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THE 2001 MOUNT PINATUBO CRATER LAKE BREAKOUT CRISIS

Ma. Antonia V. Bomas and the Quick Response Team[1]

Geology and Geophysics Research and Development Division, Philippine Institute of Volcanology and
Seismology, C.P. Garcia Ave., University of the Philippines Campus, Diliman 1101 Quezon City

1.0 INTRODUCTION

The breaching of natural dams consequent to the breakout of large reservoirs generates some of the world's largest floods and lahars (Schuster and Costa, 1986; Costa and Schuster, 1988; Costa, 1988; Catane and Gabinete, 1995; King and others, 1989; Walder and O'Connor, 1997; Waythomas, 1996; 2000; Plaza-Nieto and Zeballos, 1999). A similar and lingering threat to Botolan, Zambales (pop. ca. 40,000) emanates from Mount Pinatubo's summit caldera lake, a condition that peaked last year when the lake rose critically close to the caldera rim's lowest point, the Maraunot Notch (ca. 960 m asl; Figure 1). The lake had risen by 40m between May 1998 and July 2001, the period within which the Philippine Institute of Volcanology and Seismology (PHIVOLCS) had monitored the Maraunot freeboard. Its surface stood at 955m asl, 5 m below the notch, by July 2001. Recorded lake rise increments warned of ***definite*** overflow at the notch, or "overtopping", in the last quarter of 2001, an event fraught with grave ***possibilities*** of triggering a breach at Maraunot and the ultimate breakout of Pinatubo's crater lake.

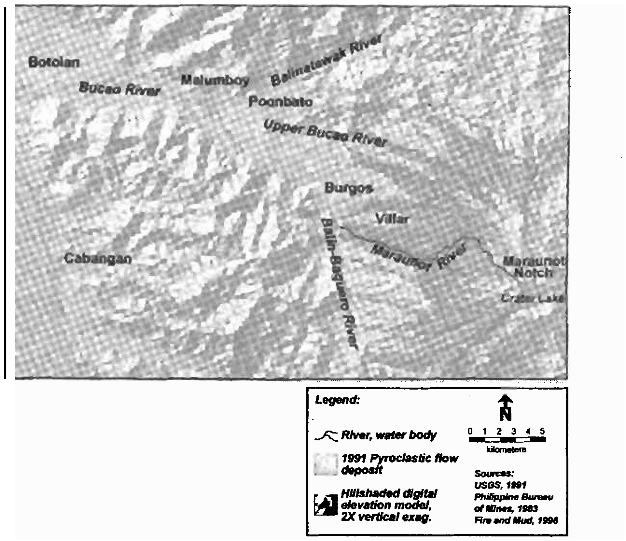

Figure 1. Digital terrain map of the northwest Pinatubo quadrant, showing the Maraunot Notch and the contiguous Maraunot-Balit-Baquero-Bucao River System. Bololan town proper and upriver villages are shown. DEM from PHIVOLCS-GIS lab.

In the previous year, engineering measures to alleviate the hazard had been solicited by the Department of Public Works and Highways (DPWH) (Inoue, Nippon Koei unpub. rep., December 2000). There were four alternatives, of which the first was the most economically and logistically feasible: (1) excavation of an artificial spiltway or trench; (2) siphoning; (3) construction of an overflow weir, and; (4) tunneling. Eight months later, as the breakout threat gained momentum, PHIVOLCS with DPWH and the Municipal Government of Botolan, under the aegis of the National Disaster Coordinating Council (NDCC), embarked on a bold mitigation plan to excavate a trench and 'intentionally breach' the Maraunot Notch. The plan neutralized short-term risk and reduced long-term hazard from a lake breakout. However, wide publicity combined with the strain of socio-political pressure left the outcome of the trenching measure open wide to speculation. In this paper, scientific data obtained and

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[1] Quick Response Team Members: Mabel Abigania, Agnes Aguilar, Paul Alanis, Rene Arante, Onie Arboleda, Maricar Arpa, Mariton Bornas, Edwin dela Cruz, Jojo Cordon, Toti Corpuz, Art Daag, Jerry Diolata, Elmer Gabinete, Del Garcia, Lito Gelido, Lito de Guzman, Sheila Insauriga, Manny Isada, Dindo Javier, Rudy Lacson, Bong Luis, Rey Lumbang, Danny Martinez, Mylene Martinez-Villegas, Chris Newhall, Jed Paladio-Melosantos, Mel Pagtalunan, Myla Panol, Jack Puertollano, Raymundo Punongbayan, Freddie Reyes, Gina Quiambao, Julie Rañola, Andoy Ramos, Paolo Reniva, July Sabit, Lester Saquilon, Steve Schilling, Jimmy Sincioco, Noli Sexon, Norman Tungol, Opet Villacorte.

