Biol Invasions (2009) 11:1767–1776
DOI 10.1007/s10530-008-9356-5

ORIGINAL PAPER

Rapid dispersal and establishment of a benthic Ponto-Caspian goby in Lake Erie: diel vertical migration of early juvenile round goby

Todd A. Hayden · Jeffrey G. Miner

Received: 17 March 2008 / Accepted: 8 September 2008 / Published online: 2 October 2008

Abstract The round goby, *Apollonia melanostoma*, a molluscivore specialist, was introduced to the Great Lakes in the early 1990s and rapidly expanded its distribution, especially in Lake Erie. Adult round goby morphology suggests low dispersal and migration potential due to the lack of a swim bladder and benthic life style. Given that the larval stage occurs inside the benthic egg, and juveniles have adult morphologies, it has been suspected that dispersal and invasion potential is low for early life stages also. However, we identified early juvenile round gobies in the nocturnal pelagic in Lake Erie and thus we conducted a sampling study to determine the extent to which this life stage uses the nocturnal pelagic. Replicate ichthyoplankton samples were collected at 3-h intervals (1900–0700 h) at three depths (2 m, 5 m, 8 m) in western Lake Erie (water depth = 10 m) in July and August 2002 and June 2006. Early juvenile round gobies (6–23 mm TL) were present almost exclusively in the nocturnal samples (2200 h, 0100 h, 0400 h) with peak densities approaching 60 individuals per 100 m^3 of water sampled. Nocturnal density was also significantly greater at 8-m depth versus 2-m and only the smallest fish (6–8 mm TL) migrated to the surface (2-m). Analyses of diet clearly demonstrated that these fish are foraging on plankton at night and thus may not be light limited for foraging in ship ballast tanks. In ships that take on thousands of tonnes of water for ballast, nocturnal ballasting could easily result in transport of thousands of young round gobies at a time. Additionally, within-lake dispersal at this lifestage is likely common and may facilitate downstream passage across barriers designed to limit range expansion.

Keywords Diel vertical migration · Dispersal · Great Lakes · Invasive species · Lake Erie · Round goby

T. A. Hayden (✉) · J. G. Miner
Graduate Program in Ecology, Evolution, and Conservation Biology, Department of Biological Sciences, Bowling Green State University, Bowling Green, OH 43403, USA
e-mail: thayden@bgsu.edu

Introduction

Biological invasion success is a function of several factors including propagule size (number of invaders), invasion frequency, attributes of the invader (fecundity, dispersal ability), as well as biotic and abiotic conditions between the source and invasion sites (species diversity, niche gaps, physical conditions) (Ricciardi and MacIsaac 2000; Vanderploeg et al. 2002). Invasion of the Great Lakes by zebra mussels, (*Dreissena polymorpha*), is an example in which biological attributes such as high fecundity, broad environmental tolerances, and rapid dispersal ability combined with human activities (e.g., transportation via ballast water) and the absence of natural predators resulted in rapid colonization (Nalepa and Schloesser 1993). Given the ecological and economic importance of limiting exotic introductions (Mills et al. 1994), it is critical to understand the mechanisms influencing species persistence and population expansion, which ultimately result in successful exotic species introductions.

Dispersal of fish from natal sites frequently occurs at a young age (larvae) soon after egg hatching (Mora and Sale 2002), although adult migration is also common in pelagic fishes (Fuiman and Werner 2002). As a result of the relatively small size of larval fish and the physical characteristics of the aquatic environment, early life stage dispersal is generally considered to be a function of water movements, such as horizontal water currents and upwelling. Additionally, many fish are able to adjust buoyancy within the water column (vertical migrations) using their swim bladder and thus utilize water currents for dispersal throughout the aquatic landscape (Fuiman and Werner 2002). Understanding dispersal mechanisms of invading species is critical because these provide potential avenues for efforts to block invasions, such as ballast water technology and import inspection procedures (MacIsaac et al. 2002).

The Great Lakes have undergone a series of biological invasions that have strongly modified biological and ecological interactions within the system, such as a loss of bivalve biodiversity (Schloesser et al. 1996; Strayer 1999), increased habitat competition with native fishes (Dubs and Corkum 1996), and increased resources to the benthic community (Stewart et al. 1998). These invasions are a direct result of human manipulation of the environment (e.g., Welland Canal, lamprey introductions) or unintentional movement of species among isolated but similar ecosystems.

A recent successful invader in the Great Lakes, the round goby (*Apollonia melanostoma*), has rapidly colonized the Great Lakes. The round goby was initially discovered in the St. Clair River near Sarnia, Ontario in 1990 (Jude et al. 1992), in Lake Erie in 1993 (Charlebois et al. 1997), and can now be found in all of the Great Lakes. Rapid population expansion was not expected because the round goby (1) is a benthic fish not adapted for long distance swimming, (2) does not have a swim bladder to regulate buoyancy, and (3) does not have a true larval stage (i.e., larval development occurs within the benthic egg; MacInnis and Corkum 2000; Moyle and Cech 2000). These life history characteristics would be expected to constrain dispersal and migration potential. However, the rapid colonization of the Great Lakes suggests round gobies utilize other mechanisms for effective dispersal.

The round goby is native to the Black and Caspian Sea areas and was probably introduced to the Great Lakes through transatlantic ballast water exchange, although the specific life stage for this introduction is not known (Charlebois et al. 1997). General life history characteristics include aggressive territoriality in adult males, repeated spawning sessions (May through August), and high fecundity (200–10,000 eggs per individual per season; Charlebois et al. 1997). Eggs are guarded from predation and environmental influences, such as siltation, by the male until hatching, resulting in up to 95% of the eggs hatching per nest (Charlebois et al. 1997). Although round gobies are found at a range of depths (0 to ≥40 m), some evidence suggests adults migrate to deeper water during winter months and return to shallow water areas in spring (Charlebois et al. 1997). This putative seasonal migration of round gobies may partially explain this species' rapid expansion in the Great Lakes; however, it is unlikely that these migrations are the lone mechanism driving their rapid range expansion. Recent observations of early juvenile round gobies in the nocturnal plankton (Miner, unpublished data; J. Hageman, pers. comm.) suggested early post-hatching juvenile round gobies are able to enter the pelagic water and may undergo water current dispersal.

The objectives of this study were to quantify the use of pelagic waters by early juvenile round gobies and address within lake water current dispersal capability.

Methods and materials

Nocturnal use of pelagic waters by early life stage round gobies was quantified at a site between South Bass and Middle Bass islands in the western basin of Lake Erie during July, August 2002 and June 2006. Ichthyoplankton samples were collected every 3 h, from 1900 to 0700 h by horizontal plankton net tows at three depths (2 m, 5 m, and 8 m) within the water column, which was always ≥ 10 m deep. Sunrise and sunset during this period ranged from 0612 h to 0634 h and from 2041 h to 2103 h, respectfully; thus, both diurnal and nocturnal use of the plankton was determined with this sampling. The nocturnal period included samples collected at 2200 h, 0100 h, and 0400 h while the diurnal samples were collected at 1900 h and 0700 h. Four-minute tows were conducted by deploying and retrieving a 0.75-m diameter, 500-µm mesh ichthyoplankton net towed at a rate of ≥ 1 m s^{-1}. Two replicate samples per depth and time were collected on each date. Depth regulation of the net was achieved using a diving plane and weights attached to the sampling gear. The tow rope angle, measured with a clinometer, and length of tow rope were used to attain the necessary depth. The volume of water sampled was estimated using a General Oceanics mechanical flowmeter (model 2030R) suspended within the ichthyoplankton net mouth. Samples were collected on three dates, July 17/18, July 25/26, and August 8/9 in 2002 and on three dates in June 2006 (June 7/8, June 20/21, and June 28/29. Collected organisms were preserved in ethanol (50%-final concentration) for future laboratory analysis.

