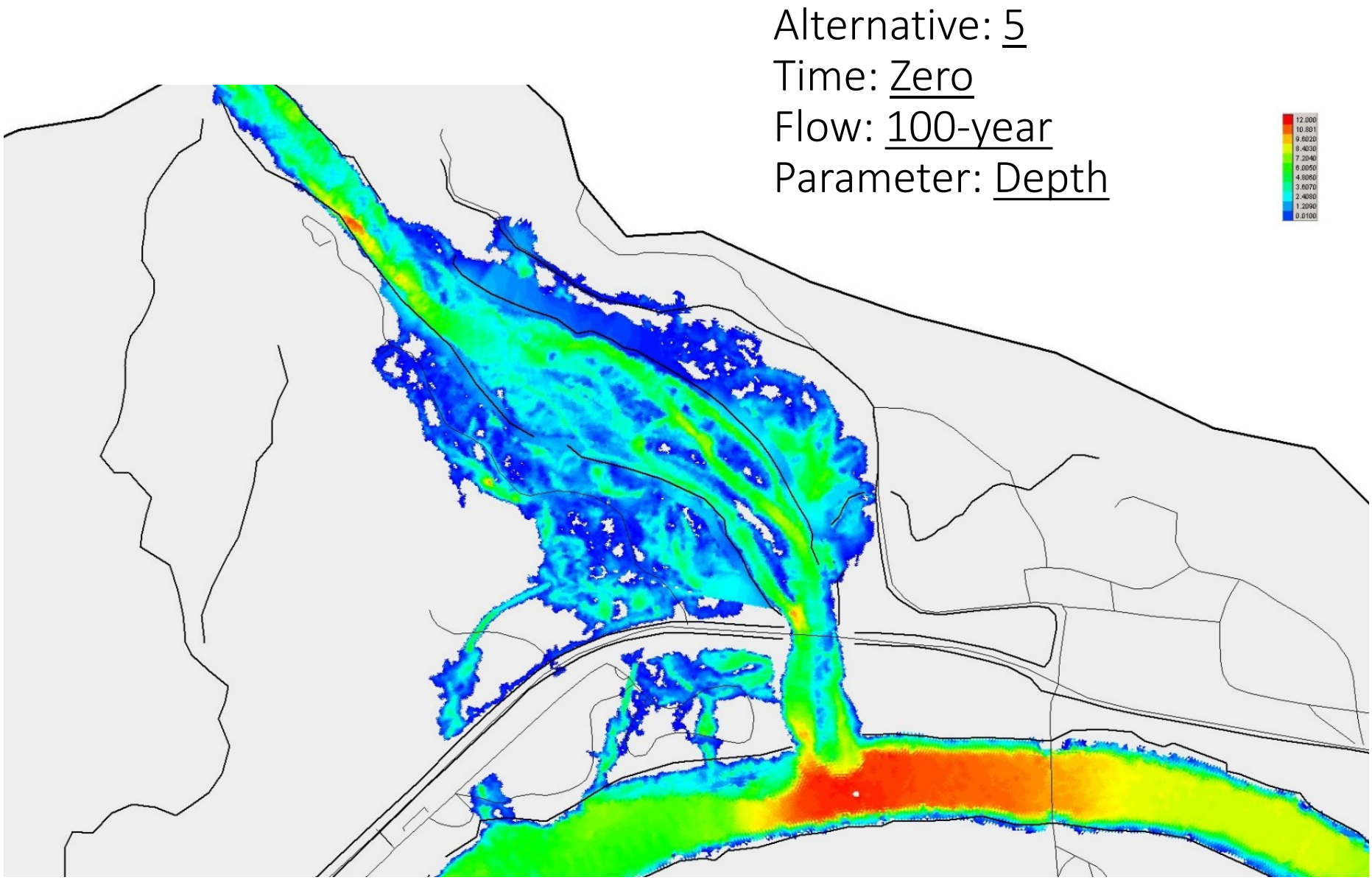
Alternative: 5
Time: Zero
Flow: 100-year
Parameter: Depth
12.000
10.801
9.6020
8.4030
7.2040
6.0050
4.8060
3.6070
2.4080
1.2090
0.0100