Table 1. Crater lake water surface level through time, and computed monthly and average lake rise increments.

Observation Date	Elevation (m asl)	Maraunot Freeboard (m)	Data Source	Monthly Ave. (m)	Cumulative Monthly Average	Annual Ave. (m)
Jun-91	780.0	180.00	JICA			
Jun-95	830.0	130.00	JICA	1.042		12.50
Jun-97	855.0	105.00	RSP	1.042	2.083	12.50
7-May-98	915.0	45.00	PHIVOLCS-VMEPD	5.455	7.538	65.45
27-Apr-99	933.0	27.00	PHIVOLCS-VMEPD	1.589	9.127	19.06
10-May-00	942.0	18.00	PHIVOLCS-VMEPD	0.726	9.853	8.72
28-Jun-00	944.0	16.00	PHIVOLCS-VMEPD	1.250	11.103	
5-Aug-00	945.7	14.30	PHIVOLCS-VMEPD	1.339	12.442	
16-Aug-00	945.9	14.10	PHIVOLCS-VMEPD	0.541	12.982	
16-Sep-00	948.4	11.60	PHIVOLCS-VMEPD	2.500	15.482	
13-Oct-00	948.7	11.35	PHIVOLCS-VMEPD	0.278	15.760	
23-Nov-00	949.2	10.78	PHIVOLCS-VMEPD	0.432	16.192	
27-Dec-00	949.7	10.33	PHIVOLCS-VMEPD	0.500	16.692	
27-Jun-01	953.5	6.50	PHIVOLCS-GGRDD	0.638	17.330	
11-Jul-01	955.0	5.00	Nippon Koei	1.327	18.657	15.17
			Average	1.166		13.23

evaluated by PHIVOLCS over a period before and after intentional breaching will show the effectiveness of the measure and its benefit to hazard and risk reduction in Pinatubo.

2.0 GEOLOGIC BACKGROUND

Pinatubo Crater Lake and Northwest Quadrant. The plinian eruption of Mount Pinatubo in 1991 exploded off 2.5 km^2 of material from its summit to produce a 2.5 km-wide 600 m-deep caldera in its place (Scott and others, 1996; Jones and Newhall, 1996). The new crater created a catchment area of 5.15 km^2 and soon began to develop a lake in September 1991 (Jones and Newhall, 1996; Campita and others, 1995). With input from rainfall as well as from hydrothermal upwelling and crater wall sedimentation (Campita and others, 1995; Bornas and others, unpub. rep, 2000), the lake elevated to a maximum depth of over 110 m (PHIVOLCS, unpub. VMEPD data, 2000). It currently impounds 250 M m^3 of water (Rañola, unpub. rep., 2000). Lake rise recorded between May 1998 and July 2001 averaged to a monthly rise of 1 m which is equivalent to –3 M m^3 of water accrued monthly (Table 1). It was projected that the amount of water needed for the lake to rise to spill point at Maraunot could be met as early as October 2001 by average rainfall alone on the crater watershed (Bornas and others, unpub. paper, 2000).

After the 1991 calderagenesis, a well-defined V-shaped valley that became known as the Maraunot Notch remained of the beheaded upper Maraunot River on the northwest flank (Figure 2). The river had an original watershed of 42 km^2 (Rodolfo and others, 1996) and flows 15 kms northwest into the Balin-Baquero River. Approximately 500 M m^3 of 1991 pyroclastic flow deposits (Scott and others, 1996) blanket the lower three-fourths of the watershed, sediment from which partly fed recent lahars of the Bucao River via its Balin-Baquero tributary. Bucao lahars have long threatened to inundate Botolan town proper on the delta 40 kms downriver of the crater (Remotigue, 1995; Pierson and others, 1996; Rodolfo and others, 1996). As with the 1991 pyroclastic flows, lahars obliterated the original upriver villages of Botolan in the Balin-Baquero and Bucao valleys (e.g. Villar, Burgos, and Poonbato).

