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Key Points:

- Animal burrows are demonstrated to be a serious threat of earthen levee failure
- Internal flow and erosion around a den can cause the collapse of the levee top
- Internal flow may initiate due to direct inflow into the den or den wall failure

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2

Correspondence to:
S. Orlandini,
stefano.orlandini@unimore.it

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Evidence of an emerging levee failure mechanism causing disastrous floods in Italy

Stefano Orlandini[1], Giovanni Moretti[1], and John D. Albertson[2]

[1]Dipartimento di Ingegneria Enzo Ferrari, Università degli Studi di Modena e Reggio Emilia, Modena, Italy, [2]School of Civil and Environmental Engineering, Cornell University, Ithaca, New York, USA

Abstract A levee failure occurred along the Secchia River, Northern Italy, on 19 January 2014, resulting in flood damage in excess of $500 million. In response to this failure, immediate surveillance of other levees in the region led to the identification of a second breach developing on the neighboring Panaro River, where rapid mitigation efforts were successful in averting a full levee failure. The paired breach events that occurred along the Secchia and Panaro Rivers provided an excellent window on an emerging levee failure mechanism. In the Secchia River, by combining the information content of photographs taken from helicopters in the early stage of breach development and 10 cm resolution aerial photographs taken in 2010 and 2012, animal burrows were found to exist in the precise levee location where the breach originated. In the Panaro River, internal erosion was observed to occur at a location where a crested porcupine den was known to exist and this erosion led to the collapse of the levee top. This paper uses detailed numerical modeling of rainfall, river flow, and variably saturated flow in the levee to explore the hydraulic and geotechnical mechanisms that were triggered along the Secchia and Panaro Rivers by activities of burrowing animals leading to levee failures. As habitats become more fragmented and constrained along river corridors, it is possible that this failure mechanism could become more prevalent and, therefore, will demand greater attention in both the design and maintenance of earthen hydraulic structures as well as in wildlife management.

1. Introduction

Burrowing animals are acknowledged by agencies responsible for earthen dams and levees to have an adverse impact on the integrity of these flood control structures [e.g., *Federal Emergency Management Agency*, 2005]. Such degradation of earthen dams and levees have been observed in the field, and advanced methods for the continuous monitoring of these structures have been proposed [*Chlaib et al.*, 2014; *Perri et al.*, 2014]. Only a few papers, however, have explicitly and mechanistically connected piping erosion responsible for the failure of earthen structures to preferential flow extending along paths developed by burrowing animals [*Carroll*, 1949; *Masannat*, 1980; *Bayoumi and Meguid*, 2011]. Information about wildlife activity and related earthen structure safety is generally limited to the gray literature and maintenance reports [e.g., *Federal Emergency Management Agency*, 2005]. Wildlife activity is not even mentioned among the relevant factors causing the failure of earthen dams and levees in many classical geotechnical engineering textbooks and specific technical reports [e.g., *Terzaghi et al.*, 1996; *Resio et al.*, 2011]. In fact, animal burrows are still rarely acknowledged by engineers, technicians, and land managers to be a serious threat of dam and levee failure.

On the other hand, wildlife activity along fluvial systems is rapidly increasing in many regions of the world as a result of the institution of fluvial parks acting efficiently as wildlife movement corridors [*Soulé and Gilpin*, 1991; *McEuen*, 1993; *Bennett*, 1999]. There is therefore an urgent need to raise awareness about the emergent risk connected to impacts on earthen flood control structures of animals, including added pressures by invasive species, habitat fragmentation and shifts, as often driven by development and climate pressures. Relevant pieces of the puzzle are available. For example, extensive biological studies exist on the structure and function of wild animal dens [e.g., *Reynolds and Wakkinen*, 1987; *Roper*, 1992a; *Monetti et al.*, 2005]. In addition, several attempts have been made to provide a hydraulic characterization of natural pipes subjected to flow and internal erosion processes [e.g., *Wilson et al.*, 2012]. However, the full picture has not yet been examined at the field scale in the context of a documented failure. Key broader research questions that need to be addressed include the following:

1. What are the ecological processes that drive burrowing animals to interact with earthen flood control structures?
2. What are the geophysical interactions between water flows and disturbed earthen structures?
3. What are the triggers of failure mechanisms affecting disturbed earthen structures?

This paper seeks to address the last two questions, while motivating work on the first question and raising awareness for design, maintenance, and risk considerations. Furthermore, within a scientific context in which ecohydrology has been expanding the appreciation for the importance of biological and physical connections in hydrology, a parallel set of interactions are highlighted here with invasive animal species behavior and impacts on hydrological and geotechnical function. The investigation reported in this paper provides observational evidence of the role played by burrowing animals in the disastrous levee failure occurred on 19 January 2014, along the Secchia River, Northern Italy. In addition, a mechanism causing the failure of earthen levees disturbed by burrowing animals is revealed by the observation of a second levee failure that occurred in the same day, under similar hydroclimatic and levee conditions, along the neighboring Panaro River. Finally, hypotheses on the related triggering processes are explored through detailed numerical modeling of rainfall, river flow, and variably saturated flow occurring in disturbed levees in response to complex hydroclimatic forcing.

2. Driving Forces

2.1. Disastrous Levee Failure on the Secchia River

On 19 January 2014, a levee failure occurred along the Secchia River at San Matteo, Northern Italy ($44^\circ 41' 57.85''$N, $10^\circ 56' 41.68''$E, Figure 1a). The breach formed on the right side of the river system (from the perspective of looking downstream) was first observed in the morning around 6:30. Since a rapid repair was impracticable at that time, the breach developed by releasing to the surrounding plain a water volume of about 36×10^6 m^3 with a peak flow discharge of about 434 m^3 s^{-1} (section A1). The ultimate extent of the flooded area was about 52 km^2 and the estimated flooding damage was in excess of \$500 million (Figure 1). The levees of the Secchia River are, at least in the perspective of the present investigation, representative of the levee systems developed in the Po Valley from the sixteenth century and now extending for about 2300 km (levees on both sides of the river) along the Po River and its tributaries. The Po Valley is the most densely populated and economically developed area in Italy.

The Secchia River flood was produced by a stratiform rainfall event that released an areal rainfall depth of about 125 mm over a 1305 km^2 contributing drainage basin. The total rainfall volume was about 163×10^6 m^3. About 65% of this volume entered the Rubiera flood control reservoir as flood volume (Figure 1). In addition to the high precipitation depth that occurred in the contributing drainage basin of the Secchia River, convective thunderstorms occurred in the low-gradient portion of the fluvial system extending downstream from Rubiera during the flood wave propagation, thus directly wetting the levee from above. The spatial distribution of rainfall depth that occurred around the location of the breach is represented by the radar image reported in Figure 2a. The rainfall hyetographs obtained by combining rain gauge and radar data for the locations of San Matteo, along the Secchia River, and Via Tronco, along the Panaro River, are reported in Figures 2b and 2c, respectively [*Orlandini and Morlini*, 2000]. These rainfall events were atypical for the considered area in the month of January. Normally winter precipitation falling in the mountainous portion of the drainage basin is in the form of snow, and thunderstorms occur normally in the low-gradient portion of the fluvial system in summer.

The flood hydrographs from December 2013 and January 2014 at the cross section of the failed levee were reconstructed by developing a level pool routing model and a dynamic wave model (section A1). Reconstructed flow discharge and river stage for the period 17–22 January 2014 are reported in Figures 3a and 3b, respectively. The breach flow loss was computed by incorporating into the dynamic wave model an explicit description of the breach evolution, obtained from photographs taken during the event (Figure 4). The combined use of observations and models yielded the results reported in Figure 3, revealing that (1) the maximum stage reached by the river flow in January 2014 was about 1.5 m below the top of the levee and (2) the magnitude of the peak river stage and the duration of high river stages along the Secchia River in January 2014 were smaller than the corresponding quantities observed in previous events such as, for instance, those observed in December 2009 (Figure 3b).