Early juvenile round gobies were identified, counted, and measured (total length) using a stereomicroscope with a graduated ocular micrometer. These data were used to estimate the size-frequency of collected round gobies and mean abundance of round gobies in the pelagic (individuals per 100 m^3 of water sampled). Total lengths for round gobies collected during 2002 sampling were analyzed using a χ^2 contingency table to test for independence of round goby total length and capture depth. Since preliminary analyses of round goby pelagic density suggested that the data violated the homogeneity of variance assumption necessary for parametric statistical analyses, all density data (+1) were $\log_{10}$ transformed (Zar 1999). Early juvenile round goby density in the pelagic was expected to be extremely variable resulting from abiotic factors (i.e., weather, lunar cycles) and the goal of this work was to evaluate diel vertical migration of early juvenile round gobies; therefore, statistical analysis incorporated a complete randomized block design with sample date as a block variable, sample depth (2 m, 5 m, 8 m) and time (nocturnal vs. diurnal) as category variables in a multifactor ANOVA (General Linear Model procedure, SAS Version 9).

A possible reason for the use of the nocturnal pelagic by juvenile round gobies is to maximize growth rate via foraging. To determine if juvenile round gobies were foraging in the pelagic and if there was selectivity for particular zooplankton during this period, we collected depth and time-specific zooplankton samples during one collection period (i.e., 8–9 August 2002) using a Schindler-Patalas trap (60-µm mesh, 24.5 l). Zooplankton abundance and planktonic round goby diet data were used to calculate Chesson's diet selectivity indices (Chesson 1978). This index quantifies diet selectivity by comparing the proportion of taxa in the environment to the proportion of the same taxa in the diet using the expression:

$$\alpha_i = (r_i/p_i) \Big/ \sum_{i=1}^{n} (r_i/p_i)$$

where r_i is the proportion of prey taxon i in an individual fish's diet, p_i is the proportion of prey taxon i in the environment, and n is the number of prey taxa in the environment.

Zooplankton abundance estimates (#/L) in the environment were determined by enumerating all zooplankton from subsamples. For each fish used in the diet selectivity analysis, the corresponding abundance of zooplankton prey was based on the average of the two replicate samples taken at that depth and time. Taxonomic groups included copepods (cyclopoid and calanoid copepods), nauplii (copepod nauplii), *Daphnia* spp. (*Daphnia retrocurva* and a few *Daphnia lumholtzi*), *Eubosmina coregoni*, dreissenid (bivalve) veligers, eggs that were likely dreissenid, rotifers, and other rare taxa (*Leptodora* sp., *Diaphanosoma* sp., and ostracods). Diet analysis consisted of identifying all prey items from 50 juvenile round gobies (6.4–20-mm TL) collected on 8–9 August and determining the proportion of each taxon in each fish's diet. Mean and 95% CI for diet selectivity were then determined for each zooplankton taxon. Positive selectivity for a particular prey taxon occurred when mean selectivity and 95% CI were greater than the estimate for neutral selectivity (i.e., $1/n$, where n = number of prey taxa = 7). Similarly, negative selectivity for prey occurred when the mean value and 95% CI were less than $1/n$. Fish with empty stomachs (n = 12) were not included in the analysis.

Results

Distribution

Pelagic early juvenile round gobies (<23-mm TL) were collected almost exclusively in the three nocturnal sample times (2200 h, 0100 h, 0400 h) during the six sampling dates (Fig. 1). Only seven round gobies were collected during the two diurnal sampling periods (1900 h and 0700 h) representing only 0.5% of the round gobies collected ($n = 1503$ total, both years). Although early juvenile round goby density was variable when compared across all sampling dates, all days had a characteristic peak of pelagic round gobies occurring during nocturnal sampling with densities declining to zero during diurnal periods (Fig. 1). Peak round goby densities ranged from 60 individuals per 100 m^3 at 8-m deep on July 17/18 to 6.5 individuals per 100 m^3 on June 7/8 (5-m deep). Of the >1500 fish collected, 23%, 34%, and 43% were caught at 2-m, 5-m and 8-m depth, respectfully.

Pelagic round goby density varied significantly by sampling time (i.e., diurnal vs nocturnal) and sampling depth, while the time-by-depth interaction was not statistically significant (ANOVA, Table 1, $P < 0.05$). Tukey post-hoc comparisons of sampling depth indicate statistically higher densities of round gobies collected at 8-m than at 2-m (no differences by