Maraunot Notch and Dam Characteristics. The valley of the Maraunot Notch is defined by 150m-high walls composed of dome rocks and lithified block-and-ash deposits that are sharply divided by steep NW- and E-trending faults (Bornas and others, unpub. rep., 2000; Bornas and others, unpub. paper, 2001; Figures 2B and 3). Dome rocks also outcrop within the first km-reach of the Maraunot channel and are inferred to form its bedrock. Less competent deposits fill the valley floor (Figure 2B, 3C) and edge off abruptly at the crater, effectively 'damming' its lake from the Maraunot channel bedrock (Figure 3C). This dam is approximately

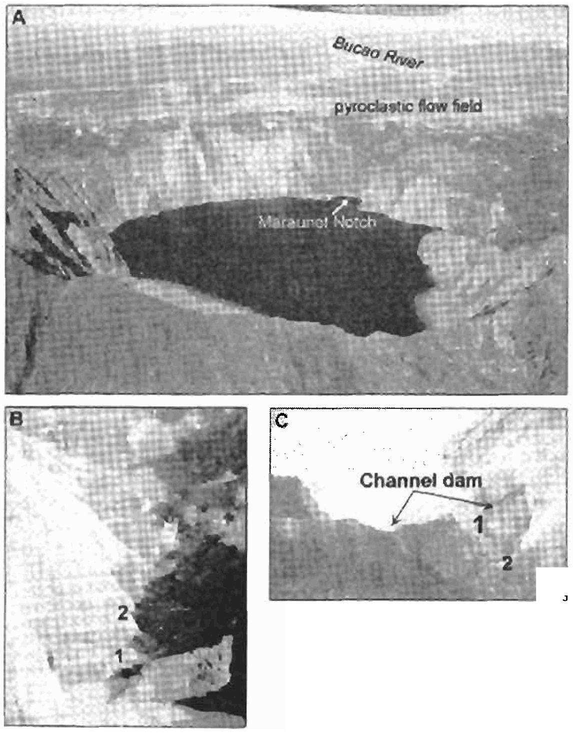

Figure 2. (a) Oblique aerial view of Pinatubo Crater, Maraunot Notch and the Maraunot-Bucao River System (looking NW). Photo courtesy of S. Suto, 2000. (b) Perpendicular and (c) top view of the Maraunot Notch channel dam (30 July 2001). Crest or spill point (1) and toe at dome nose (2) are indicated.

85-m wide at the edge or "crest" but narrows as it slopes 8° down to its "toe" (S6 of Figure 3C) at a prominent "nose" of dome rock 70m away and 10m below the crest.

Comprising the dam are a lower pre-1991 terrace of three boulder-rich breccia units and an upper sequence of 1991 deposits (Figure 4). Pre-1991 breccia units are poorly indurated and contain 40%-70% proportion of dense dacite-andesite clasts (median diameter 10-15 cms) in coarse (B1) or fine (B2) ash or coarse sand (B3) matrix. Freeboard exposure of the dam in 1998 indicates that pre-1991 breccia may be as much as 14 m thick at the crest. The units also occur as in-channel terraces along the first 700-m reach of the Maraunot River.

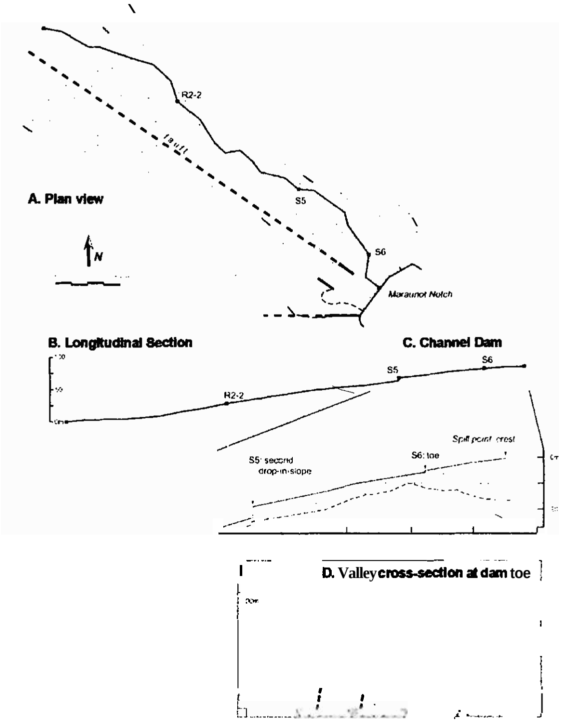

Figure 3. Geologic sections of the Maraunot channel. The patterns represent bedrock (dashed), lithified block-and-ash (dotted) and pre-91 breccia and 1991 eruption deposits (dot-anddash). Thick lines are faults in the valley walls. The subsurface configuration of the channel dam (C) is depicted based on the long (A) and cross-sectional data (D). Potential breach depths of 10 m to 20 m are inferred from the depth of channel bedrock wrt the crest. Modified from Bornas and others (2001).