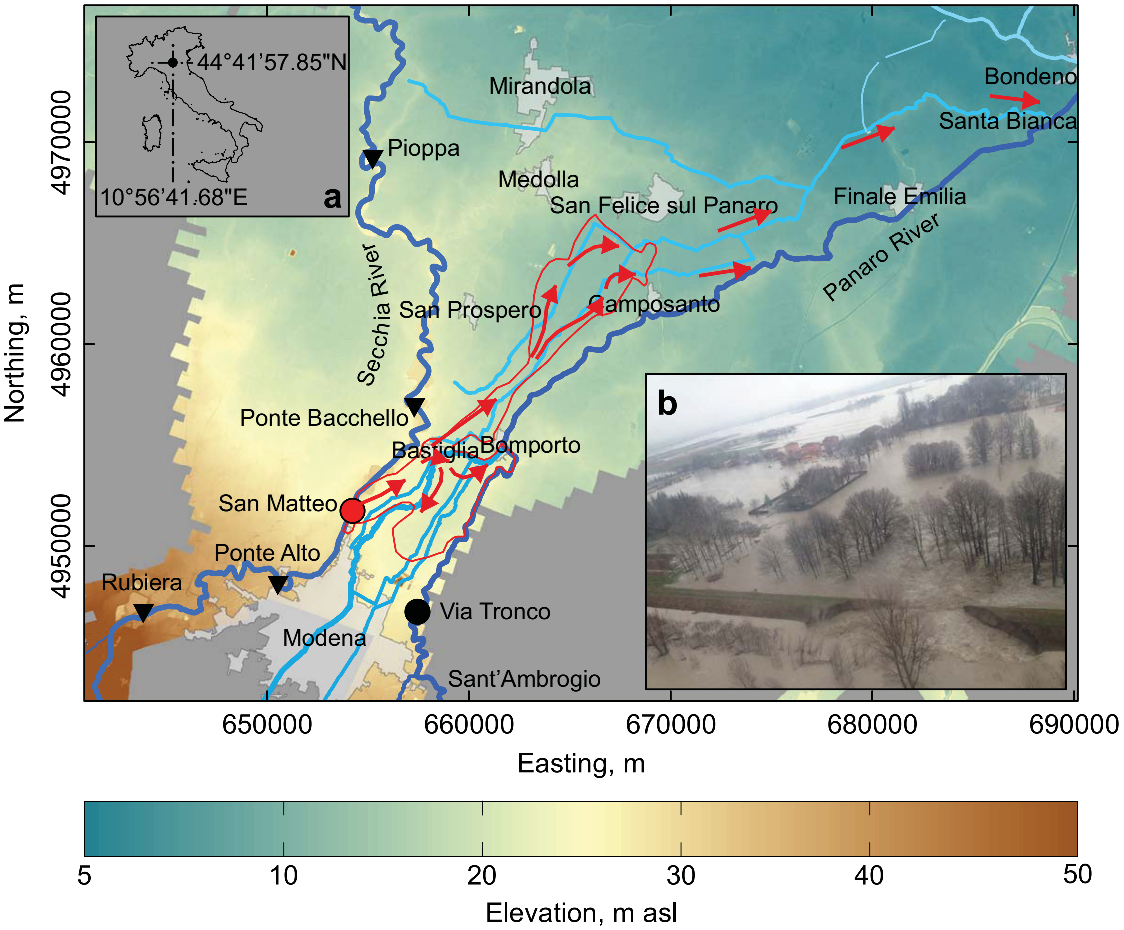

Figure 1. (a) Map of the land flooded after the levee failure occurred along the Secchia River at San Matteo (Northern Italy) on 19 January 2014. (b) The delineation of the flooded areas is based on aerial surveys carried out by the Civil Protection as part of the emergency response plan for the occurred disaster. A volume of water of about 36×10^6 m^3 (Figure 3a, area under the breach loss hydrograph) left the Secchia River by flooding (red arrows) an area of about 52 km^2. Topographic gradients and barriers are shown by the 1 m resolution digital elevation model reported in the background.

2.2. Wildlife Impact on the Levee

Evidence of wildlife impact on the failed levee was derived from the analysis of 10 cm resolution aerial photographs taken in 2010 and 2012 (Figures 5a and 5b, respectively). This evidence was confirmed by field inspection of the Secchia River after the disaster (Figure 5c). More generally, extensive field inspection conducted along the Secchia and Panaro Rivers revealed an emergent risk connected to the activity of crested porcupines *Hystrix cristata* (Linnaeus, 1758), European badgers *Meles meles* (Linnaeus, 1758), red foxes *Vulpes vulpes* (Linnaeus, 1758), and nutria *Myocastor coypus* (Molina, 1758) (insets A, B, C, and D, respectively, in Figure 5c). The information of the photographs taken from helicopters in the early stage of breach development, at 10:11 and 12:22 (Figure 4), and of previously taken aerial photographs (Figures 5a and 5b) were combined to determine the precise location of the levee where the failure mechanism originated (section A2). Animal burrows (B1, B2, B3, and B4) were found to exist in the levee location where the breach originated (Figures 5a and 5b). In addition, terrain analysis based on a 1 m resolution digital elevation model (DEM) generated from a lidar survey revealed the positions of the animal burrows observed in Figure 5b along the cross section of the failed levee (section A2). Results are reported in Figure 6.

3. Failure Mechanism

The breach that occurred along the Secchia River on 19 January 2014 (Figures 1 and 4) was first detected at 6:30. It has been reported by several observers that the breach developed from above and that a large erosive flow was spilling out from the river to the landside bank of the levee at the time of the detection. Given

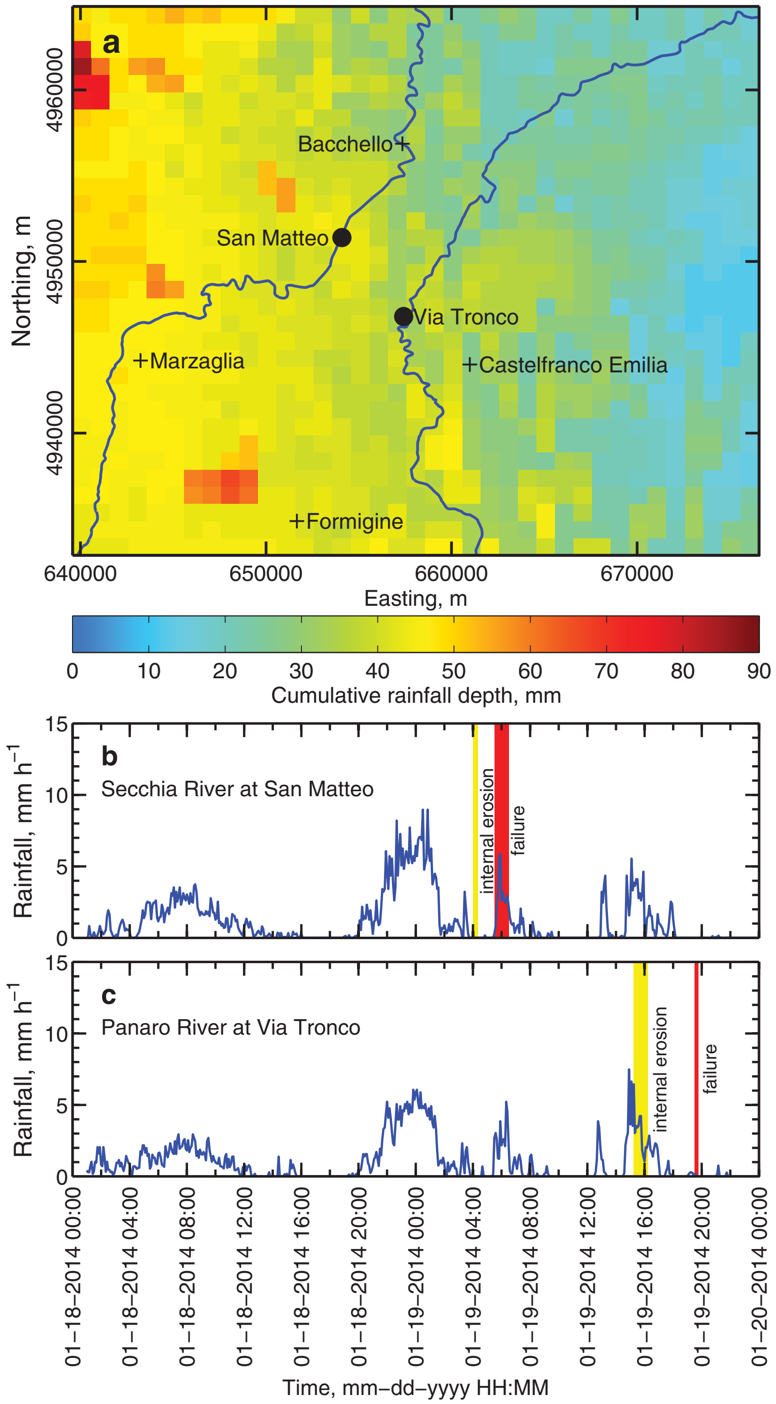

Figure 2. Rainfall occurred along the Secchia and Panaro Rivers in the period of time from 18 January 2014 at 2:00 to 19 January 2014 at 2:00. A radar image at 1 km × 1 km spatial resolution of the cumulative rainfall depth is shown in Figure 2a. The hyetographs extracted from radar images at 5 min temporal resolution, for the locations of the levee failures occurred along the Secchia River at San Matteo and the Panaro River at Via Tronco, are shown in Figures 2b and 2c, respectively. The estimated times at which the internal erosion was triggered and levee failure occurred are indicated in Figures 2b and 2c by the yellow and red bands, respectively.

the advanced state of development of the breach at the time of the detection, no attempt to repair the altered levee was readily possible. While the observed clues are helpful, nonetheless, the failure mechanism causing the breach along the Secchia River was not entirely observed. Therefore, plausible hypotheses about the actual failure mechanism and the related triggering processes are explored here.