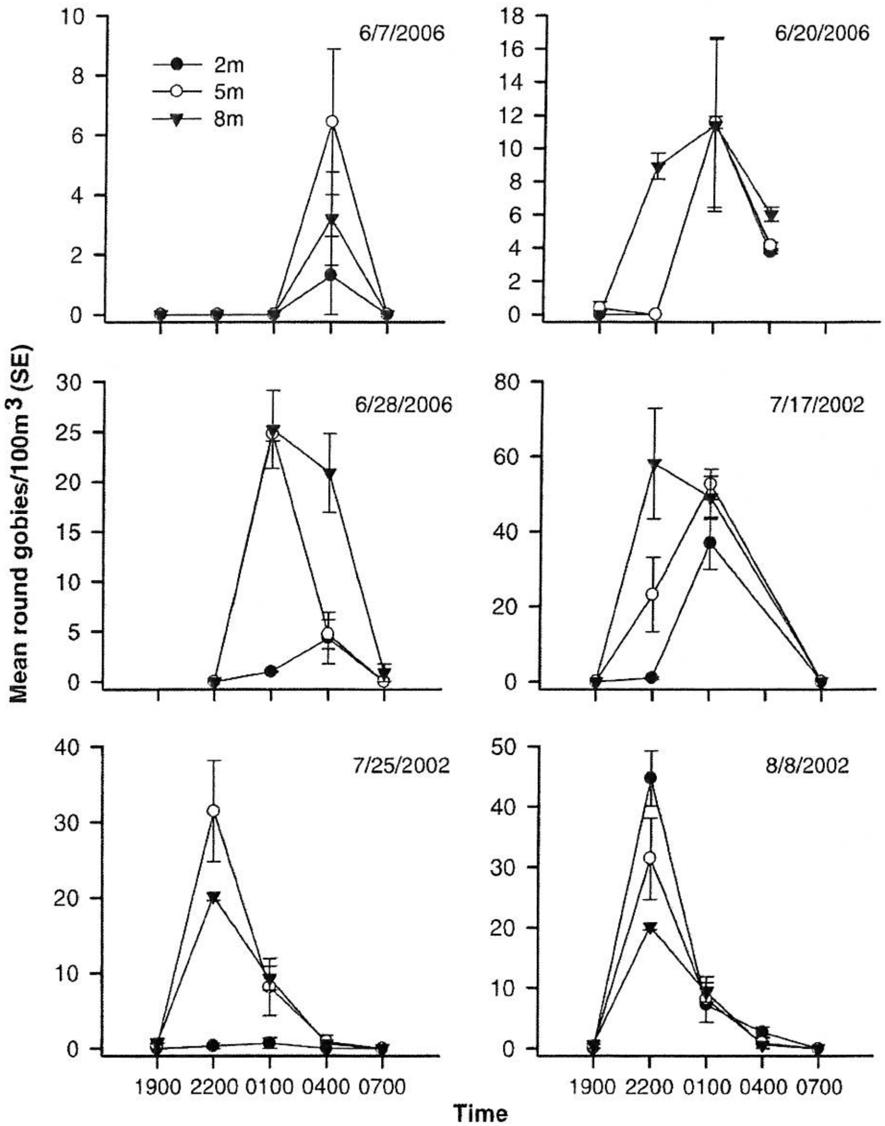


Fig. 1 Pelagic juvenile round goby density for six sampling dates in western Lake Erie. Filled circles indicate density at 2-m depth; open circles = 5-m depth; triangles = 8-m depth. Fish were collected with an ichthyoplankton net at 2 m, 5 m, and 8 m depth in water ≥10-m deep. Means (and ± 1 standard error) are based on two replicate samples ($\log_{10}$(density + 1) transformation). Nocturnal samples were collected at 2200 h, 0100 h, and 0400 h. *Note*: no data collected on 7/18/02 at 0400 h, 6/20/06 at 0700 h, and 6/28/06 at 1900 h and differences in scale for all sampling dates

Table 1 Multiple-factor ANOVA for the abundance of pelagic juvenile round gobies on three sampling dates in 2002 and three dates in 2006 in western Lake Erie

Treatment	df	MS	*F*	*P*
Time (T)	1	95.57	86.48	<0.0001
Depth (D)	2	3.71	3.36	0.0371
D × T	2	0.54	0.49	0.6137
Error	172	1.11		

Date was used as a blocking variable. Fish were collected with an ichthyoplankton net at five times (1900 h, 2200 h, 0100 h, 0400 h, and 0700 h) at 3 depths (2 m, 5 m, 8 m) in water ≥10 m deep. Times were classified as nocturnal (2200 h, 0100 h, 0400 h) or diurnal (1900 h, 0700 h) for analysis

depth with 5-m). The significant depth effect suggests individuals do not distribute randomly throughout the water column. Additionally, round goby abundance in the nocturnal pelagic was significantly greater than abundance during diurnal periods (1900 h and 0700 h, i.e., a time effect, Fig. 1).

A size-dependent depth distribution of pelagic round gobies was clear in the nocturnal samples collected in 2002 (not addressed with 2006 data). Individuals ≥10-mm TL were found only in 5- and 8-m deep samples, while individuals <10-mm TL were found at all sample depths (Fig. 2, $\chi^2 = 80.57$, df = 14, $P < 0.0001$). Overall, length of individuals ranged from 5.6-mm total length (TL) to 23-mm TL with a median length of 8.0-mm TL. Maximum length of individuals captured at the 2, 5, and 8-m depths were 9.4-mm TL, 20.0-mm TL, and 23.0-mm TL, respectively (Fig. 2).

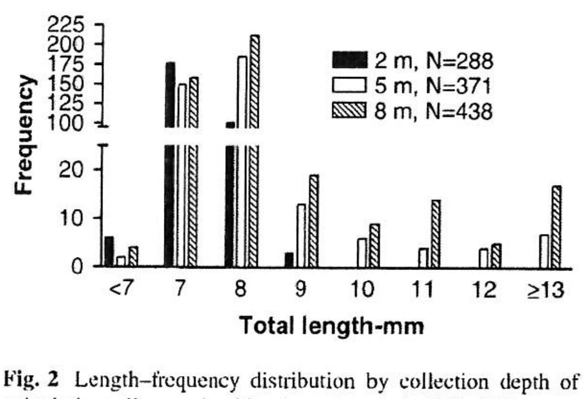


Fig. 2 Length–frequency distribution by collection depth of pelagic juvenile round gobies in western Lake Erie. Chi-square analysis consisted of 1-mm length classes and the class ≥13-mm TL. $n = 1097$. Fish collected over three sample dates in 2002 were pooled

Diet and selectivity

Early juvenile round goby diet in August consisted primarily of four pelagic taxa. Numerically, dreissenids (eggs and veligers) comprised 35% of round goby diets, while copepods comprised 31% of the diet (Fig. 3a). *Eubosmina coregoni* and *Daphnia retrocurva* represented 22% and 11% of the diet, respectively (Fig. 3a). Rotifers, copepod nauplii, and miscellaneous taxa, such as *Leptodora kindti*, *Diaphanosoma* sp. and ostracods occurred infrequently in the diet, less than 1% combined (Fig. 3a). Zooplankton in the environment was numerically dominated by *Dreissena* veligers and eggs (mean = 64.6%,

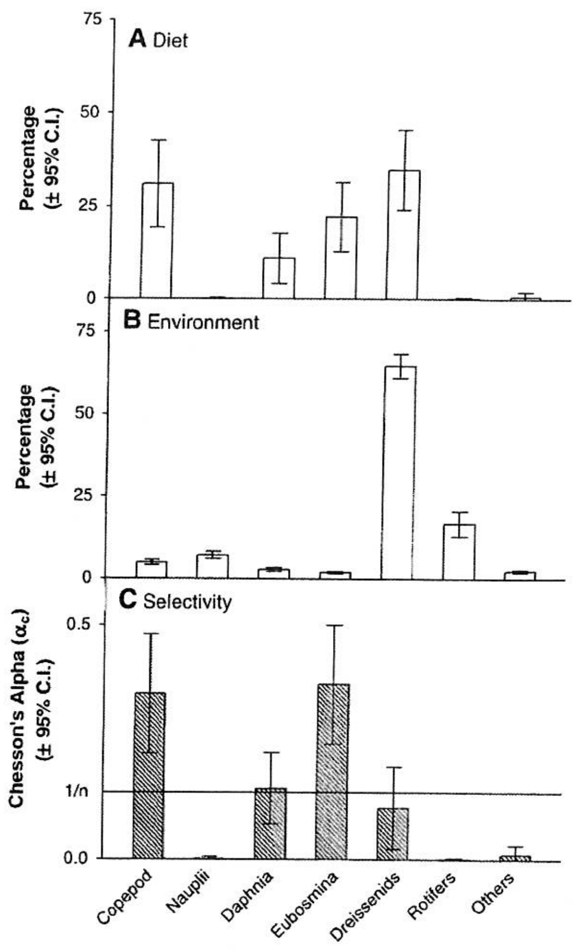


Fig. 3 Diet analysis of nocturnal juvenile round gobies collected in the pelagic of western Lake Erie. (**a**) Percentage of taxa in diet (mean ± 95% CI), (**b**) percentage of taxa in environment (mean ± 95% CI), and (**c**) diet selectivity (α) (mean ± 95% CI)

145 organisms l^{-1}) and rotifers (mean = 16.6%) (Fig 3b), while no other taxon accounted for more than 10% of the zooplankton in Lake Erie at this location (Fig. 3b).