The overlying 1991 eruption sequence consists of a thin pre-climactic surge layer (E1) and pyroclastic lag breccia (E2) and a post-climactic surge deposit (E3) called Layer D (Paladio-Melosantos and others, 1996). The lag breccia is 1m-2m thick, loose, matrix-supported and consists of dome fragments, pumice and dense or altered lithics in pumiceous ash matrix. Layer D is flat-lying, stratified loose and cohesive ash up to 6m thick. It is gullied down to a meter thick along the channel thalweg, creating a 5m-wide natural 'spillway' at the axis of the dam.

3.0 PREDICTED FAILURE MODE AND BREAKOUT WORST-CASE PARAMETERS

There exists the probability that the make-up and size of the ash-and-breccia dam make it suceptible to rapid erosion once the lake overflows. Of the failure of natural dams

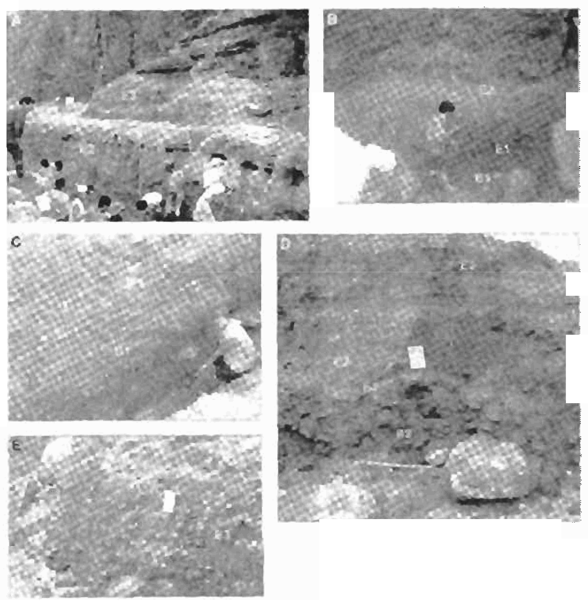

Figure 4. Stratigraphic units comprising the Maraunot channel dam exposed along the trench. B1, B2 and B3 are pre-1991 breccia, while E1, E2 and E3 are 1991 eruptive deposits, viewed at the (a) mouth; (b) and (c) 20-30 m reach; (d) and (e) terminus.

worldwide such as landslide and moraine dams, more than half is incurred from overtopping-induced erosion (Schuster and Costa, 1986; Costa and Schuster, 1988). The danger at Maraunot is magnified by the presence of loose 1991 eruption deposits at the upper part of the dam, a presumably rapid erosion of which may be enough to trigger a catastrophic breach.

A potential breach was expected on occasion of a strong typhoon or monsoonal trough from which intense rainfall (e.g. 1993 Typhoon ***Kadiang;*** Remotigue, 1995) causes the lake to overflow across the channel spillway. Dam failure is initiated by erosion or headcutting of 1991 deposits where the valley narrows or "noses" and the channel drops. The removal of material is accompanied by increasing flow perimeter and head which increases discharge and weakens the dam. Discharge escalates into a tremendous rush of water, accelerating erosion headward in a runaway process that culminates in dam failure. This same process has been documented in numerous cases of overtopped natural and man-made dams that have breached (Schuster and Costa, 1986; Costa and Schuster, 1988).

In the worst-case (refer to Figure 3C), a 10m- to 20m-depth of the channel dam corresponding to the vertical gap between the crest and shallow channel bedrock may be breached. Respective lake volumes of 28 to 55 M m^3 may be released into the Maraunot channel (Bornas and others, unpub. paper, 2001). Estimated peak discharges at the breach are at a tremendous 3,000 and 11,000 m^3/sec for a 10m- to 20m-deep breach, respectively (Bornas and others, unpub. paper, 2001), following Walder and O'Connor (1997).