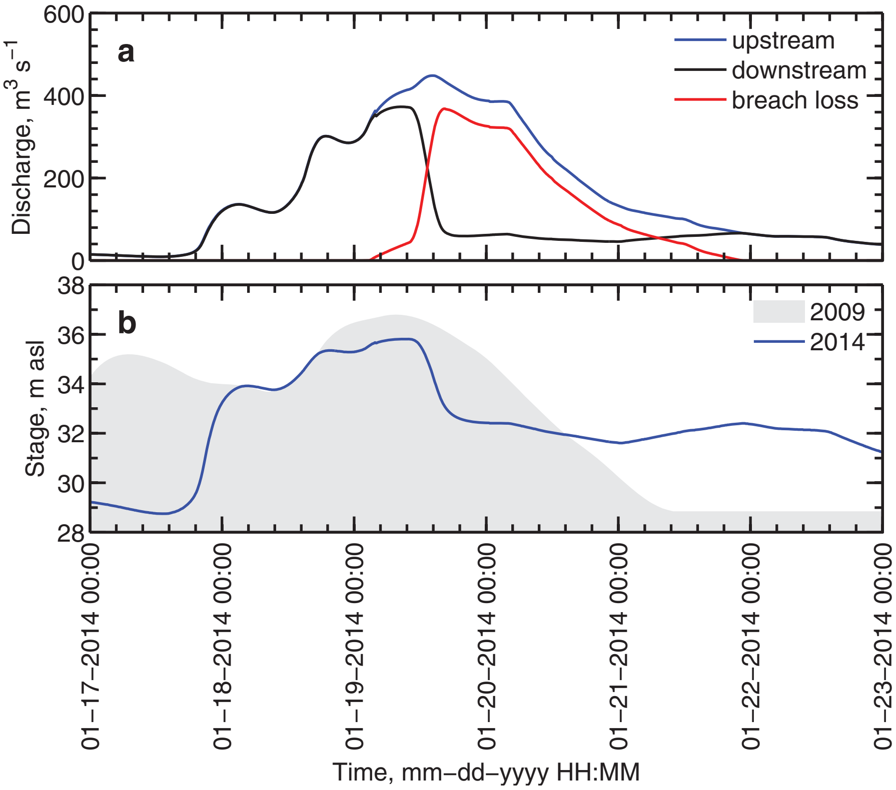

Figure 3. Reconstructed flow discharges (Figure 3a) and river stages (Figure 3b) at the cross section of the Secchia River at San Matteo where the levee failure occurred. A longer simulation period (from 22 December 2013 at 0:00 to 3 February 2014 at 24:00) than that reported in Figures 3a and 3b was considered to provide a sound analysis of the hydraulic response of the levee to the river stage forcing. The flood hydrograph occurred in December 2009 (from 23 December 2009 at 14:00 to 28 December 2009 at 14:00) is reported in the background of Figure 3b to enable a visual comparison.

The examination is aided by a related event. In the afternoon of the same day (19 January 2014), the early stage of a levee failure was observed along the Panaro River under similar hydroclimatic conditions (Figure 7a). The failure mechanism can realistically be inferred to be similar to that which occurred along the Secchia River.

3.1. Repaired Levee Failure on the Panaro River

Having observed the disastrous levee failure along the Secchia River, the technical staff of the responsible agency, the “Agenzia Interregionale per il Fiume Po,” and of the Civil Protection executed an emergency response plan by closely watching the levee systems of the Secchia and Panaro Rivers. On 19 January 2014, a developing internal erosion process was observed on a levee along the Panaro River at Via Tronco (Figure 1), at a site where a crested porcupine den was known to exist (Figure 7). The internal erosion process shown in Figure 7a (inset A) was observed at 16:01 on 19 January 2014, but it most likely started at least 1 h before, as indicated by the ponding depth of turbid water lying on the soil surface at the landside of the levee in Figure 7a. The internal flow and erosion processes depicted in Figure 7a are focused at the den of a crested porcupine (inset A of Figure 5c) that was observed and had been filled with earth in the past. The internal erosion process was observed to continuing developing during the period of time from about 16:01 to 19:50 as sketched in the inset 1 of Figure 7b. At about 19:50, the top of the levee was observed to collapse on the gallery caused by internal erosion as sketched in the inset 2 of Figure 7b. The levee top then, lowered by about 3 m, would have been further eroded and overtopped by a river flow loss if a rapid repair operation were not carried out by filling the breach with earth and compacting this earth with an excavator. The collapsed levee was thus repaired, preventing a second disaster.

This levee failure mechanism observed along the Panaro River can realistically be inferred to be similar to the disastrous levee failure mechanism that occurred along the Secchia River at San Matteo (Figure 1).

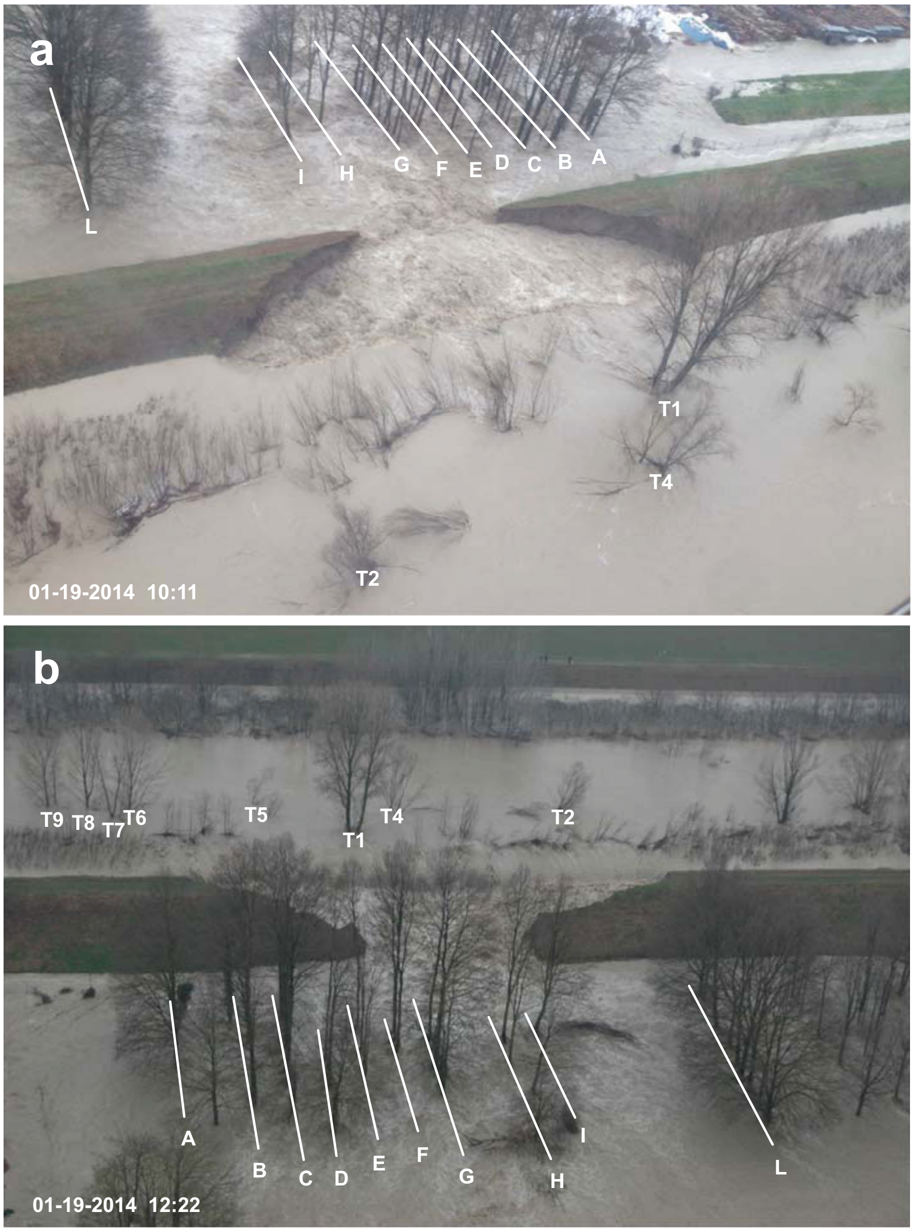

Figure 4. Photographs of the breach formed along the Secchia River at San Matteo taken from helicopters at 10:11 (Figure 4a) and 12:22 (Figure 4b) of 19 January 2014. Relevant geometrical features of the land surface close to the breach (trees T1–T9 in the riverbed and tree rows A–L in the landside plain) are identified on the photographs to allow the breach configuration to be georeferenced and transferred to relevant aerial photographs (Figures 5b and 5c).

First, the hydroclimatic conditions were very similar in the two cases, with both the failed levees directly wetted by vertical infiltration from local convective rainfall during the transit of the flood wave (Figure 2). Second, high river stages were reconstructed or observed to occur in both the river systems before the levee failures, but these stages were significantly below the top of the levees, so that overtopping of the original levee top can be excluded. Thirdly, in both the cases, dens of burrowing animals were found to exist in the locations in which the levees failed (Figures 5 and 7). In addition, other possible causes of levee failure were evaluated and found, in the cases of the considered levee structures and hydroclimatic events, to be significantly less plausible than a levee failure induced by burrowing animals [*D'Alpaos et al.*, 2014]. In any case, the event observed along the Panaro River and documented in Figure 7 provides clear evidence of this levee failure mechanism caused by burrowing animals. This is examined mechanistically below.