Early juvenile round gobies exhibited strong positive diet selection for copepods and *Eubosmina coregoni* (Fig. 3c). All other taxa had mean selectivity and 95% CI values less than or equal to $1/n$, indicating negative or neutral selectivity (Fig. 3c). These results clearly demonstrate that planktonic juvenile round gobies feed in the nocturnal pelagic, and are not simply utilizing the pelagic water currents as a mechanism of dispersal. The extent to which this nocturnal planktonic foraging supplements diurnal benthic consumption is not known.

Discussion

Results of this study confirm that early juvenile round gobies undergo diel vertical migrations in Lake Erie. In a similar study, density of early juvenile round gobies were quantified in the surface waters of a Lake Michigan estuary and Lake Erie (Hensler and Jude 2007). Although results are similar between these studies and suggest early juvenile round gobies undergo diel vertical migrations, Hensler and Jude (2007) reported lower round goby densities than observed in this study at a similar sampling location in western Lake Erie. In our study, horizontal tows were collected at 2, 5, and 8-m depths and suggest a significant non-random vertical distribution of early juvenile round gobies with generally higher densities at the 8-m sampling depth. In comparison, Hensler and Jude (2007) only conducted surface tows and did not quantify early juvenile round goby density at different depths in the water column. As such, differences between round goby density estimates of these two studies may be explained by depth-dependent vertical migrations, abiotic factors such as weather and lunar cycles influencing vertical migration, or more likely, a combination of abiotic and biotic factors regulating vertical migration.

Previous research into the life history of round gobies (Charlebois et al. 1997; Charlebois et al. 2001) and its likely mechanism for dispersal and invasion of new habitat has not identified the use of the pelagic by early juveniles. A planktonic life stage is a common characteristic of aquatic taxa with a high potential for invasion (Ricciardi and Rasmussen 1998; Vanderploeg et al. 2002) and the results of this study demonstrate the potential planktonic abundance and nocturnal distribution of early juvenile round gobies.

Diel vertical migration by aquatic organisms is well established, (Hutchinson 1967; Wright et al. 1980; Neilson and Perry 1990) although, factors that drive and regulate vertical migration of fishes are thought to vary widely (Brett 1971; Hall et al. 1979). Vertical migration by larval fishes may be (1) an adaptive strategy for thermoregulation of resource processing (i.e., digestive, metabolism; Brett 1971; Wurtsbaugh and Neverman 1988), (2) a mechanism for predator avoidance (Eggers 1978), (3) a strategy to maximize foraging success (Janssen and Brandt 1980) or (4) a combination of these hypotheses (i.e., predator avoidance-foraging hypothesis; Clark and Levy 1988). Given that Lake Erie is generally isothermal to depths of 10–11 m, it is unlikely that the adaptive significance of vertical migration by early juvenile round gobies can be explained by thermoregulation. The predator avoidance hypothesis suggests predation risk is partially dependent on detection ability by the predator, and thus, predation risk may be reduced at times with low light intensity (Clark and Levy 1988; Appenzeller and Leggett 1995). Thus, round gobies may enter the pelagic water only at night when visual predators are light limited and remain close to the substrate during diurnal periods while predators are actively foraging. In our study, >99% of the juvenile round gobies collected in the pelagic were obtained during the nocturnal period. Although we do not know the percentage of the overall juvenile round goby population that vertically migrates, it is clear that mass vertical migration during nocturnal periods is occurring, given the densities observed. In conjunction with predator avoidance, vertical migration may facilitate planktonic feeding (Clark and Levy 1988). If early juvenile round gobies were not feeding in the nocturnal pelagic, we would expect to find few individuals with prey items in the diet or prey items not distributed uniformly throughout the gut. However, our analyses suggest pelagic zooplankton prey were present throughout the water column as well as uniformly distributed throughout the gut. In general, actively feeding larval and juvenile fish have short gut evacuation times that decrease with increasing water temperatures (Persson 1979; Mills et al. 1984; Pedersen 1984). Therefore, prey items consumed by early juvenile round gobies during benthic periods were presumably evacuated from the gut before entering the nocturnal pelagic because they were not reflected in our diet analyses. Although we cannot definitively say that these fish were foraging in the pelagic, our results suggest it is likely. Additionally, our attempts to age these individuals were unsuccessful because we could not identify daily increments on otoliths. Daily otolith increment formation in larval and juvenile fish may be a function of feeding periodicity resulting from fish unable to effectively forage during nocturnal periods and undergoing a period of starvation (Campana and Neilson 1985). Therefore, if early juvenile round gobies do effectively forage throughout the diurnal and nocturnal periods, daily otolith increments may not develop.

Given the importance of rapid growth on survival, nocturnal vertical migration may be an adaptive strategy to minimize predation risk and maximize foraging/growth success. Jude et al. (1995) have shown that round gobies, with their exposed neuromasts, are better able to capture nocturnal zooplankton than indigenous mottled sculpins, *Cottus bairdi*, which raises the question why juvenile round gobies are migrating into the pelagic when benthic resources available during the day should also be accessible at night. Clearly, exploring the predation risk-growth rate tradeoff between diurnal and nocturnal periods in the benthos versus the pelagic is needed (Werner et al. 1983; Anholt and Werner 1995).

Size-frequency distributions of planktonic round gobies varied significantly by sample depth. This may indicate decreasing benefits (or increasing costs) for juvenile round gobies entering the nocturnal water column as length increases. Individuals $\geq$10-mm TL were only captured at 5- or 8-m depth and not in surface waters (2-m depth). Energy expenditure by round gobies to enter and maintain location within the nocturnal pelagic, in addition to increased risk of predation (resulting from increased size) must be offset by the energetic gains of feeding on pelagic zooplankton; this appears to occur when these fish are small, but the trade-off advantage appears to be lost rapidly as they increase in size. Ontogenetic habitat shifts similar to this are common (e.g., bluegill, *Lepomis macrochirus*, Werner and Hall 1988). Another potential explanation for size-dependent vertical migration is that individuals $\geq$10-mm TL may be less gape limited for benthic prey, therefore lowering the benefits to entering the nocturnal pelagic.

Logachev and Mordvinov (1979) suggest that round gobies are active and able to swim immediately following hatching and rapidly improve swimming ability. Newly hatched round gobies are active 7% of the time and have an average swimming rate of 2 cm s^{-1}, while three-day old round gobies are active 29% of the time and are able to swim 4 cm s^{-1}. Given these results, early juvenile round gobies may be able to enter the pelagic water by swimming and are not constrained to the benthos by the lack of a swim bladder. Similarly, the pelagic lifestage of marine gobies in the family Gobiidae is well documented (Sponaugle and Cowen 1994; Kingsford 2001; Radtke et al. 2001; McIlwain 2003). Clearly, a better understanding of swimming ability for this life stage is needed, as well as factors regulating use of the pelagic.