4.0 PREDICTED FLOW AND INUNDATION WORST-CASE PARAMETERS

The breakout flow may be expected to erode and incorporate pyroclastic flow and lahar sediments at the mid- to lower reaches of the Maraunot River. This causes the breakout flow to bulk up between 3 to 6 times (Rodolfo and others,. 1996; Pierson, 1997; Remotigue, 1996) and peak discharge 2 to 3 times (Pierson, 1997; 1998; Mizuyama and others, 1992), transforming it into large-volume lahars. Estimated non-attenuated lahar peak volume and discharge along the Maraunot River ranges between 80 to 330 M m^3 and 6,000 to 33,000 m^3/sec, respectively. The maximum predicted volume and discharge are respectively 3X and 7X larger than those of the largest lahars recorded along the Bucao River (1993 Typhoon ***Kadiang;*** Remotigue, 1995). In the least, the peak flow along Maraunot River will endanger new-sprung settlements of Villar and Burgos adjacent to the Maraunot-Balin-Baquero confluence.

To gauge lahar risk to Botolan proper, Schilling (2001) approximated inundation extents for a range of volumes using the USGS lahar routing program LAHARZ (Schilling 1998). The program assumed a specified volume of water "suddenly" released from the notch and routed this on digital Pinatubo terrain using statistical data from historical lahars. A resulting inundation model for volumes of 1 to 300 M m^3 signified potential risk of inundation for Botolan by lahars >100 M m^3 (Figure 5). Based on lahar travel time records, the peak flow is likely to cross the distance between the notch and Botolan within 1 and 2 hours (Remotigue, 1995; Pierson, 1998). Peak discharge based on empirical data may correspond roughly to peak discharge at the breach (Newhall, open memo to PHIVOLCS, 2001).

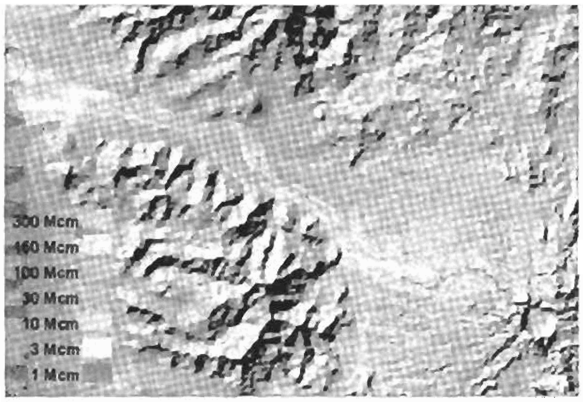

Figure 5. Breakout lahar inundation hazard model simulated by Schilling (2001) using the routing program LAHARZ (Schilling, 1998). Different colored zones are resulting inundation extents for the indicated breakout volumes. The model signifies inundation of Botolan proper for lahar volume magnitudes >100 Mcm.

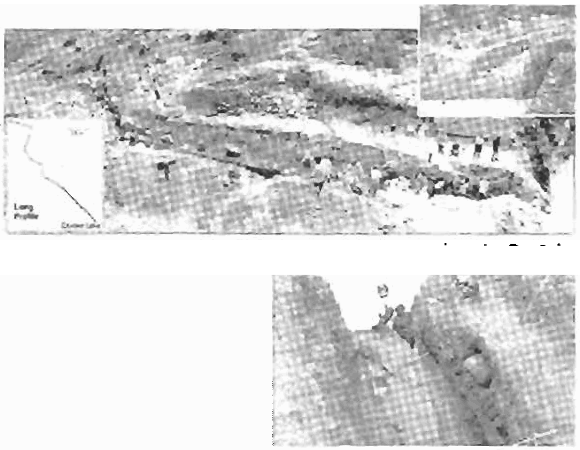

Figure 6. (Top) Oblique photo of the Maraunot Trench looking northeast, taken before unplugging day.. Top righthand inset shows the mount on 01 September, ca. 2 m above the lake level; bottom lefthand inset in the profile of the trench. (Right) View of the mouth and the terraced inner geometry of the trench, 06 September.

5.0 BREAKOUT RISK MITIGATION

Faced with the quantified hazard (Bornas and others, unpub. paper, 2001; Newhall, open memo to PHIVOLCS, 2001), PHIVOLCS proposed in early August 2001 to intentionally breach the Maraunot Notch by trenching across the channel dam. The procedure had been used to successfully breach other natural dams elsewhere (e.g. Bairaman [King and others, 1989]; Mt. Saint Helens [Meyer and others, 1986]). The primary purpose of the effort was to induce once and for all a scheduled breach before the lake attains maximum level and overtops the channel dam. Intentional breaching eventually formed the core element of a rapid mitigation plan that included information drives in Botolan, evacuation of risk areas and lahar watch along the Balin-Baquero and Bucao Rivers.