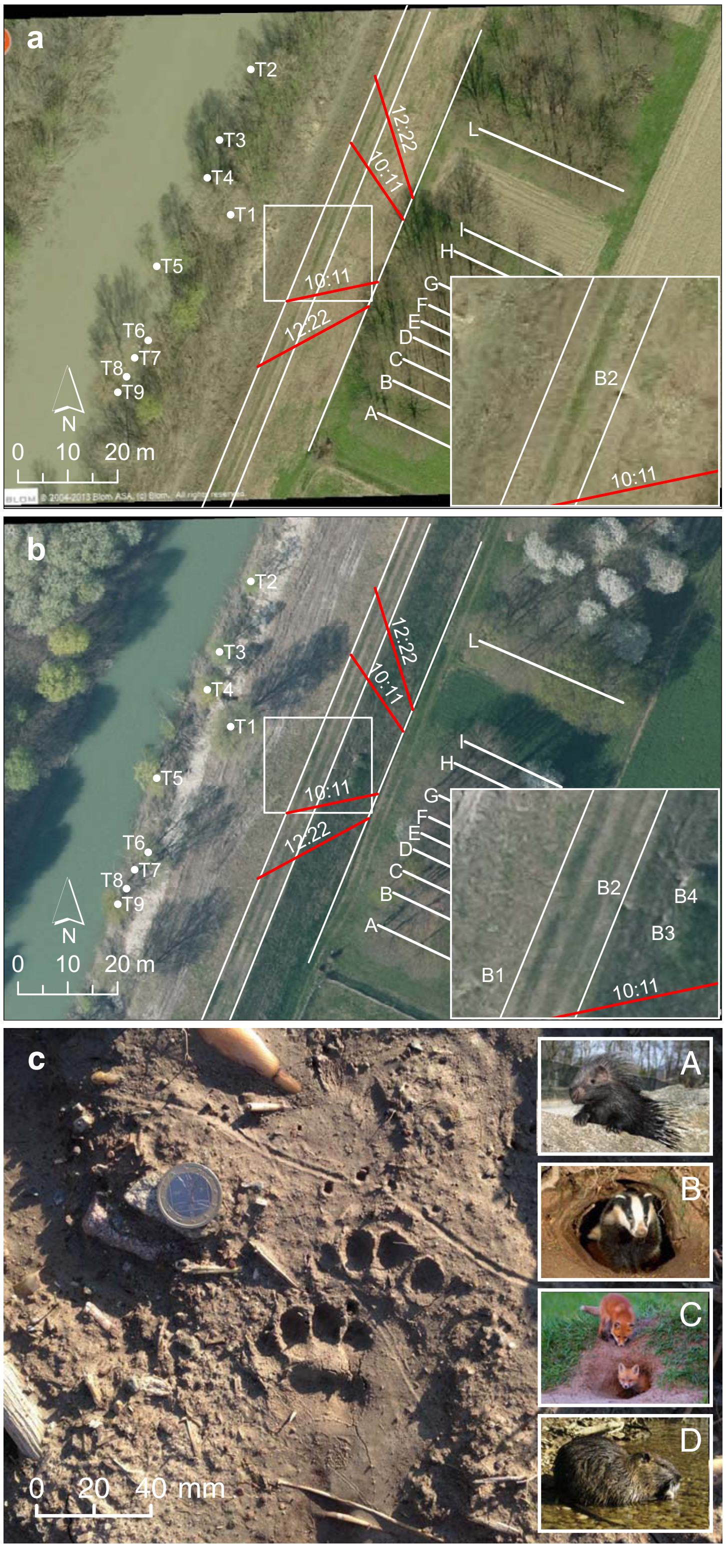

Figure 5. Evidence of burrowing animals in the location of the Secchia River levee that failed on 19 January 2014. Long parallel lines mark the top and landside bottom boundaries of the levee. Figure 5a shows animal burrows appearing in the 10 cm resolution aerial photography taken on 27 March 2010. Figure 5b indicates that on 29 March 2012, animal burrows were further developed. Figure 5c shows the footprint of a wild animal (probably a badger or a crested porcupine) observed on 24 February 2014, along the repaired levee. The burrowing animals that have impacted the levees of the Secchia River include those shown in the insets of Figure 5c: (a) crested porcupine *Hystrix cristata* (Linnaeus, 1758), (b) European badger *Meles meles* (Linnaeus, 1758), (c) red fox *Vulpes vulpes* (Linnaeus, 1758), and (d) nutria *Myocastor coypus* (Molina, 1758).

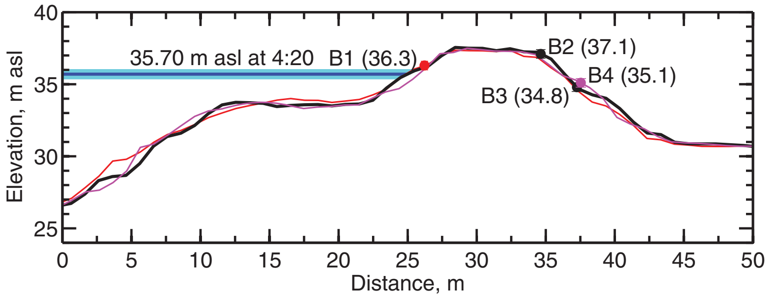

Figure 6. Geometrical relationship between the elevations of burrows B1, B2, B3, and B4 observed (in 2010 and 2012) in aerial photographs (Figures 5a and 5b) of the Secchia River at San Matteo and the river stage reconstructed from hydraulic modeling for the same levee location on 19 January 2014 at 4:20 (Figure 3). Direct river inflow into the den system can be considered possible if an uncertainty of 0.3 m in the determination of both burrow elevations (uncertainty bars) and river stages (light blue band) is acknowledged (hypothesis 1 and section 4.1).

4. Possible Triggers

The justification for attributing the Secchia levee failure to the same mechanism as that observed on the Panaro levee include (1) direct rainfall on the levee surface, (2) river stage, and (3) biological disturbance of the levee. These factors are combined by advancing the three competing hypotheses for failure triggers.

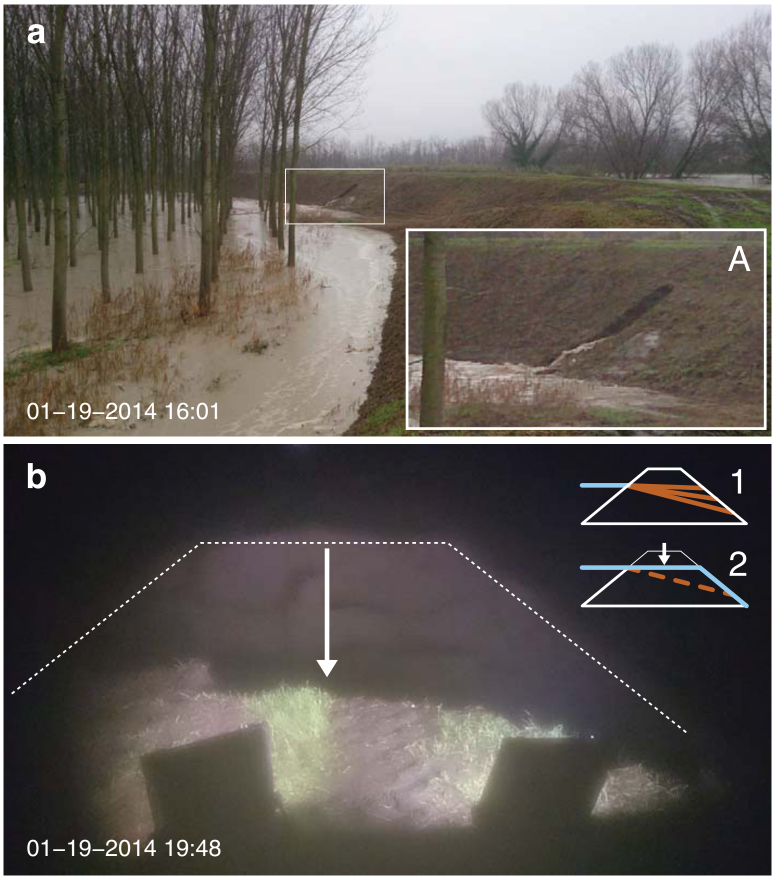

Figure 7. Observational evidence of the levee failure mechanism occurred along the Panaro River at Via Tronco (Figure 1) on 19 January 2014, under hydroclimatic conditions similar to those occurred along the Secchia River at San Matteo (Figure 2). An internal erosion process was observed at 16:01 as documented in Figure 7a. This internal flow process developed around a crested porcupine den that was observed and filled with earth in the past. The collapse of the levee top over the gallery formed by internal erosion was documented at 19:48 as reported in Figure 7b. The picture reported in Figure 7b was taken from the top of the levee close to the collapsed portion highlighted by the arrow directed downward. The failure mechanism consisted therefore of two stages. In stage 1 (Figure 7a and sketch labeled "1" in Figure 7b), the internal erosion develops around the animal den. In stage 2 (Figure 7b and sketch labeled "2" in Figure 7b), the levee top collapses by filling the gallery in the eroded levee and by exposing the collapsed material to further erosion and overtopping. The collapsed levee was rapidly repaired, preventing a second disaster.