Figure G-63

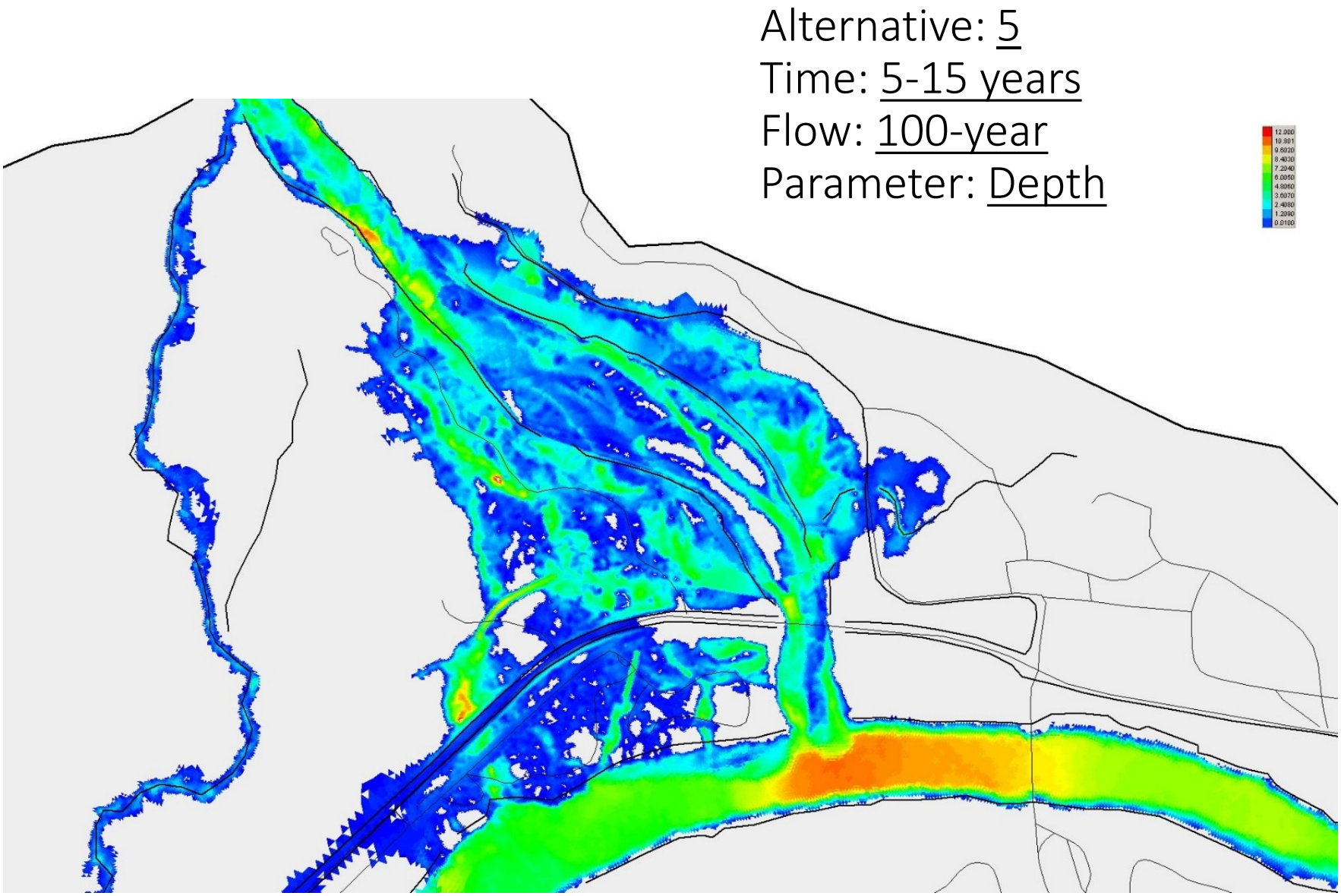
Alternative: 5
Time: 5-15 years
Flow: 100-year
Parameter: Depth
12.000
10.801
9.6020
8.4030
7.2040
6.0050
4.8060
3.6070
2.4080
1.2090
0.0100

Figure G-64

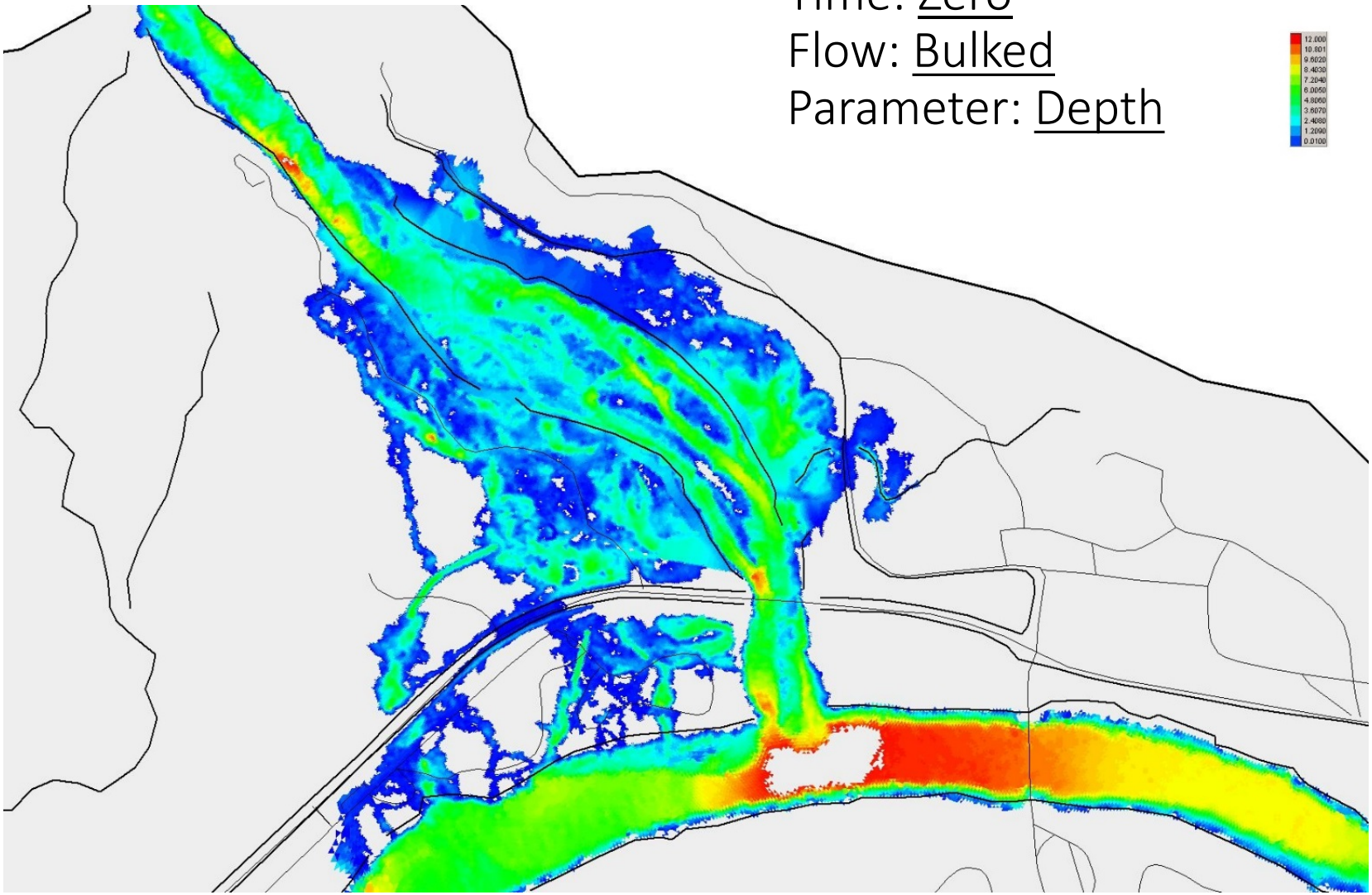
Alternative: 5
Time: Zero
Flow: Bulked
Parameter: Depth
12.000
10.801
9.6020
8.4030
7.2040
6.0050
4.8060
3.6070
2.4080
1.2090
0.0100