Intentional Breaching. Trenching took approximately 2 weeks from 23 August to 5 September 2001 under the supervision of DPWH's Mount Pinatubo Rehabilitation – Project Management Office (MPR-PMO). The trench was manually dug by an 80-man ethnic Aeta crew using pick axes and shovels and, later, sluicing with a portable 50 m-long pressure hose. Excavation followed the channel thalweg or the natural "spillway" from crest to toe of the dam. The fully-excavated trench was 70m long, 4m wide and nearly 3.5 m deep with a 1m-wide and 1.5m-deep inner terrace that resulted from belated prioritization of depth over width (Figure 6). Its bottom originally graded ~2% and sloped steeply at the mouth into 5m-long plug. In the end, about 700 m^3 of material was excavated. On 04 September, lahar watchpoints were deployed to four sites and evacuation of Botolan begun the following day in anticipation of potential breakout lahars along the Balin-Baquero and Bucao Rivers.

On 06 September, with a 10cm-head of water, the plug was removed by sluicing by a skeleton crew of less than 10 workers. At 0653H, after less than 1.25 hours of sluicing, lakewater spill into the trench commenced. Discharge was very sluggish in the first four hours (~ 0.03 m^3/sec) but increased with additional trenching. Staff from the Philippine National Police (PNP) and the Armed Forces of the Philippine (AFP) arrived to augment, then later replace, the trenching crew. Political developments, however, led to the pullout of DPWH, PNP and AFP between 07 and 08 September. With this departure, the trench was left in a final configuration that offered no hope of rapid and surgical breaching. The *possibility* of eventual breaching under *sustained intense rainfall* in the next days and weeks, however, compelled

PHIVOLCS to remain at Maraunot and monitor for developments. All lahar watchpoints were decamped by 09 September and evacuation centers, by 10 September.

Long-term vs. Short-term Goals. Much of the subsequent confusion on the outcome of the intentional breaching plan stems from the unanticipated trade-off between PHIVOLCS long-term vs. DPWH short-term goals for trenching.

PHIVOLCS proposed to trigger a **scheduled, short-term and rapid breach** by facilitating relatively ***rapid erosion*** of the channel dam with trenching. The intent was to ***induce*** and ***constrain*** lake breakout within a schedule so that pre-emptive evacuation of Botolan can be carried out, thereby neutralizing the risks. A scheduled short-term breach would also eliminate: (1) added hazard from **14** (11 by the time of trenching) M m^3 of water the crater can still accommodate before reaching maximum level and spill point; (b) the ***uncertain time element*** involved in natural overtopping, and; ***(3)*** the ***high probability*** of overtopping during the worst-possible conditions attending a strong typhoon. Removal of the problematic channel dam so that the erosion-induced breakout hazard could be eradicated in the **long-term** required that a rapid, surgical breach occur. This would have been **very risky,** however, as truly large lahars would have been produced along the Bucao River, possibly at grave socio-economic and political cost.

DPWH excavated a **low-scour trench** that would **relieve water from the lake without rapidly breaching** the channel dam. The purpose was to ***circumvent*** natural overtopping by providing the lake a more or less stable outlet to escape through. This effectively averted the immediate release of breakout lahars along the Bucao River System and its socio-economic consequences, easing the breakout problem in the **short-term.** There remained, however, the future possibility that a breach may be precipitated by escalating head and discharge incurred from ***sustained intense precipitation*** over the lake (e.g. during a strong typhoon). Since the channel dam still blocks the Maraunot bedrock, lake outflow can still be afforded the chance of eroding and breaching it in due time. The trench would effectively end up **suspending** the breaching process for an **unknown time in the future.** Breaching in the short-term had been circumvented, but the long-term breakout hazard remained unresolved.

It would take PHIVOLCS two months and DPWH even longer continuous monitoring of the trench to deduce the actual long-term consequences from a low-scour Maraunot trench.

6.0 MARAUNOT TRENCH MONITORING DATA

Monitoring Parameters. From 06 September to **05** November, outflow conditions and changes in configuration of the Maraunot trench were monitored using basic and improvised field techniques (Figure 7). Rainfall was recorded daily by a prism gauge at the Maraunot base camp. Discharge across the trench was measured at least twice daily and calculated from flow velocity and flow area. The averaged repeated runs of wood buoys between the 5-15m and 50-60m (later, 55-65m) reaches of the trench were converted to velocity; flow area was measured directly with tape. Trench floor profiles were generated through a modified leveling technique using a clinometer and improvised stadia rods, then later using fixed reference points leveled off at the trench terrace.