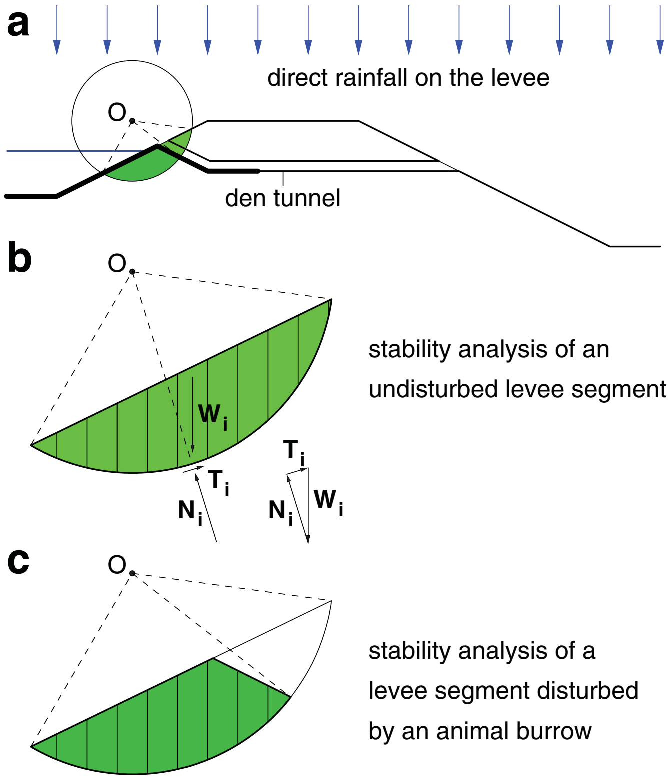

Figure 8. Sketch of the slope stability analysis performed to assess the impact of animal burrows on equilibrium conditions (hypothesis 2 and section 4.2). The bold line in Figure 8a indicates the levee portion on which the analysis focuses. The equilibrium of green segments shown in Figures 8b and 8c is evaluated: *O* is the center of the circular sliding surface, W_i is the weight of the *i*th element composing the sliding segment, T_i and N_i are the shear and normal components of W_i to the sliding surface. The blue vertical arrows indicate the direct rainfall on the levee. The blue horizontal line indicates the river stage. The two cases in which the animal burrow is not present (Figure 8b) or is present (Figure 8c) are considered.

4.1. Hypothesis 1: Pipe Flow Only

The first hypothesis explored in the present investigation is that of direct inflow into the den system as simply due to river stage raising. From image processing and terrain analysis, it was found that the elevation of the animal burrow B1 located on the levee riverside was at about 36.3 m above sea level (asl), whereas the elevations of the animal burrows B2, B3, and B4 located on the levee landside were in the range from 34.8 to 37.1 m asl (Figure 6). From river flow modeling, it was found that river stages on 19 January 2014 did not reach the burrow elevation observed (in 2012) on the levee riverside, but they significantly overcome the burrow elevations observed (in 2012) on the levee landside (Figure 3b). However, by simply acknowledging uncertainties on the order of 0.30 m on both reconstructed burrow elevations and river stages, it may be concluded that even by considering the positions of the animal burrows observed in 2012, the river flow may have reached the burrow located on the riverside of the levee (36.3 ± 0.3 m asl) at 4:20, when the river stage was estimated to be 35.70 ± 0.30 m asl (Figures 3b and 6). Since it can be clearly observed that the system of dens developed significantly from 2010 (Figure 5a) to 2012 (Figure 5b), and burrowing animals like badgers or crested porcupines were still living along the repaired levee in 2014 (Figure 5c), it is likely that the den system was more developed at the time of the levee failure than shown in the photograph taken in 2012 (Figure 5b). This would further support the triggering of internal flow and erosion processes by direct river inflow into the riverside entrance of the den system.

4.2. Hypothesis 2: Pipe Flow Following the Collapse of the Riverside Den Entrance

The second hypothesis explored in the present investigation is the collapse of the riverside den entrance under the effects of direct rainfall on the levee surface and simultaneous river stage raising. The instability of the riverside slope of the disturbed levee would provide an explanation for the triggering of internal flow and erosion. The investigated system is sketched in Figure 8. Unsteady seepage flows in the variably saturated, disturbed levee system are reconstructed by solving the 3-D Richards equation (section A3). Initial conditions of soil saturation were assigned on 22 December 2013, at 0:00, in order to mitigate the memory effects on the reconstructed seepage flow and soil matric potential at the time of the levee failure. Boundary conditions were assigned to each surface node of the levee and den systems by switching automatically from Neumann-type (assigned flux) to Dirichlet-type (assigned potential) conditions to represent the hydroclimatic forcing composed of direct rainfall on the levee surface (Figure 2b) and river stage wetting the levee riverside (Figure 3b) [*Camporese et al.*, 2010]. Surface runoff generation over the levee and

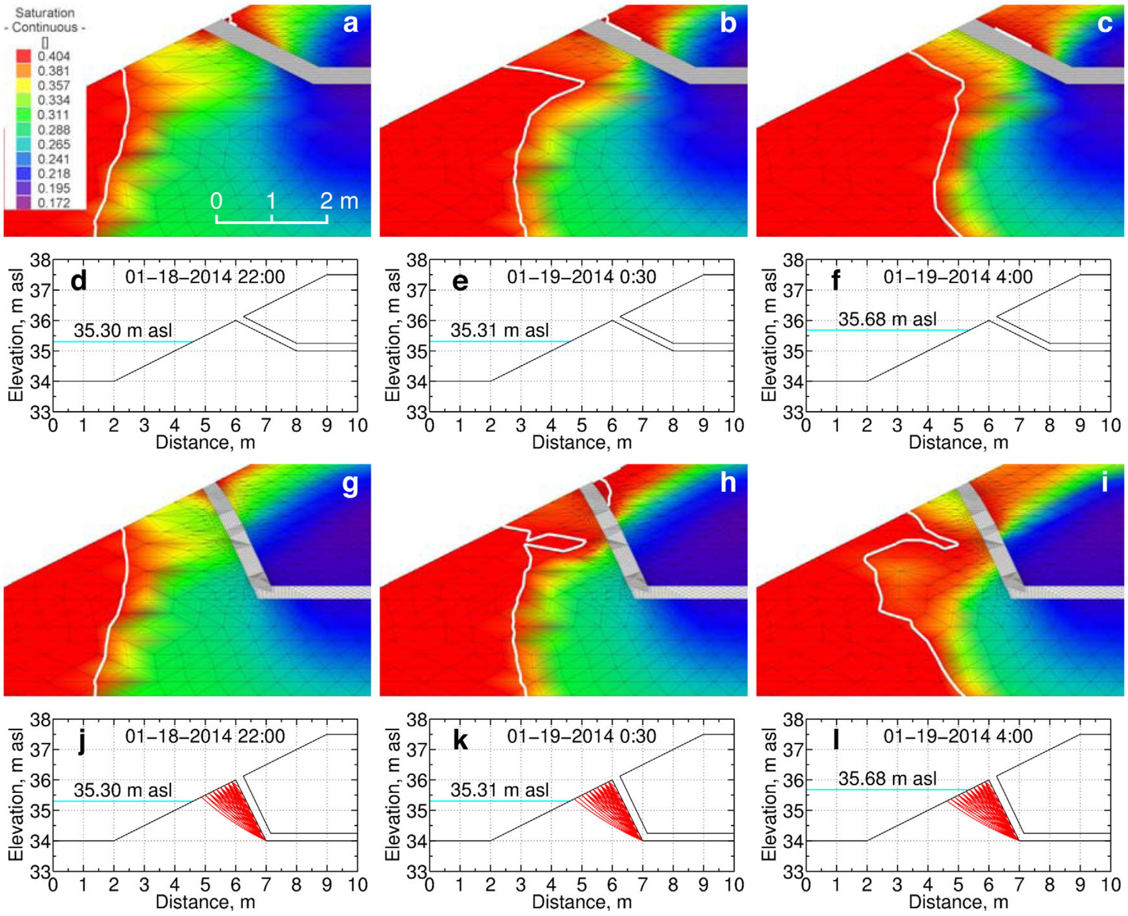

Figure 9. Simulated response of the levee of the Secchia River at San Matteo to direct rainfall on the levee (Figure 2b) and river stage (Figure 3b) in the case sketched in Figure 8 (hypothesis 2). Two possible hypothetical configurations for the tunnel extending from the riverside animal burrow into the levee are reported in Figures 9a–9f and 9g–9l, respectively. The simulation period started at time 22 December 2013 at 0:00 to mitigate the memory effects on the reconstructed levee status. The reconstructed fields of volumetric soil water content are reported at times 18 January 2014 at 22:00 (Figures 9a, 9d, 9g, and 9j), 19 January 2014 at 0:30 (Figures 9b, 9e, 9h, and 9k), and 19 January 2014 at 4:00 (Figures 9c, 9f, 9i, and 9l). The term "saturation" reported in the legend of Figure 9a is used in the FEFLOW program to denote the volumetric soil water content. The white line in Figures 9a–9c and 11g–11i denotes the phreatic (zero pressure) surface.

evaporation from the levee were both assumed to be insignificant during the considered events. Under these assumptions, conservative representations of infiltrated rainfall and soil saturation are obtained.