Prevailing hypotheses suggest that adult round gobies were entrained in ballast tanks and transported to Lake Erie. However, our results demonstrate that early juvenile round gobies are able to enter the nocturnal pelagic and thus high densities of this life stage may have been entrained in ballast tanks and released in Lake Erie and at harbors throughout the Great Lakes and Europe. Modern ships with high capacity ballast tanks could easily provide substantial propagule size (i.e., number of new colonists in a single invasion event) to increase the likelihood of establishment (Groves and Burdon 1986; Ricciardi and Rasmussen 1998). In our study, the highest abundance in the pelagic was 60 individuals m^{-3}. Therefore, a ballast water uptake of 10,000 m^3 with juvenile round gobies at this density could result in approximately 600,000 individuals entrained in the ballast water. Furthermore, because adult round goby densities are highest in the cobble/riprap substrates common around harbors (Ray and Corkum 2001), densities of planktonic juvenile round gobies may be even higher where ballast tank filling occurs. Certainly, the hypothesis of a small founding population in the Great Lakes is not supported by genetic studies, as genetic variability of the round goby is similar between European and Great Lakes populations (Dougherty et al. 1996; Dillon and Stepien 2001).

In addition to being the most likely source of transatlantic dispersal, early juvenile use of the nocturnal planktonic may contribute strongly to intra-lake dispersal of round gobies. As an exercise to estimate potential dispersal distances of early juvenile round gobies, time spent in the pelagic was multiplied by an estimate of water current velocity. Given the results of our pelagic sampling, juvenile round gobies appear to spend as much as 6 h per night in the pelagic (although we could not track individuals). Mean summer current velocity estimates in Lake Erie range from 0.1 to 4.4 cm s^{-1} (Kovacik 1972; Beletsky et al. 1999). Combining these variables suggests early juvenile round goby dispersal ability for a 6-h pelagic night is about 1 km. In this example, seasonal mean current velocities were used to estimate dispersal ability. Therefore, high velocity water currents resulting from extreme weather may result in substantial variability in dispersal ability. This example does not suggest dispersal direction, or take into consideration the ability of early juvenile round gobies to direct dispersal outcome through swimming; however it does illustrate the likely importance of early life stage drift dispersal in population expansion within the Great Lakes.

The 'invasional meltdown' hypothesis suggests ecosystems become less invasion resistant with increasing species diversity (Simberloff and Von Holle 1999; Ricciardi 2001). This hypothesis suggests perturbations of the community by previous successful invasions may facilitate future invasions by creating and modifying existing niches, effectively opening the door to invaders adapted to those niches (Simberloff and Von Holle 1999). In the Great Lakes, the establishment of the zebra mussel (*Dreissena polymorpha*), an important prey for the round goby, may have facilitated the subsequent establishment of the round goby by providing an unexploited food resource (Charlebois et al. 1997; Simonovic et al. 2001). The Great Lakes may be undergoing an 'invasional meltdown' and are likely to experience future successful invasions (Ricciardi 2001). Therefore, it is critical to identify all invading species dispersal mechanisms and understand how those mechanisms regulate successful species introductions. It seems unlikely that the round goby invaded successfully from just a few adults in ballast water. Instead, even a single introduction of thousands of early juveniles at multiple locations may have been the lifestage and propagule size necessary to 'seed' the Great Lakes.

Acknowledgments This work was funded by the Lake Erie Protection Fund grant (SG185-02) to J. Miner and a research assistantship from the Department of Biological Sciences at Bowling Green State University to T. Hayden. Thanks to John Hageman and The Ohio State University Stone Lab for logistical support. We thank Chris Winslow, Edward Carruthers, James Bales, and Jennifer Hayden for helping with field collections and sample preparations. This manuscript benefited from critiques by Dan Wiegmann and anonymous reviewers.

References

Anholt BR, Werner EE (1995) Interaction between food availability and predation mortality mediated by adaptive behavior. Ecology 76:2230–2234. doi:10.2307/1941696

Appenzeller AR, Leggett WC (1995) An evaluation of light-mediated vertical migration of fish based on hydroacoustic analysis of the diel vertical movements of rainbow smelt (*Osmerus mordax*). Can J Fish Aquat Sci 52:504–511. doi:10.1139/f95-051

Beletsky D, Saylor JH, Schwab DJ (1999) Mean circulation in the Great Lakes. J Great Lakes Res 25:78–93

Brett JR (1971) Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*). Am Zool 11:99–113

Campana SE, Neilson JD (1985) Microstructure of fish otoliths. Can J Fish Aquat Sci 42:1014–1032. doi:10.1139/f85-127

Charlebois PM, Marsden JE, Goettel RG, Wolfe RK, Jude DJ, Rudnika S (1997) The round goby, *Neogobius melanostomus* (Pallas), a review of European and North American literature. Illinois-Indiana Sea Grant Program and Illinois Nautral History Survey. INHS Special Publication No. 20, 76 pp

Charlebois PM, Corkum LD, Jude DJ, Knight C (2001) The round goby (*Neogobius melanostomus*) invasion: current research and future needs. J Great Lakes Res 27:263–266

Chesson J (1978) Measuring preference in selective predation. Ecology 59:211–215. doi:10.2307/1936364

Clark CW, Levy DA (1988) Diel vertical migrations by juvenile sockeye salmon and the antipredation window. Am Nat 131:271–290. doi:10.1086/284789

Dillon AK, Stepien CA (2001) Genetic and biogeographic relationships of the invasive round (*Neogobius melanostomus*) and tubenose (*Proterorhinus marmoratus*) gobies in the Great Lakes versus Eurasian populations. J Great Lakes Res 27:267–280

Dougherty JD, Moore WS, Ram JL (1996) Mitochondrial DNA analysis of round goby (*Neogobius melanostomus*) and tubenose goby (*Proterorhinus marmoratus*) in the Great Lakes basin. Can J Fish Aquat Sci 53:474–480. doi:10.1139/cjfas-53-3-474

Dubs DOL, Corkum LD (1996) Behavioral interactions between round gobies (*Neogobius melanostomus*) and mottled sculpins (*Cottus bairdi*). J Great Lakes Res 22:838–844

Eggers DM (1978) Limnetic feeding behavior of juvenile sockeye salmon in Lake Washington and predator avoidance. Limnol Oceanogr 23:1114–1125

Fuiman LA, Werner RG (2002) Fishery science. Blackwell Science, Malden, 326 pp

Groves RH, Burdon JJ (1986) Ecology of biological invasions. Cambridge University Press, Cambridge

Hall DJ, Werner EE, Gilliam JF, Mittelbach GG, Howard D, Doner CG (1979) Diel foraging behavior and prey selection in the golden shiner (*Notemigonus chrysoleucas*). J Fish Res Board Canada 36:1029–1039

Hensler SR, Jude DJ (2007) Diel vertical migration of Round Goby larvae in the Great Lakes. J Great Lakes Res 33:295–302. doi:10.3394/0380-1330(2007)33[295:DVMORG]2.0.CO;2

Hutchinson GE (1967) A treatise on limnology. Wiley, New York

Janssen J, Brandt SB (1980) Feeding ecology and vertical migration of adult alewives (*Alosa pseudoharengus*) in Lake Michigan. Can J Fish Aquat Sci 37:177–184. doi:10.1139/f80-023