Figure G-65

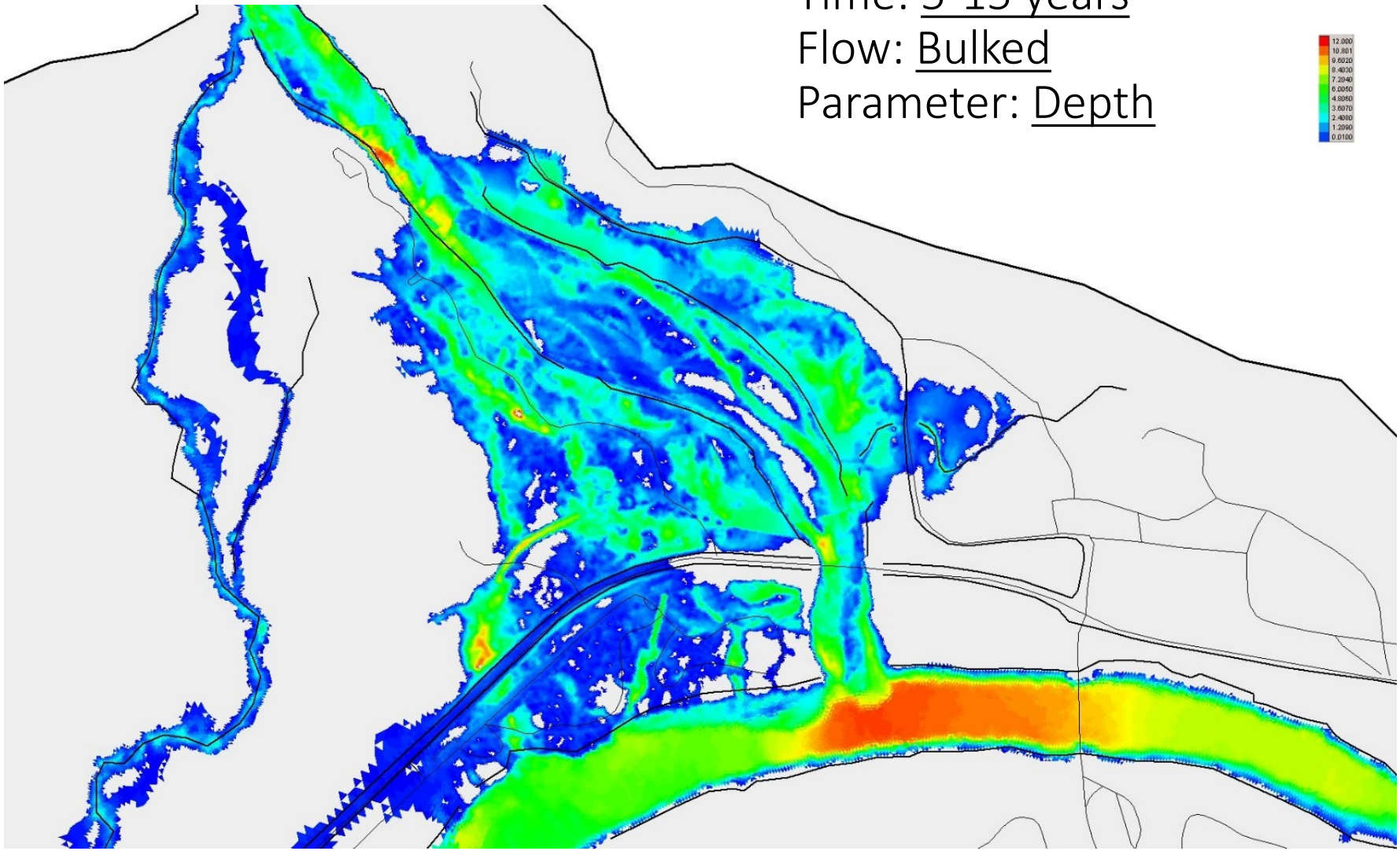
Alternative: 5
Time: 5-15 years
Flow: Bulked
Parameter: Depth
12.000
10.801
9.6020
8.4030
7.2040
6.0050
4.8060
3.6070
2.4080
1.2090
0.0100