A Fellenius slope stability analysis was then performed by varying the center of the circular sliding surface and considering all the forces acting on the variably saturated sliding soil segment (section A4). It is important to note that this was a simplified 2-D stability analysis, and as such the results should be both meaningful for evaluating hypothesis 2 and on the conservative side. The results are reported in Figure 9. A first set of numerical experiments reveals that no instabilities occur by considering a realistic configuration of the tunnel extending from the riverside den entrance into the levee (Figures 9a–9c). No red lines indicating critical sliding surfaces are shown in Figures 9d–9f. The (unknown) internal tunnel geometry is varied in the second set of numerical experiments until red lines indicating critical sliding surfaces came out (Figures 9g–9i). These critical geometrical settings are, however, found to be unrealistic because they produce levee failures also in times when no failures were observed to occur (Figures 9j–9l).

4.3. Hypothesis 3: Pipe Flow Following the Collapse of a Den Chamber Wall

The third hypothesis explored in the present investigation is that a den system similar to the one sketched in Figure 10 was present at the time of the levee failure [*Roper*, 1992a,1992b]. A hypothetical 1 m earthen wall separating the levee riverside from an internal den chamber was assumed to exist. This is a realistic hypothesis given the development of the den system observed in aerial photographs from 2010 to 2012

(Figures 5a and 5b, respectively) and the reconstructed elevations of the burrows on riverside and landside of the failed levee (Figure 6). In addition, since burrowing animals typically excavate in soils that are easy to dig [*Vleck*, 1979; *Roper*, 1992b], a weak soil portion is assumed to exist around the den entrance as sketched in Figure 10 (section A5).

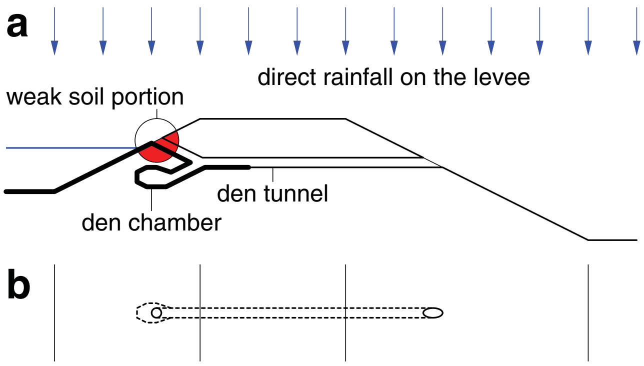

Figure 10. Sketch of the den system hypothesized to explore the possible triggers of internal flow and erosion processes occurred on 19 January 2014, along the Secchia River at San Matteo (hypothesis 3 and section 4.3). Plan and profile views are reported in Figures 10a and 10b, respectively. The bold line in Figure 10a indicates the levee portion on which the analysis focuses. The red circular segment indicates the portion of weak soil centered around the den entrance. The blue vertical arrows indicate the direct rainfall on the levee. The blue horizontal line indicates the river stage.

Unsteady seepage flows in the variably saturated, disturbed levee system are reconstructed by solving the 3-D Richards equation under the effects of direct rainfall on the levee surface (Figure 2b) and river stage (Figure 3b) (section A3). Results are reported in Figure 11. It was found that the volumetric soil water content (Figures 11a–11c) and water pressure (Figures 11d–11f) become critical at 4:00 of the day 19 January 2014 (Figures 11c and 11f), and that these critical conditions do not occur in other times of the simulation period (December 2013 and January 2014) as should be expected (e.g., Figures 11a–11c and 11f). At 4:00 of 19 January 2014, the ceiling of the chamber became saturated and the soil water pressure became positive. This occurrence would have likely implied the collapse of the den system and the triggering of internal flow and erosion, even with the elevations of animal burrows observed in 2012 (section A5).

It is remarked that the geometry of the considered den system is hypothetical. However, the results reported in Figure 11 provide a reliable proof-of-concept about the processes that may have triggered internal flow and erosion along the Secchia River on 19 January 2014, because critical conditions are only reproduced at the day of the observed failure and not in other days of the simulation period. It is finally reported that numerical modeling of the system considered in the present section (hypothesis 3) reveals that no critical soil saturation around the den chamber occurs by applying separately one of the two components of the observed hydroclimatic forcing, namely river stage and direct rainfall on the levee (see supporting

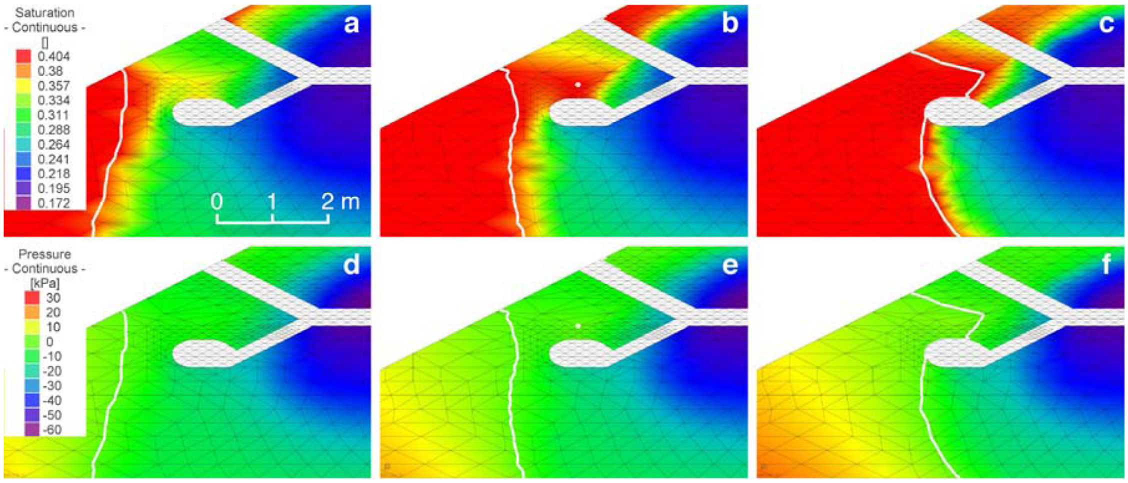

Figure 11. Simulated response of the levee of the Secchia River at San Matteo to direct rainfall on the levee (Figure 2b) and river stage (Figure 3b) in the case sketched in Figure 10 (hypothesis 3). The simulation period started at time 22 December 2013 at 0:00 to mitigate memory effects on the reconstructed levee status. The reconstructed fields of volumetric soil water content and pressure are reported at times 18 January 2014 at 22:00 (Figures 11a and 11d), 19 January 2014 at 0:30 (Figures 11b and 11e), and 19 January 2014 at 4:00 (Figures 11c and 11f). The term "saturation" reported in the legend of Figure 11a is used in the FEFLOW program to denote the volumetric soil water content. The white line denotes the phreatic (zero pressure) surface.

information, Figures S1 and S2). This suggests that the combination of the two factors may indeed provide a critical hydroclimatic condition.

5. Discussion

The reconstructed flood hydrographs that have forced the levee of the Secchia River at San Matteo in December 2013 and January 2014 were found to be smaller in terms of peak river stage and duration of high river stages than other recent flood hydrographs (e.g., the 2009 hydrograph reported in Figure 3b). The causes of the levee failure on the Secchia River at San Matteo were, therefore, sought by considering other factors that could have induced a variation in the hydroclimatic forcing or a disturbance of the levee. As shown in Figure 2, direct convective rainfall on the levees of the Secchia River at San Matteo (Figure 2b) and the Panaro River at Via Tronco (Figure 2c) occurred before the failures of these levees. The simultaneous occurrence of high river stages and intense direct rainfall on the levees is atypical for the considered geographical area and season. Flood events normally form in the mountain portions of the Secchia and Panaro River drainage basins in response to intense stratiform precipitations occurring generally in fall or in spring, or to rapid snowmelt events occurring in winter. Flood waves propagate along the low-gradient portion of these drainage basins by displaying a lag of about 12 h from the centroids of the generating hyetographs. Normally, neither local stratiform rainfall nor convective storms affect directly the levees during the lagged transit of the flood waves in the low-gradient portions of the fluvial systems. In addition, the aerial photographs reported in Figure 5 indicate clearly that a den system was rapidly developing from 2010 (Figure 5a) to 2012 (Figure 5b), and was likely to be even more developed in 2014 due to the activity of burrowing animals (Figure 5c). The combination of an atypical hydroclimatic forcing composed of simultaneous high river stages and direct rainfall on the levees, with a disturbance of the levee system produced by burrowing animals was investigated in the present study. Since the conditions of the animal dens at the time of the levee failure are unknown, the analysis reported in the present study was based on the levee condition observed in 2012 and hypothetical geometries of den tunnels and chambers (Figures 5b, 9, and 11).