Jude DJ, Reider RH, Smith GR (1992) Establishment of Gobiidae in the Great Lakes basin. Can J Fish Aquat Sci 49:416–421. doi:10.1139/f92-047

Jude DJ, Janssen J, Crawford G (1995) Ecology, distribution, and impact of the newly introduced round and tubenose gobies in the biota of the St. Clair and Detroit rivers. In: Munawar M, Edsall T, Leach J (eds) The Lake Huron ecosystem: ecology, fisheries, and management. Ecovision World Monograph Series, S. P. B. Academic Publishing, The Netherlands, pp 447–460

Kingsford MJ (2001) Diel patterns of abundance of presettlement reef fishes and pelagic larvae on a coral reef. Mar Biol (Berl) 138:853–967. doi:10.1007/s002270000455

Kovacik TL (1972) Information on the velocity and flow pattern of Detroit River water in western Lake Erie revealed by an accidental salt spill. Ohio J Sci 72:81–86

Logachev VS, Mordvinov YE (1979) Swimming speed and activity of larvae of round goby and some predatory crustaceans of the Black Sea. Biol Morya 3:77–80

MacInnis AJ, Corkum LD (2000) Fecundity and reproductive season of the round goby *Neogobius melanostomus* in the upper Detroit River. Trans Am Fish Soc 129:136–144. doi:10.1577/1548-8659(2000)129<0136:FARSOT>2.0.CO;2

MacIsaac HJ, Robbins TC, Lewis MA (2002) Modeling ships' ballast water as invasion threats to the Great Lakes. Can J Fish Aquat Sci 59:1245–1256. doi:10.1139/f02-090

McIlwain JL (2003) Fine-scale temporal and spatial patterns of larval supply to a fringing reef in Western Australia. Mar Ecol Prog Ser 252:207–222. doi:10.3354/meps252207

Mills EL, Ready RC, Jahncke M, Hanger CR, Trowbridge C (1984) A gastric evacuation model for young yellow perch, *Perca flavescens*. Can J Fish Aquat Sci 41:513–518. doi:10.1139/f84-061

Mills EL, Leach JH, Carlton JT, Secor CL (1994) Exotic species and the integrity of the Great Lakes. Bioscience 44:666–676. doi:10.2307/1312510

Mora C, Sale PF (2002) Are populations of coral reef fish open or closed? Trends Ecol Evol 17:422–428. doi:10.1016/S0169-5347(02)02584-3

Moyle PB, Cech JJJ (2000) Fishes—an introduction to ichthyology. Prentice Hall, Upper Saddle River, 612 pp

Nalepa TF, Schloesser DW (1993) Zebra mussels: biology, impacts, and control. Lewis, Boca Raton

Neilson JD, Perry RI (1990) Diel vertical migrations of marine fishes: an obligate or facultative process? Adv Mar Biol 26:115–168. doi:10.1016/S0065-2881(08)60200-X

Pedersen BH (1984) The intestinal evacuation rates of larval herring (*Clupea harengus*) predating on wild plankton. Dana 3:21–30

Persson L (1979) The effects of temperature and different food organisms on the rate of gastric evacuation in perch (*Perca fluviatilis*). Freshw Biol 9:99–104. doi:10.1111/j.1365-2427.1979.tb01493.x

Radtke RL, Kinzie RA III, Shafer DJ (2001) Temporal and spatial variation in length of larval life and size at settlement of the Hawaiian amphidromous goby. J Fish Biol 59:928–938

Ray WJ, Corkum LD (2001) Habitat and site affinity of the Round Goby. J Great Lakes Res 27:329–334

Ricciardi A (2001) Facilitative interactions among aquatic invaders: is an "invasional meltdown" occurring in the Great Lakes? Can J Fish Aquat Sci 58:2513–2525. doi:10.1139/cjfas-58-12-2513

Ricciardi A, MacIsaac HJ (2000) Recent mass invasion of the North American Great Lakes by Ponto-Caspian species. Trends Ecol Evol 15:62–65. doi:10.1016/S0169-5347(99)01745-0

Ricciardi A, Rasmussen JB (1998) Predicting the identity and impact of future biological invaders: a priority for aquatic resource management. Can J Fish Aquat Sci 55:1759–1765. doi:10.1139/cjfas-55-7-1759

Schloesser DW, Nalepa TF, Mackie GL (1996) Zebra mussel infestation of unionid bivalves (Unionidae) in North America. Am Zool 36:300–310

Simberloff D, Von Holle B (1999) Positive interactions of nonindigenous species: invasional meltdown? Biol Invasions 1:21–32. doi:10.1023/A:1010086329619

Simonovic P, Paunovic M, Popovic S (2001) Morphology, feeding, and reproduction of the round goby, *Neogobius melanostomus* (Pallas), in the Danube River Basin, Yugoslavia. J Great Lakes Res 27:281–289

Sponaugle S, Cowen RK (1994) Larval durations and recruitment patterns of two Caribbean gobies (Gobiidae): contrasting early life histories in demersal spawners. Mar Biol (Berl) 120:133–143

Stewart TW, Miner JG, Lowe RL (1998) Quantifying mechanisms for zebra mussel effects on benthic macroinvertebrates: organic matter production and shell generated habitat. J North Am Benthol Soc 17:81–94. doi:10.2307/1468053

Strayer DL (1999) Effects of alien species on freshwater mollusks in North America. J North Am Benthol Soc 18:74–98. doi:10.2307/1468010

Vanderploeg HA, Nalepa TF, Jude DJ, Mills EL, Holeck KT, Liebig JR et al (2002) Dispersal and emerging ecological impacts of Ponto-Caspian species in the Laurentian Great

Lakes. Can J Fish Aquat Sci 59:1209–1228. doi:10.1139/f02-087

Werner EE, Hall DJ (1988) Ontogenetic habitat shifts in Bluegill: the foraging rate-predation risk trade-off. Ecology 69:1352–1366. doi:10.2307/1941633

Werner EE, Gilliam JF, Hall DJ, Mittelbach GG (1983) An experimental test of the effects of predation risk on habitat use in fish. Ecology 64:1540–1548. doi:10.2307/1937508

Wright D, O'Brien WJ, Vinyard GL (1980) Adaptive value of vertical migration: a simulation model argument for the predation hypothesis. In: Kerfoot WC (ed) Evolution and ecology of zooplankton communities. University Press of New England, Hanover, pp 138–147

Wurtsbaugh WA, Neverman D (1988) Post-feeding thermotaxis and daily vertical migration in a larval fish. Nature 333:846–848. doi:10.1038/333846a0

Zar JH (1999) Biostatistical analysis. Prentice Hall, Englewood Cliffs, NJ, 663 pp

Dye Testing Kaukuana Lock 1

8-16-17

FRNSA: Tim Rose, Jeremy Cords
raSmith: Jeff Mazanec

Test 1 – Blue Dye Test

Test was to see if there was any backwash through the lock gates from downriver side into the upriver side. Outcome - No dye was detected on the upriver side.