Figure G-66

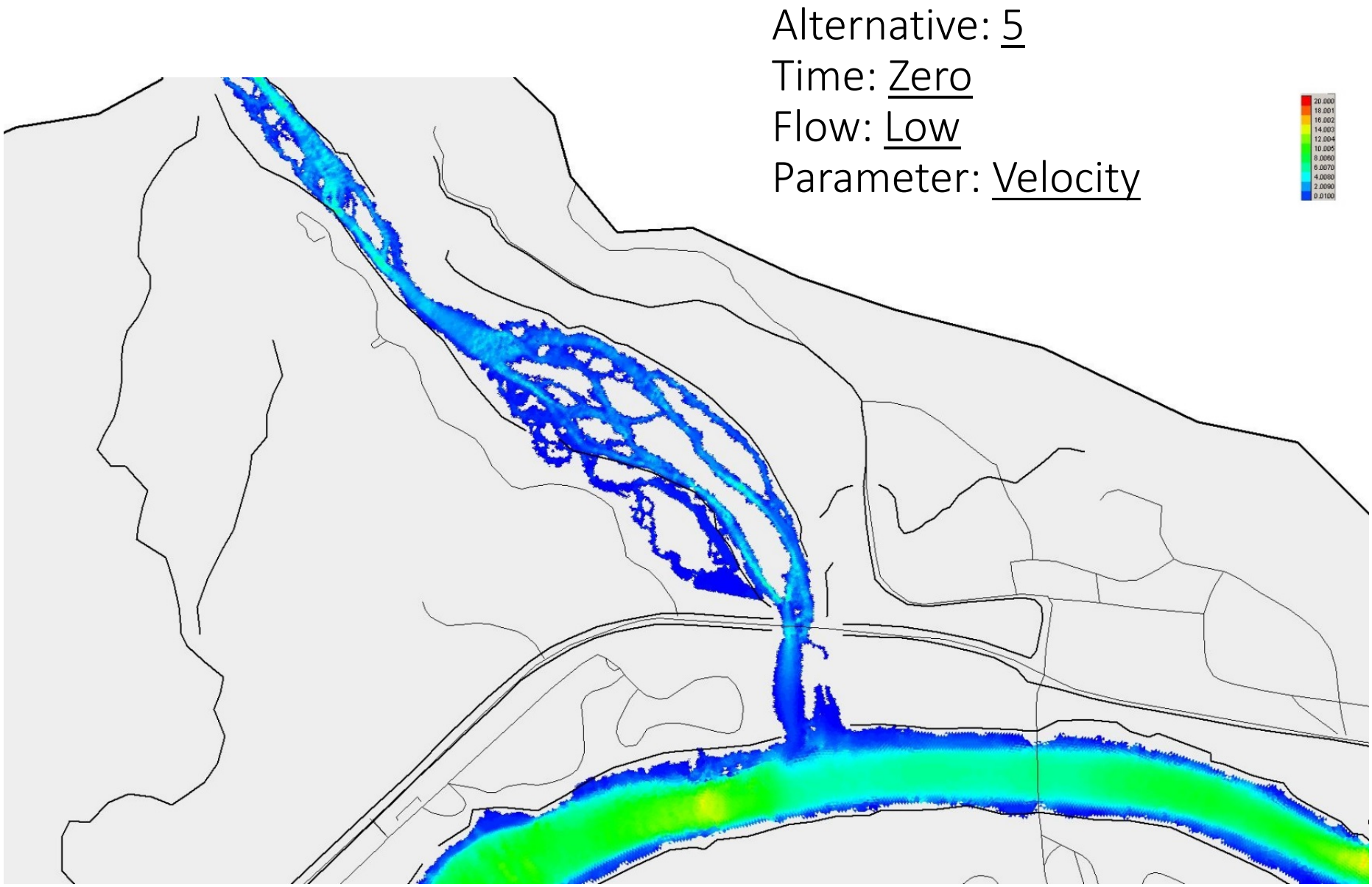
Alternative: 5
Time: Zero
Flow: Low
Parameter: Velocity
20.000
18.001
16.002
14.003
12.004
10.005
8.0060
6.0070
4.0080
2.0090
0.0100

Figure G-67

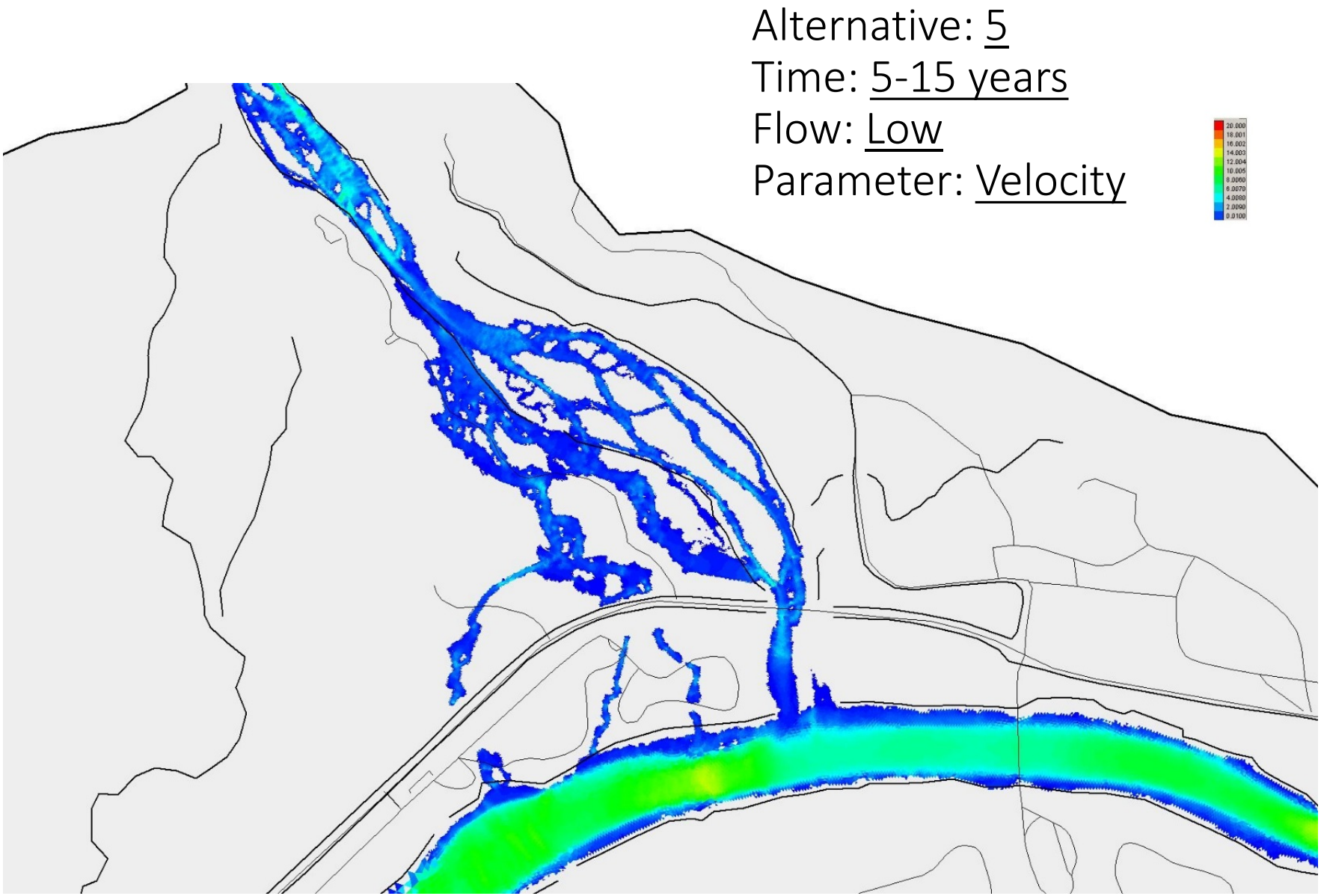
Alternative: 5
Time: 5-15 years
Flow: Low
Parameter: Velocity
20.000
18.001
16.002
14.003
12.004
10.005
8.0060
6.0070
4.0080
2.0090
0.0100