By considering that burrowing animals were disturbing both the levees of the Secchia River at San Matteo (Figure 5b) and the Panaro River at Via Tronco (Figure 7) and that the hydroclimatic forcing to the two levee systems was similar (Figures 2b and 2c), the levee failure mechanism observed along the Panaro River at Via Tronco (Figure 7) can realistically be inferred to be similar to the levee failure mechanism occurred along the Secchia River at San Matteo (Figures 1 and 4). The event observed along the Panaro River (Figure 7) provides scientists and engineers with an extraordinary evidence of the levee failure mechanism that may occur in earthen levees disturbed by borrowing animals. The documentation of this event was made possible by the exceptionally large number of watchers employed along the Secchia and Panaro Rivers after the disastrous levee failure occurred in the morning of 19 January 2014 (Figure 1). In addition, the operational ability of the technical staff of the responsible agency and the Civil Protection has allowed watchers to be directed towards the sites where animal dens were observed in the past and filled with earth. The evidence presented in Figure 7 would have hardly been collected if a severe hydroclimatic forcing would not have caused a disaster along the Secchia River and similar conditions along the Panaro Rivers a few hours later. Clearly, the event observed along the Panaro River (Figure 7) provides further support to the belief that the integrity of earthen levees cannot be simply ensured by filling periodically observed animal dens with earth [*Bayoumi and Meguid*, 2011].

Levees disturbed by crested porcupines, badgers, and red foxes were repaired in the past (before the disaster occurred on 19 January 2014), along the Secchia and Panaro Rivers, by filling the detected dens with earth. In some cases, the earthen levees around the detected dens were demolished and rebuilt with an excavator, and the soil was compacted. However, for dens extending along tunnels having lengths as large as 10 m or more, the repair may not have been performed over the full extent of the tunnel system. This is because the excavation associated with a complete levee repair would in practice expose, although temporarily, the protected lands to a risk level comparable to or larger than the one associated with keeping the levees in their disturbed condition, especially in the periods when floods are more likely to occur. In addition, burrowing animals were often observed to re-excavate their dens in the same locations where the levees were repaired, despite the presence of protective metallic nets applied locally around the repairs. In some cases, new dens were excavated close to the repaired portions of the earthen levees. In fact, recent geophysical surveys carried out (after the disaster occurred on 19 January 2014) by using (1) electrical resistivity tomography, (2) frequency domain electromagnetic induction, (3) ground penetrating radar, and (4) infrared imaging have revealed the presence of levee segments that are still disturbed, despite previous repair efforts (F. Pellegrini, personal communication, 2015).

Burrowing animals like crested porcupines and badgers can dig a den in a few days, and introduce therefore a significant source of risk in low-gradient areas protected against floods by earthen dams and levees. Since effective detection and corresponding correction of these animal-induced internal erosion channels during the flood event is very challenging, prevention plans remain the most suitable protective measure. An interdisciplinary effort is needed to cope with complex meteorological, hydrological, geotechnical problems induced by time-dependent biological disturbances impacting engineering systems. To promote this interdisciplinary effort, it is first important to acknowledge that the problem addressed in this investigation is an emergent one. Field inspections conducted along the Secchia and Panaro Rivers after the events of 19 January 2014, revealed that burrowing animals like crested porcupines are now widespread along these fluvial systems. For instance, at least 30 dens actively frequented by crested porcupines were found immediately after the events of 19 January 2014, along a 45 km reach of the Panaro River extending downstream from Sant'Ambrogio to Finale Emilia (Figure 1). These animals (an invasive species from the South) have never been observed along the low-gradient course of the Panaro River before 2010, and were not even present in the mountain part of the Panaro River drainage basin before 1970. Shifts could have been driven by population growth (due to the decrease of competitors, hunters, and poachers), as well as development and climate pressures [*Monetti et al*., 2005].

Second, it is important to acknowledge all the biological factors explaining the activity of burrowing animals in low-gradient areas protected by earthen dams and levees. For instance, it may be relevant to consider that burrowing animals like to dig where there is a steep slope, such as on the side of a hill, or in a bank. Water drains away better on a slope, and this means that the den stays dry. Roughly 90% of badger setts are in areas of sloping ground [*Neal*, 1977; *Roper*, 1992b; *Clements et al*., 1988; *Thornton*, 1988]. In this perspective, earthen dams and levees may represent quiet, sought-after places for burrowing animals shifted from mountain to plain areas. As also mentioned in section 4.3, given that digging is a costly activity, dens are typically excavated in soils that are easy to dig [*Vleck*, 1979; *Roper*, 1992b]. Hence, the weakest sites that can be found along an earthen structure represent the best places for a burrowing animal where to excavate a den. Therefore, effective monitoring of animal burrows disturbing earthen dams and levees can help detecting the weakest portions of the structures that need to be reinforced and certainly not to be left exposed to further weakening induced by burrowing animals.

Since the triggers of the levee failures occurred along the Secchia (Figures 1–5) and Panaro (Figure 7) Rivers were not observed, three hypotheses for these triggers were explored in the present investigation by evaluating the compatibility of assumptions with observed data. The hypothesis that internal flow and erosion were simply triggered when the river stage has reached the animal burrow located on the riverside (hypothesis 1) can be considered consistent with the reconstructed elevations of the animal burrows observed in 2012 (Figure 6) and of the river stage on 19 January 2014 at 4:20 (Figures 3b and 6) if uncertainties on the order of 0.3 m of both burrow elevation and river stage are acknowledged (Figure 6). In addition, riverside animal burrows at lower elevations than the one observed in 2012 were possible in 2014, just before the levee failure, and compatible with the observed evolution of the den system (Figures 5a and 5b). While the hypothesis of slope instability around the animal burrow observed (in 2012) on the riverside of the levee (hypothesis 2) was not supported by numerical experiments (Figure 9), the existence of a den chamber separated from the riverside of the levee by a 1 m earthen wall (hypothesis 3) was found to provide a plausible explanation of the failure occurred during the night of 19 January 2014, at about 4:00, and not in other previous circumstances (Figure 11). All the triggering conditions compatible with observed data were found to occur between 4:00 and 4:20 of 19 January 2014, indicating that a more rapid internal flow and erosion process occurred in the Secchia River (about 2 h between the yellow and red bands in Figure 2b) than in the Panaro River (about 4 h between the yellow and red bands in Figure 2c).

6. Conclusions

The present investigation revealed the role played by burrowing animals in the disastrous levee failure occurred along the Secchia River at San Matteo on 19 January 2014 (Figures 1–6), and thus raises the distinct possibility that other disastrous levee failures in Italy may have been connected to the activity of burrowing animals [e.g., *Camici et al.*, 2015]. Evidence collected suggested that it is quite likely that the levee failure of the Secchia River was of a similar mechanism as the observed failure of the Panaro River (Figure 7). Detailed numerical modeling of rainfall, river flow, and variably saturated flow occurring in disturbed levees in response to complex hydroclimatic forcing indicated that the levee failure of the Secchia River may have been triggered by direct river inflow into the den system or collapse of a hypothetical den separated by a 1 m earthen wall from the levee riverside, which saturated during the hydroclimatic event (Figures 6 and 11, respectively). The plausible scenarios obtained from detailed modeling suggested that the levee failure of the Secchia River was more rapid than the one observed in the Panaro River (Figures 2, 6, and 11).

The investigation reported in the present paper informs flood risk analysis as classically conceived by hydrologists and geotechnical engineers, but it also points to future interdisciplinary considerations such as: (1) the meteorological conditions needed significant rains on the levee surfaces at a time delay from the headwater rainfall that is comparable to the river flood wave travel time, (2) the hydrological analysis involves river flows, variably saturated infiltration, and pipe erosions, (3) the geotechnical stability analysis involves complex 3-D domains, and (4) the animal activity may increase with shifts and fragmentation of habitats of both native and invasive species. Especially in the shorter term, geophysical survey methods are useful tools for determining the extent and degree of damage caused by burrowing animals to earthen dams and levees, as well as for evaluating the effectiveness of structural repairs. In a broader perspective, it is important to bring the processes highlighted in this paper to the attention of hydrologists and geotechnical engineers as well as to trigger an interdisciplinary discussion on habitat fragmentation and shifts due to development and climate pressures. These all come together with changes in extreme events to inform the broader concern of risk analysis due to floods.