Photo

1-1 – upriver side of lock before dye

1-2 – down river side of lock turbulence from butterfly valves

1-3 – similar to 2 and 4 showing turbulence

1-4 – Turbulence associated on down river side with butterfly valves open 4, 5, 6 valves open

1-5 – dye application by raSmith down river side of lock door

1-6 – dye application by raSmith down river side of lock door

1-7 - dye on down river side of lock door

1-8 – dye down river lock door butterfly valves opened

1-9 – Dye Application

1-10 – FRNSA and raSmith inspecting dye application

1-11 – Turbulence associated with butterfly valves open

1-12 – Turbulence

1-13 – Turbulence at lock door associated with butterfly valves open and no dye present

1-14 – Turbulence at lock door no dye present

1-15 – Turbulence at lock door no dye present

1-16 – Water level upstream side of lock door at end of test

1-17 – Lock doors partially open showing no dye present

1-18 – Lock doors completely open showing no dye present

1-19 – Lock doors closed and lock chamber refilled

Test 2 – Blue Dye Test

To check the backwash from the downriver side to the upriver side with the butterfly valves open. Dye was applied to surface of water on downriver side. Outcome – No backwash was detected on the upriver side.

Dye Testing Kaukuana Lock 1
8-16-17

FRNSA: Tim Rose, Jeremy Cords
raSmith: Jeff Mazanec

Photo

2-1 – Lock gates closed no dye added

2-2 – Blue dye added to upriver side of lock gate

2-3 – Downriver side of lock no blue dye detected

2-4 – Downriver side turbulence when lock gates open

Test 3 – Blue Dye Test

Butterfly valves and gates closed upriver side. Dye injected on the upriver side of the gates at the level of the butterfly valve with PVC pipe

Photo

3-1 – Injecting blue dye to level of butterfly valve through a ¾ inch PVC pipe

3-2 – upriver side dye present when butterfly valves opened

3-3 – same as 3-2

3-4 – Downriver side of the gate no blue dye detected

3-5 – Downriver side of gates with butterfly valves open no dye detected

Test 4 – Blue Dye Test

Water surface various locations upriver side of lock gate. Gate closed

4-1 – Dye being applied

4-2 – Various sites of dye application upriver side

4-3 – same as 4-2

4-4 – No dye present down river side of lock gate. Lock gates closed

Test 5 – Yellow Dye Test

Downriver side of lock gates to evaluate currents and eddies that develop when butterfly valves open.