Figure G-68

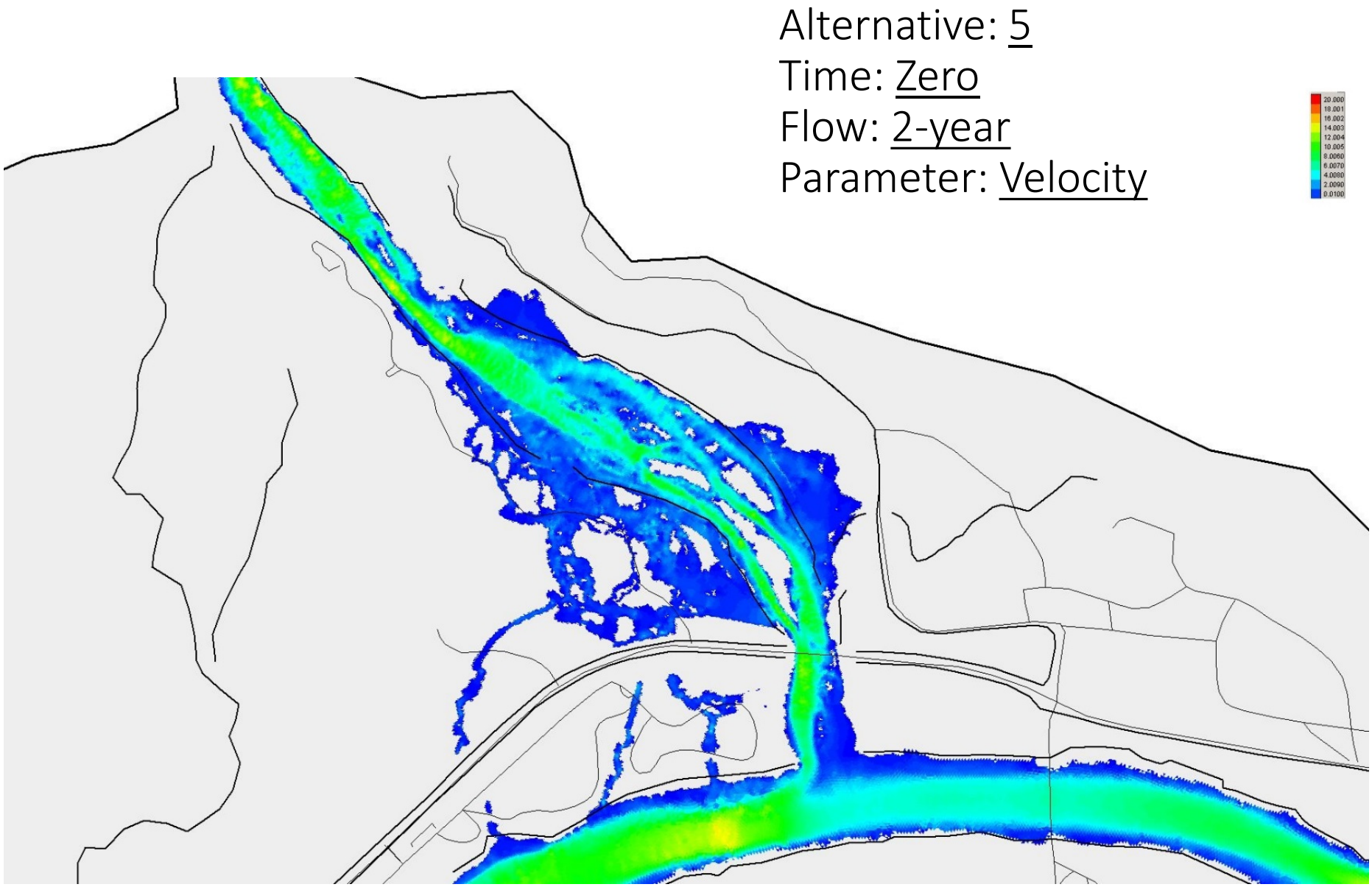
Alternative: 5
Time: Zero
Flow: 2-year
Parameter: Velocity
20.000
18.001
16.002
14.003
12.004
10.005
8.0060
6.0070
4.0080
2.0090
0.0100