Rainfall, Discharge and Lake Level Change. An estimated **4.4** M m^3 (–86,000 m^3/day) of water was added by staggered rainfall over the crater between 06 September and 05 November (Figure 7A, 7C). In response, discharge across the trench fluctuated but rarely exceeded 1 m^3/sec under a lake head generally <1m (Figure 76). The total trench output was roughly 3 M m^3 (–59,000 m^3/day) for the same period, by the end of which discharge had increased its efficiency to about 60% of total lake input (Figure 7C). As a result, lake level that had been rising until 27 September began to decline thereafter due to decreasing net lake input (Figure 7B).

Trench Gradient and Configuration. Time-series profiles of the trench floor yield a total 1.5m of downcutting in the period 8 September-21 October, an average of **~3.5cm/day** (Figure 7D). As the terminus lowered close to channel bedrock (at the nose) and precipitation waned, however, the floor more or less stabilized, as did mouth-to-terminus elevation drop at -2.2m (Figure 7E). No substantial lateral

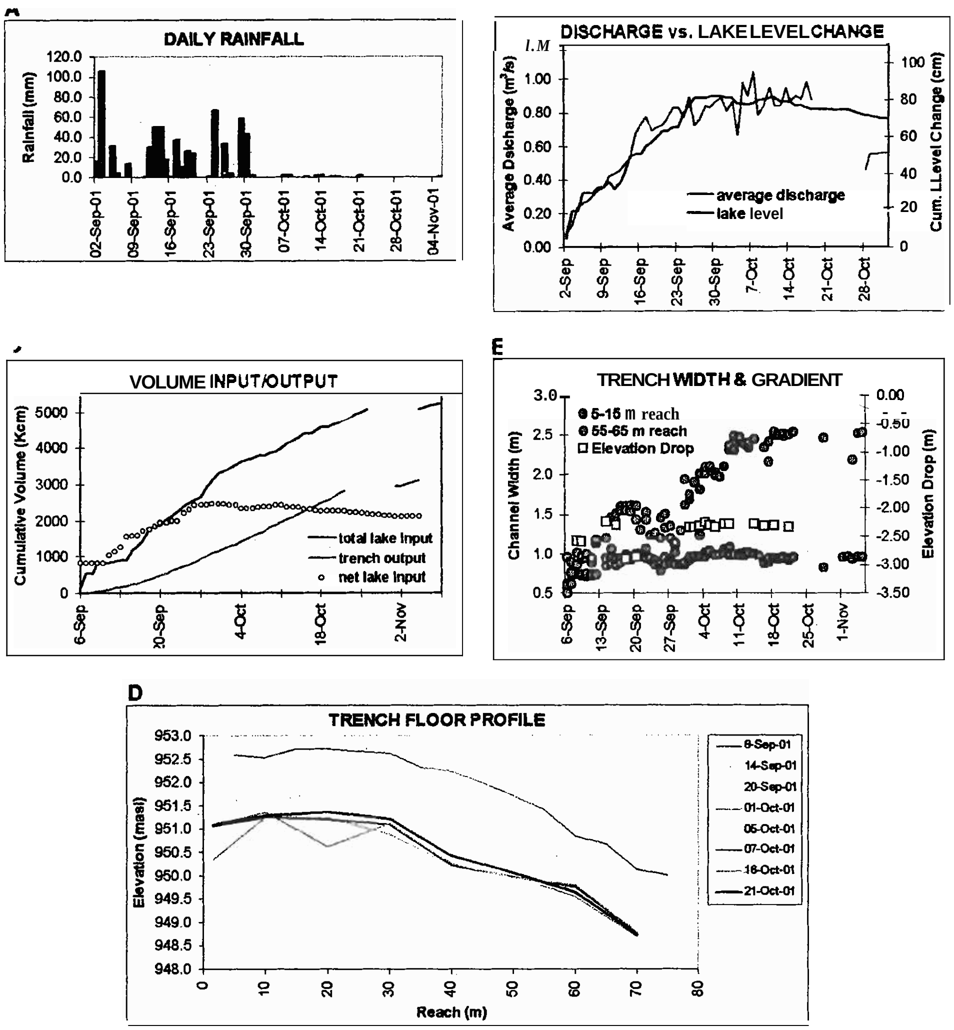

Figure 7. Monitoring record for the Maraunot Notch for the period 02 September - 05 November 5 2002.

erosion occurred at the 5-15 reach or in the first 30m reach for that matter between 06 September-05 November. Nevertheless, there was significant lateral erosion of as much as 2m at the 55-65m reaches and beyond. Erosion is attributed largely to the steeper channel and more turbulent flow at the terminal reaches of the trench.