Appendix A: Methods

A1. River Flow Modeling

The flood waves from December 2013 and January 2014 along the Secchia River were reconstructed by developing a level pool routing model [*Fiorentini and Orlandini*, 2013] of the Rubiera flood control reservoir and a dynamic wave model (full De-Saint Venant equations) [*Brunner*, 2010] of the river reach extending downstream from the Rubiera reservoir to Pioppa (Figure 1). The characteristic "water level-storage" and "storage-outflow discharge" relationships of the Rubiera reservoir were determined from the 1 m resolution DEM and the known geometry of both gated bottom outlets and spillways [*Fiorentini and Orlandini*, 2013]. The hydraulic geometry of the river reach was described by combining bathymetric topographic surveys and a 1 m resolution DEM generated from a lidar survey carried out in 2009. Friction slopes S_f are estimated through the Gauckler-Manning-Strickler constitutive equation $U=k_S\,R^{2/3}\,S_f^{1/2}$, where U is the mean flow velocity, k_S is the Gauckler-Strickler coefficient, and R is the hydraulic radius. Coefficients k_S were allowed to vary in space and time [*Orlandini*, 2002], so that the obtained parameterization is compatible with the experimental flow rating curves at the stations of Ponte Alto, Ponte Bacchello, and Pioppa (Figure 1). The considered values of k_S were in the range 10–16 $\mathrm{m}^{1/3}\ \mathrm{s}^{-1}$. The breach formed on 19 January 2014, at San Matteo was described explicitly in the dynamic wave model by synthesizing the observations collected during the event (Figures 1 and 4). The breach length varied from 0 to 80 m during the event. The flood hydrograph observed at the station of Rubiera was used to provide a Neumann-type (assigned flow discharge) upstream boundary condition for the fluvial system, and the river stages observed at the station of Pioppa were used to provide a Dirichlet-type (assigned river stage) downstream boundary condition. The reliability of the developed river flow model was tested against available observations of the river stage (Rubiera flood control reservoir, Ponte Alto, and Ponte Bacchello stations reported in Figure 1) and water level marks left on trees located near the breach. The reconstructed flow discharges and river stages at the cross section of the failed levee are reported in Figures 3a and 3b, respectively. The uncertainty in the reconstructed river stages is on the order of 0.3 m.

A2. Image Processing and Terrain Analysis

A metric analysis of the photographs of the breach taken on 19 January 2014, at 10:11 and 12:22 (Figure 4), and of the aerial photographs taken in 2010 and 2012 (Figures 5a and 5b, respectively) was performed by using the program Blom Desktop Viewer developed by Blom CGR SpA. The positions of relevant geometrical features of the land surface that can be found in Figures 4, 5a, and 5b, such as the trees T1–T9 in the riverbed and tree rows A–L in the landside plain, were determined and used as a reference to determine the positions of the observed breach limits. The obtained results are reported in Figures 5a and 5b. In addition, a 1 m DEM generated from a lidar survey was used to determine the geometry of the failed levee and the elevations of the animal burrows observed in the most recent aerial photograph, so that these animal burrows could be positioned along the profile of the failed levee. The obtained results are reported in Figure 6. The uncertainty in the reconstructed burrow elevations is on the order of 0.3 m.

A3. Seepage Flow Modeling

Seepage fluxes, soil moisture status, and related soil matric potential that occurred in the (disturbed) earthen levees in response to the reconstructed hydroclimatic forcing were determined by solving the 3-D Richards equation through the FEFLOW model [*Diersch*, 2014]. The computational soil domain was defined by considering the land surface profile described by the 1 m resolution DEM generated from a lidar survey, a planar extension along the river cross section of about 330 m, and a soil thickness of about 30 m. A portion of this domain is shown in Figure 6. The hydraulic properties of the soil were determined experimentally from undisturbed soil samples collected after the flood disaster in a levee cross section located immediately downstream from the site of the levee failure [*Romano and Santini*, 1999]. The constitutive equation relating volumetric soil water content θ and soil matric potential ψ ($\psi=p/\gamma$, where p is the soil water pressure and γ is the specific weight of water) was given by the van Genuchten equation $\Theta=\{1/[1+(\alpha|\psi|)^n]\}^m$, where $\Theta=(\theta-\theta_r)/(\theta_s-\theta_r)$, $\theta_r=0.079$, $\theta_s=0.404$, $n=1.495$, $m=1-1/n=0.331$. The constitutive equation relating the (unsaturated) hydraulic conductivity K to the volumetric soil water content θ was given by the Mualem model as $K=K_s K_r$, where $K_s=1.88\times10^{-6}$ m s^{-1}, and $K_r=\Theta^{1/2}\{1-[1-\Theta^{1/m}]^m\}^2$. The hydroclimatic forcing was determined from rainfall and river flow modeling as reported in Figures 2b and 3b, respectively (section A1). Boundary conditions assigned to the land surface can switch automatically from Neumann-type (assigned flux) conditions, representing a levee boundary affected by direct rainfall on the levee surface, to Dirichlet-type (assigned potential) conditions, representing a levee boundary wetted by river flow [*Camporese et al*., 2010]. A no-flux boundary condition is assigned to the bottom of the domain, whereas a Dirichlet-type (assigned potential) was assigned to the lateral boundaries (far from the levee) to represent a water table depth of about 2 m.

A4. Slope Stability Analysis

The stability of the riverside slope of the disturbed levee under the reconstructed hydroclimatic conditions was assessed by applying the Fellenius method [*Fellenius*, 1927] to the hypothetical system sketched in Figure 8. The hypothetical tunnel geometries considered are compatible with reconstructed animal burrows (section A2) and data describing badger setts in the literature [*Roper*, 1992a,1992b]. The hydroclimatic forcing was determined from rainfall and river flow modeling as reported in Figures 2b and 3b, respectively (section A1). Soil saturation and soil matric potential were determined by solving the 3-D Richards equation through the FEFLOW model [*Diersch*, 2014] (section A3). The center of the circular segment subjected to stability analysis was varied numerically to consider all the possible geometries of the potentially unstable (disturbed) levee portions. The weight of the elements composing the segment were computed by considering the porous medium and the water (partially) filling the voids in response to variable infiltrated rainfall and river stage as obtained from detailed seepage flow modeling. In the performed analysis, the effective cohesion was assumed to be $c'=0$, the effective angle of internal friction was assumed to be $\phi'=32^\circ$, and the unit weight in saturated state was assumed to be $\gamma_{\mathrm{sat}}=19,000$ N m^{-3}.

A5. Wall Stability Analysis

The stability of a hypothetical earthen wall separating the riverside of the levee from a hypothetical den chamber located inside the levee was assessed by considering the disturbed levee sketched in Figure 10. The hypothetical tunnel and chamber geometries are compatible with the reconstructed animal burrows (section A2) and data describing badger setts in the literature [*Roper*, 1992a,1992b]. The hydroclimatic forcing was determined from rainfall and river flow modeling as reported in Figures 2b and 3b, respectively (section A1). Soil saturation and soil matric potential were determined by solving the 3-D Richards equation through the FEFLOW model [*Diersch*, 2014] (section A3). The saturated hydraulic conductivity of the weak soil portion around the den entrance sketched in Figure 10 was assumed to be $K_s=11.10\times10^{-6}$ m s^{-1}, a value on the order of magnitude of the largest values observed in the undisturbed soil samples mentioned in section A3. The collapse of the hypothetical den is assumed to occur when the ceiling of the den becomes fully saturated ($\theta=\theta_s$) and both soil matric potential (ψ) and soil water pressure (p) become greater than or equal to zero. The related loss of soil matric suction is related directly to a critical decrease in the shear strength of the soil.

In geotechnical terms, the collapsing behavior of the granular soils around the den system can be described by using the principle of effective stress for unsaturated soils [e.g., *Fredlund and Rahardjo*, 1993; *Lu and Likos*, 2004; *Lu et al.*, 2014]. *Bishop*'s [1959] effective stress for unsaturated soils can be expressed as $\sigma'=(\sigma-u_a)+\chi(u_a-u_w)$, where σ is the total stress, u_a is the pore air pressure, $(\sigma-u_a)$ is the net normal stress, χ is the effective stress parameter, u_w is the pore water pressure, (u_a-u_w) is the matric suction, and χ (u_a-u_w) is the suction stress. The pore water pressure u_w is the same quantity as the soil water pressure p introduced in section A3. The parameter χ is often set equal to the degree of saturation Θ introduced in section A3. In any case, χ is imposed to vary from 0 for dry soils to 1 for saturated soils, enabling a simple transition from partially to fully saturated states, and recovering *Terzaghi*'s [1923, 1936] expression $\sigma'=\sigma-u_w$ for the saturated case. The granular soil with little or no classical effective cohesion (i.e., $c'\approx0$) placed around the den chamber reaches a critical condition for stability at saturation because the suction stress and the related capillary cohesion (i.e., $c''=\chi_f(u_a-u_w)_f\tan\phi'$, where $\chi_f(u_a-u_w)_f$ is the maximum suction stress at failure and ϕ' is the effective angle of internal friction) drop to zero [e.g., *Lu and Likos*, 2004, p. 253]. In the saturated soil placed around the den chamber, where $\sigma-u_a\approx0$ and $\chi(u_a-u_w)\approx0$, the effective stress reduces essentially to zero. The related complete loss of shear strength causes soil liquefaction and, especially for a weak soil (in the sense specified in section 4.3) under seepage, progressive collapse of the saturated wall separating the levee riverside from the internal den chamber.

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