Figure G-69

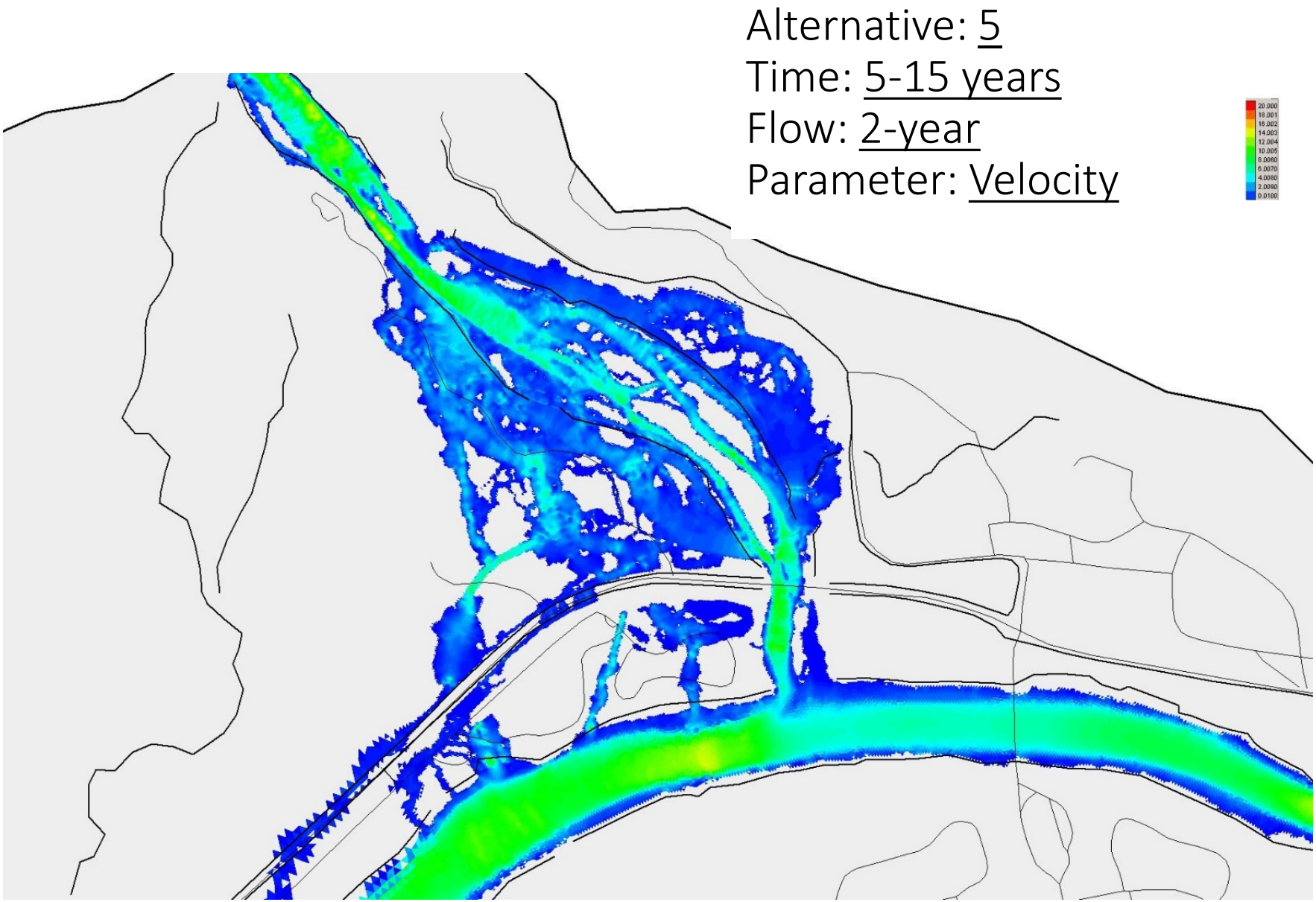
Alternative: 5
Time: 5-15 years
Flow: 2-year
Parameter: Velocity
20.000
18.001
16.002
14.003
12.004
10.005
8.0060
6.0070
4.0080
2.0090
0.0100

Figure G-70

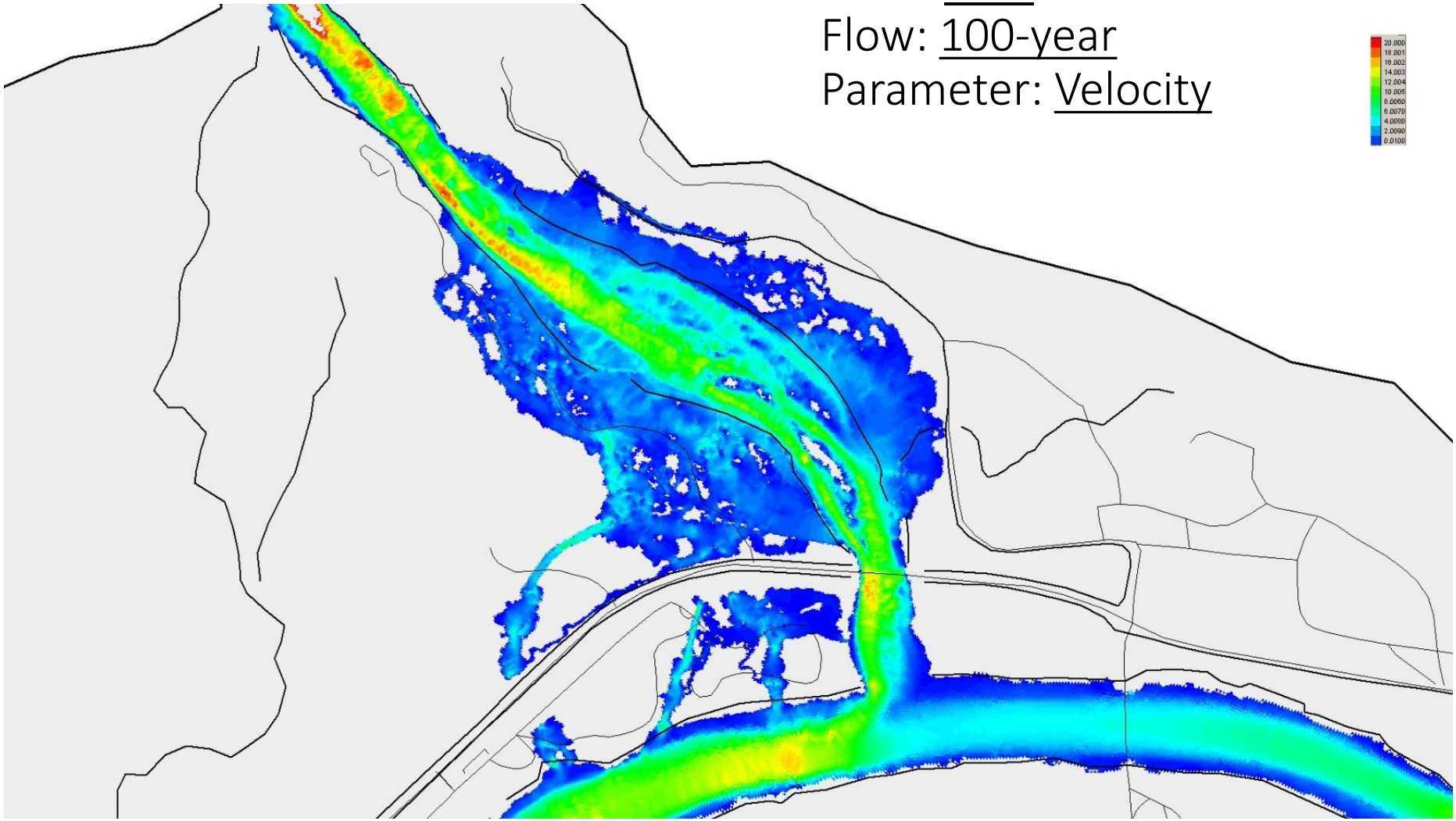
Alternative: 5
Time: Zero
Flow: 100-year
Parameter: Velocity
20.000
18.001
16.002
14.003
12.004
10.005
8.0060
6.0070
4.0080
2.0090
0.0100