The adjustments are observed to be caused by erosion of pre-1991 breccia **matrix,** with vertical scour experienced uniformly across the entire floor and lateral scour (sidecutting) confined to the terminal reaches. Matrix erosion also promoted observable ***armoring*** of the trench floor with the dense boulders that remained from attrition of the pre-1991 breccia. The development of a bed armor accounts partly for the restrained vertical scouring shown by both closely staggered floor profiles and quasi-stabilized elevation drop.

7.0 TRENCHING IMPACTS TO THE LAKE BREAKOUT PROBLEM.

Although the trench did not trigger a short-term rapid breach as PHIVOLCS originally intended, the monitoring record paints a truly optimistic outlook for the Maraunot trench and encourages a second look at its positive impacts to breakout problem.

- The first positive sign is in the stability attained from the **armoring capability** of coarse pre-1991 breccia that **restricts**

rapid vertical scouring of the dam. Later adjustments to fluctuating head can then expectedly be confined to modest, mostly lateral matrix erosion and bank collapse that delivers even further armor to the trench bed. If the armoring process persists, and providing no drastic leaps in lake head occur, there is a huge chance of a very protracted sideways and harmless natural breach of the notch transpiring in due course.

- Having stated the above, trenching by itself then had significantly reduced the breakout hazard by **fast-tracking** flow downsection of the dam **onto pre-1991 breccia** level. ***Had natural overtopping been allowed to occur under sustained intense rainfall,*** initial ouflow could have easily scoured a wider channel across the loose 1991 deposits, attaining discharge rates possibly too high for pre-1991 breccia to counteract with armoring.

- Small but significant erosion of pre-1991 breccia also proved that excavation of the channel dam is the long-term solution to the hazard it occasions. The fact that outflow of less than **1 m^3/sec at lake head less than I m** had caused observable erosion of the pre-1991 breccia stresses the need to lessen or even remove it from the channel. With the trench, and downcutting bringing the trench floor close to bedrock, the total thickness of pre-1991 breccia removed to date nears 7m. This corresponds to a significant reduction in the volume magnitude, and hazard, of potential breakout.

- The trench still needs to be tested by ***sustained intense rainfall*** over the lake, but at this point moderate improvements in the trench such as widening may be all that is necessary. Improving **trench outflow capacity** to ***counterbalance*** the inflow from sustained maximum intensity rainfall can prevent critically large head from ever developing in the lake. With help from armoring, this will make the channel dam **stable** and eliminate the probability of erosion-induced breakout **in the long-term.**

- In the final analysis, the trench did **eradicate short-term risk** and significantly **minimized long-term hazard** by ***precluding overtopping at maximum lake tevel.*** The lake was averted from growing an extra **14** M **m^3** and relieved of another **3** M **m^3** with a trench now draining it. This minimizes the magnitude, and thus, the hazards of erosion-induced lake breakout at Maraunot.

There are two natural long-term paths that can be predicted for the Maraunot trench. **First,** under ***staggered and tolerably intense rainfall,*** the trench enlarges sideways and transforms into a fully efficient spillway. At this point, it will have developed the capacity to efficiently and harmlessly subtract inflow even from sustained maximum intensity rainfall before any significant leaps in head develops in the lake. If this condition is achieved, the breakout hazard could be negated in the long-term.

Secondly, if ***sustained maximum intensity rainfall*** occurs (e.g. 1993 Typhoon ***Kadiang;*** Remotigue, 1995) before any trench enlargement can be achieved, escalating lake head and discharge could overcome armoring and rapidly downcut the channel dam. The process is likely to culminate in a ***suspended*** rapid breach. Nonetheless, a significant magnitude of hazard from both added and removed lake volume and a more ominous onset at the original 1991 channel surface has already been removed by trenching itself. By this token alone, the hazard and risk from a suspended breach will be significantly reduced.

8.0 CONCLUSIONS

It is evident from forecast and monitoring data that trenching at Maraunot Notch had **significantly downsized** the Pinatubo crater lake breakout hazard. A long-term resolution of the problem, however, is still under way as the Maraunot trench awaits transformation into a completely efficient spillway. The trench still needs to attain a configuration with the outflow capacity equal to inflow from sustained maximum intensity rainfall over the crater. Any process promoting a safe natural or artificial enlargement of the trench towards this condition should be considered the optimum prospect.

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