Figure G-71

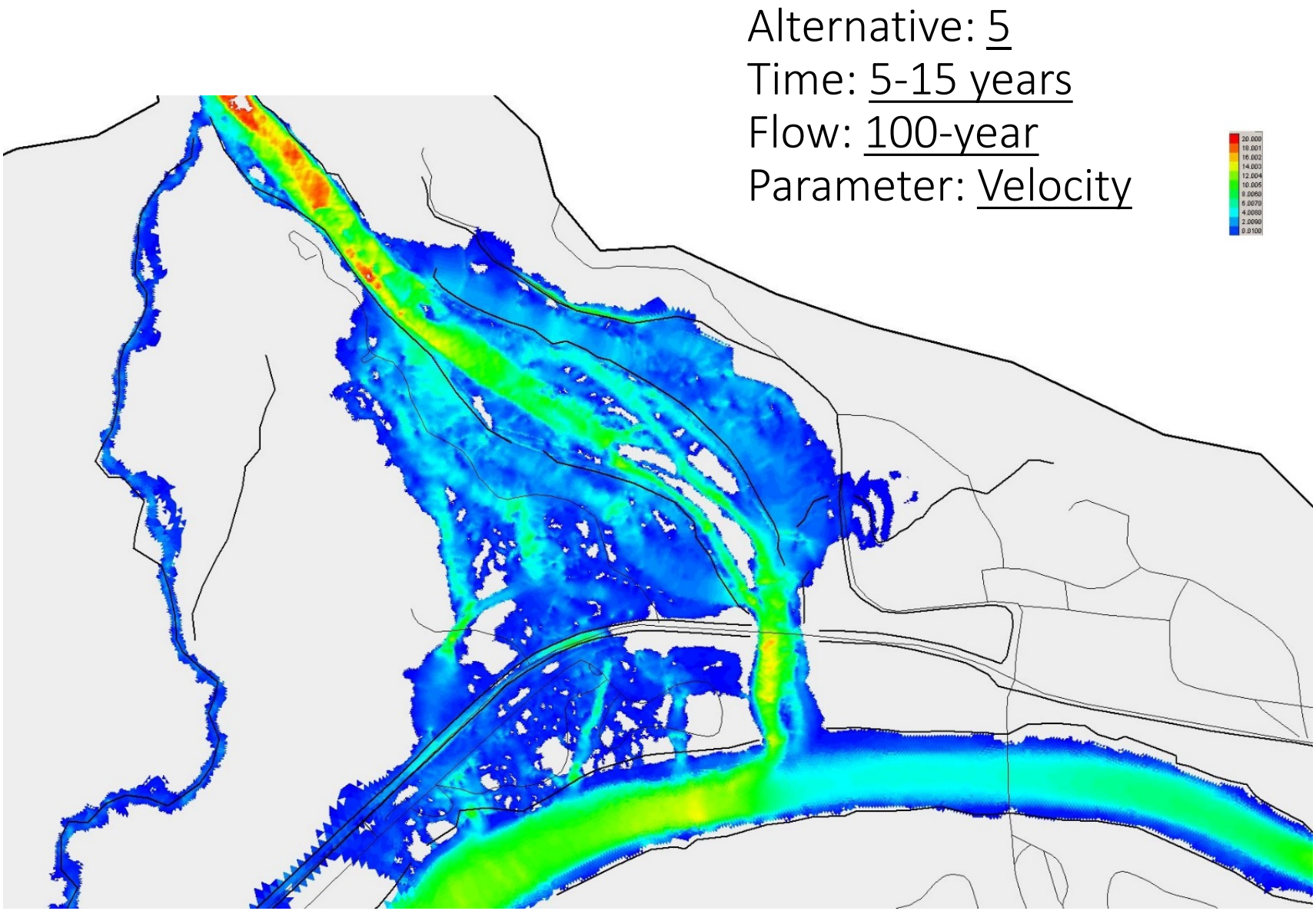
Alternative: 5
Time: 5-15 years
Flow: 100-year
Parameter: Velocity
20.000
18.001
16.002
14.003
12.004
10.005
8.0060
6.0070
4.0080
2.0090
0.0100

Figure G-72

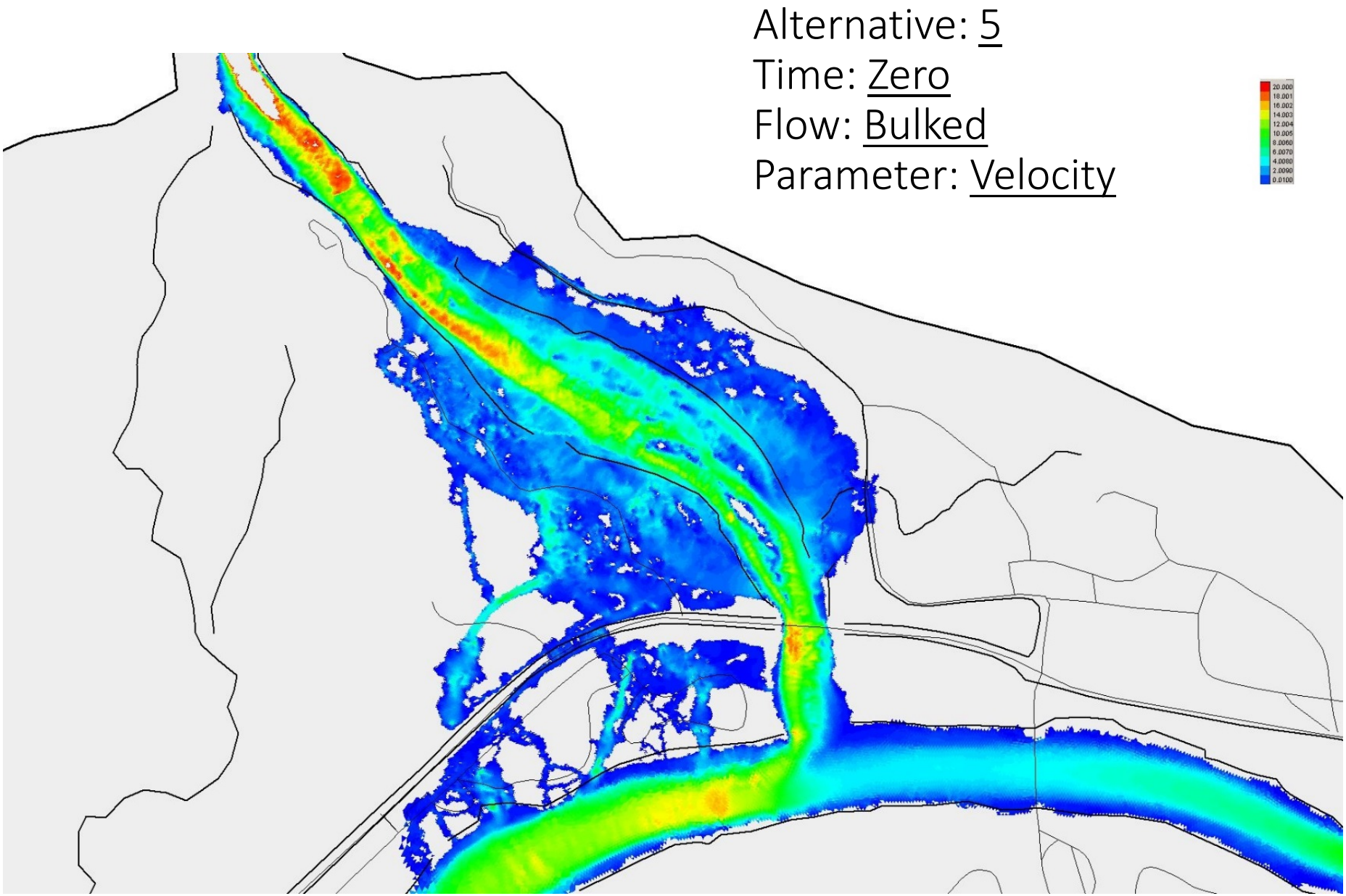
Alternative: 5
Time: Zero
Flow: Bulked
Parameter: Velocity
20.000
18.001
16.002
14.003
12.004
10.005
8.0060
6.0070
4.0080
2.0090
0.0100

Figure G-73

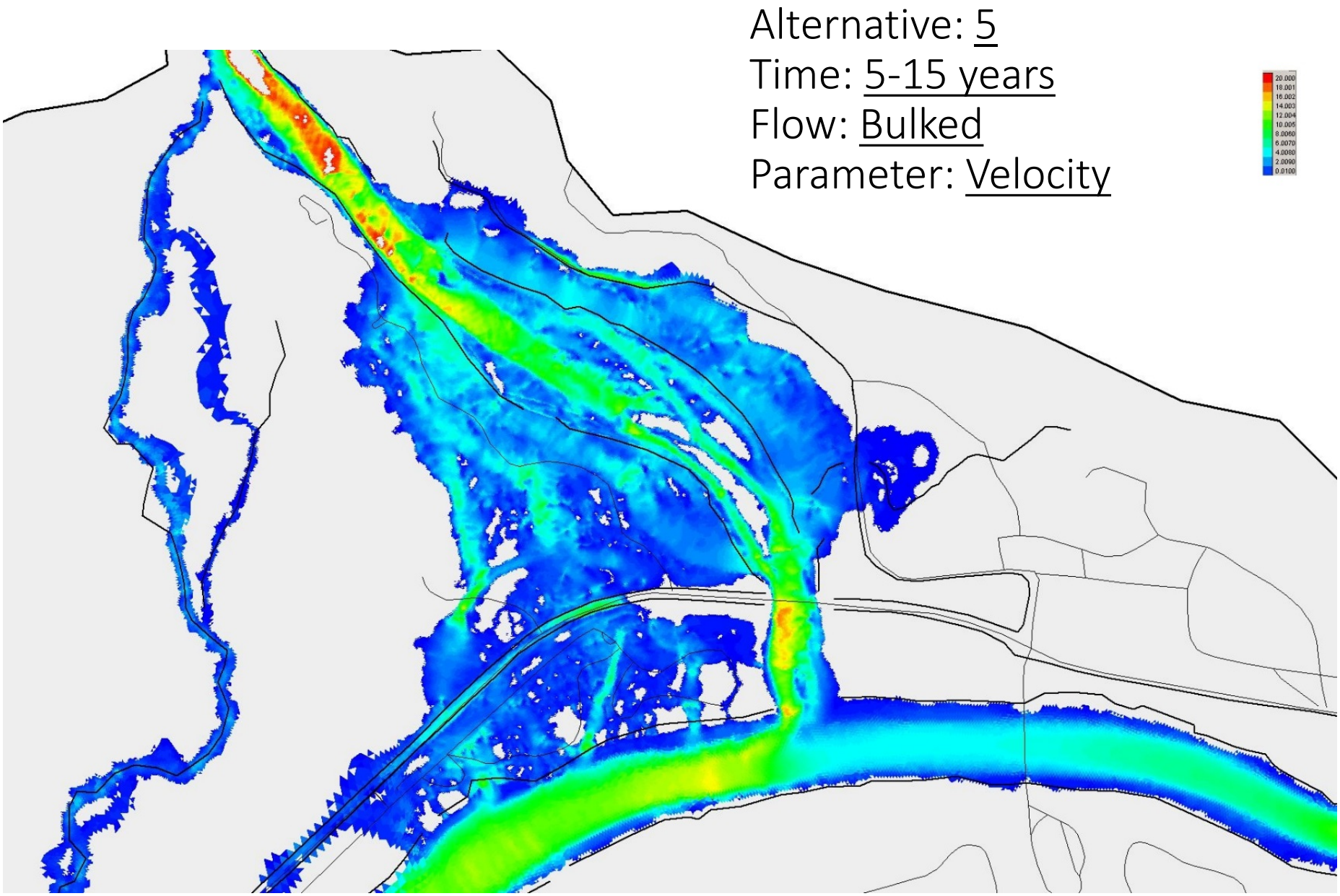
Alternative: 5
Time: 5-15 years
Flow: Bulked
Parameter: Velocity
20.000
18.001
16.002
14.003
12.004
10.005
8.0060
6.0070
4.0080
2.0090
0.0100

Figure G-74