5-1 – Yellow dye added to downriver side of lock gates

5-2 – same as 5-1

5-3 – Dye dispersal along lock gate downriver side

5-4 – Dispersal on both sides of lock gates

5-5 – Dye migration into the area of eddies between lock gate and lock wall

Dye Testing Kaukuana Lock 1

8-16-17

FRNSA: Tim Rose, Jeremy Cords
raSmith: Jeff Mazanec

5-6 – Eddy formation at lock wall and lock gate

5-7 – Migration of dye from lock wall and lock gate to center of lock gates

5-8 – same as 5-7

5-9 – Dye migration pattern downriver when butterfly valves open

5-10 – same as 5-9

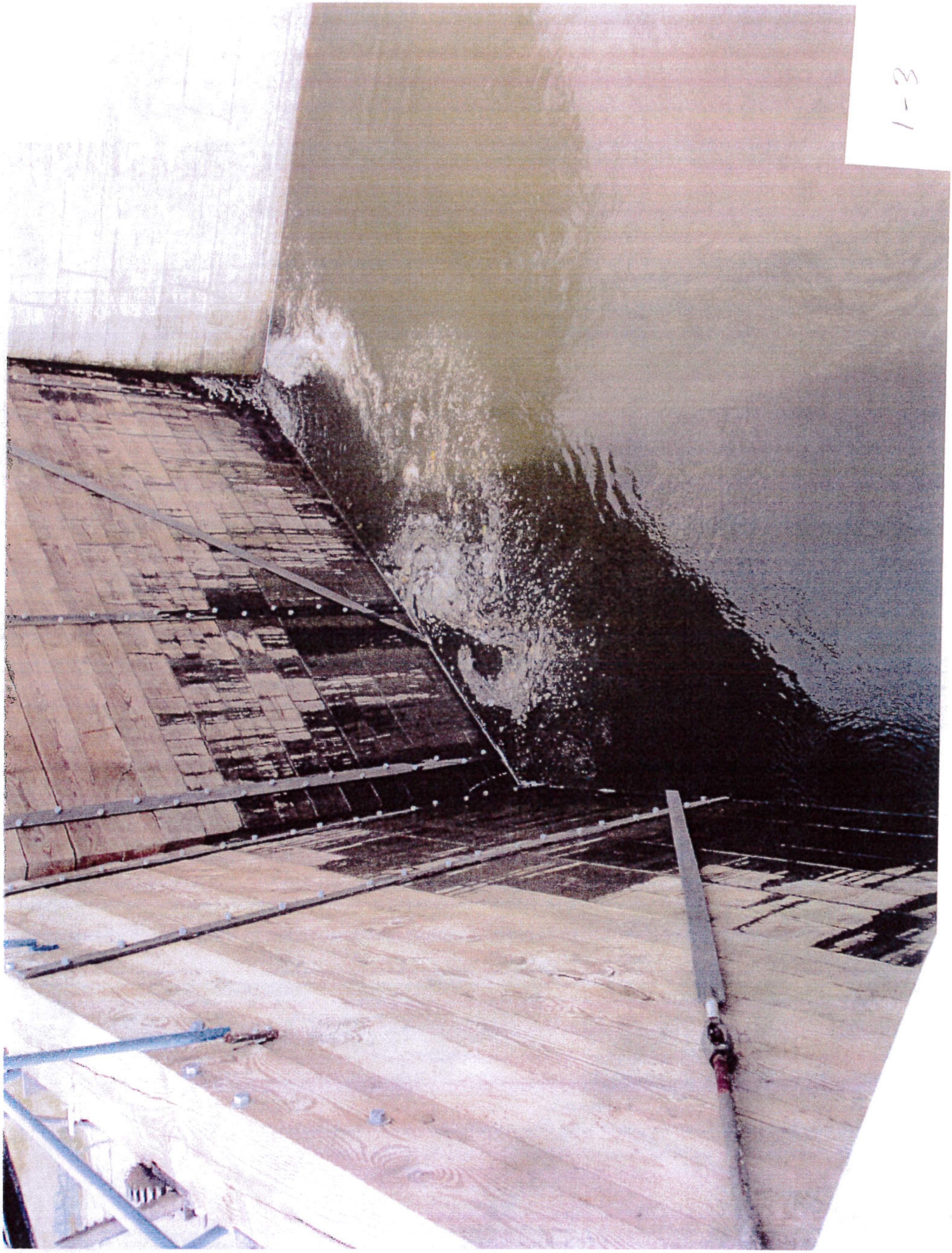
5-11 – same as 5-9

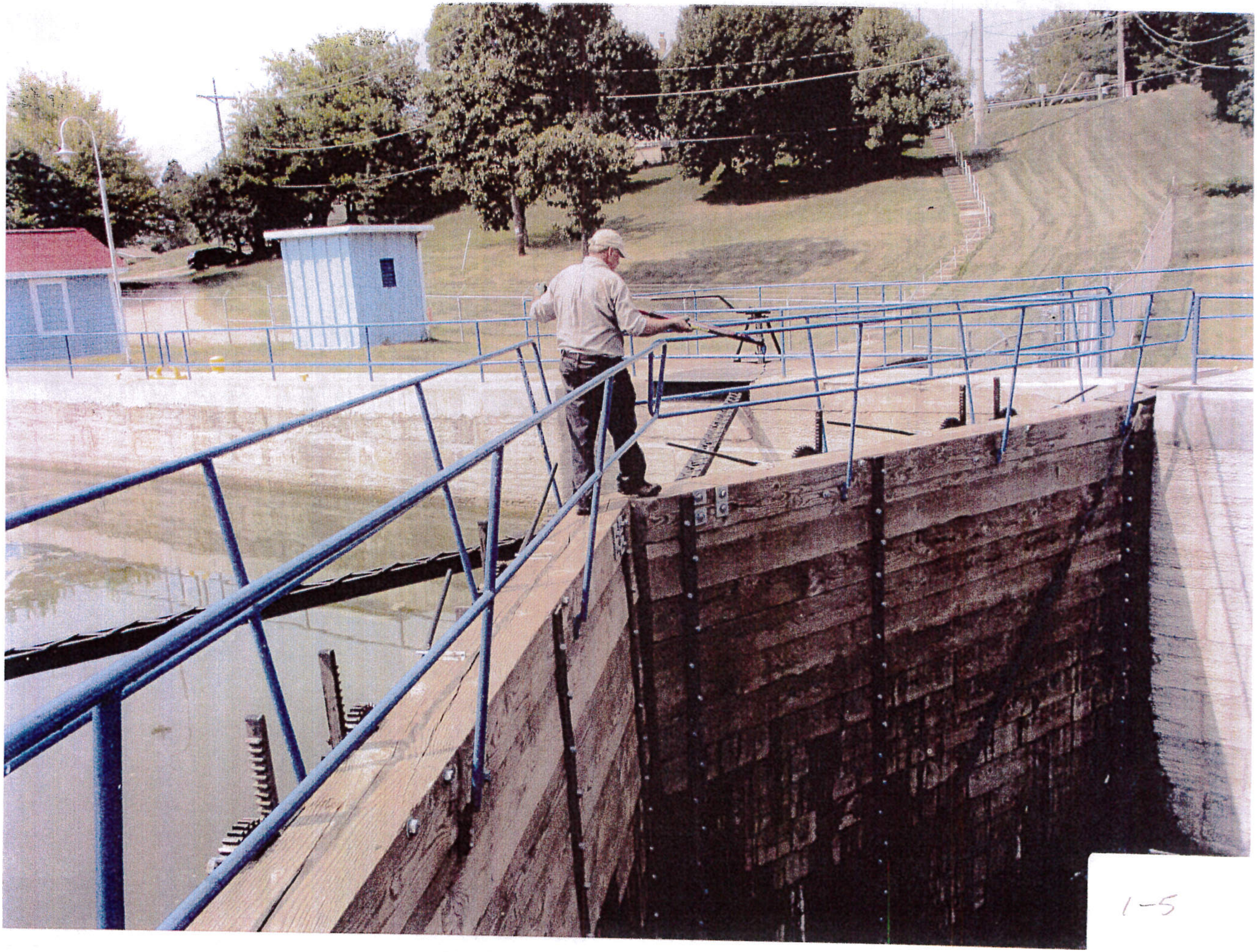
5-12 – No dye present on downriver side of lock gates

5-13 – same as 5-12

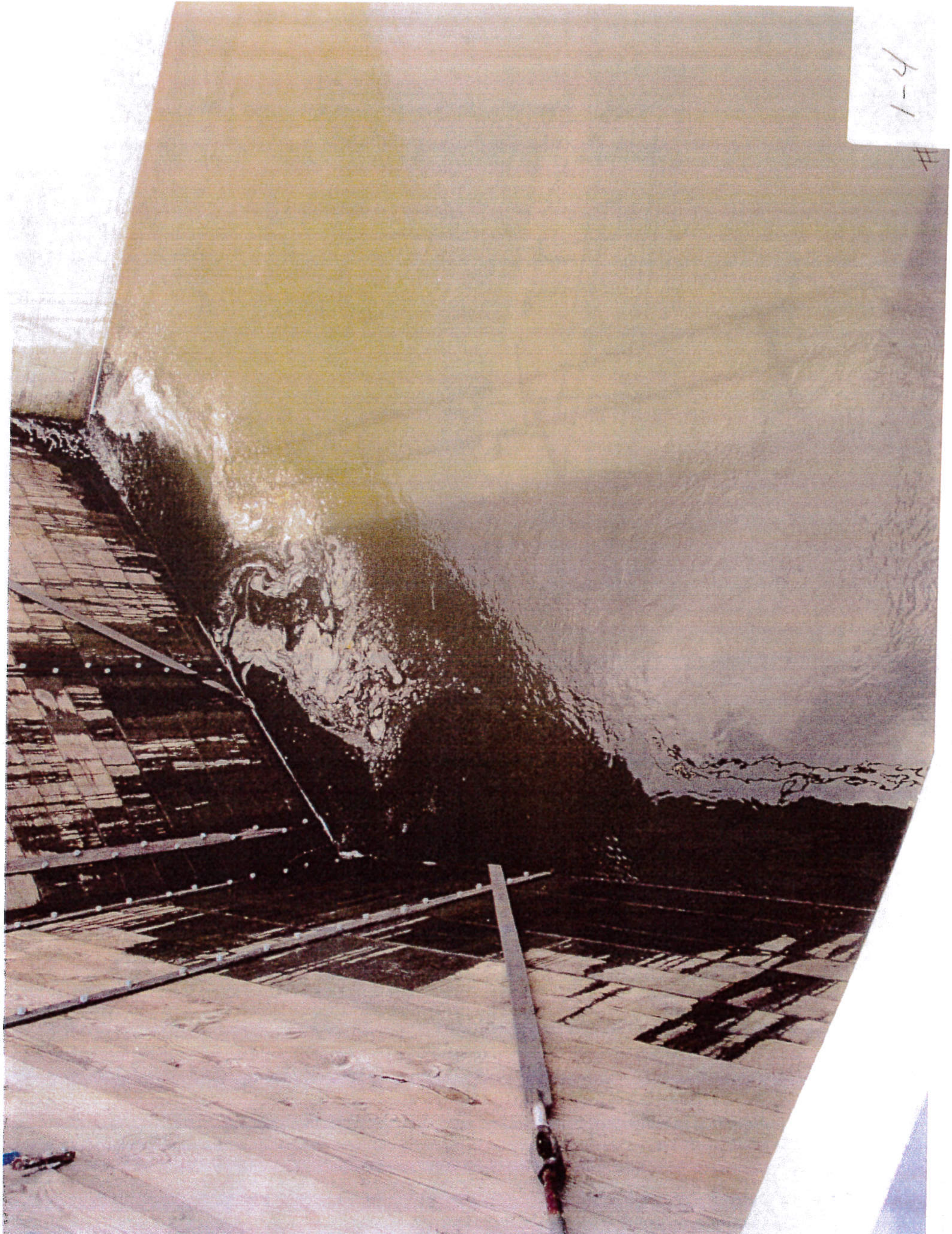
1-2

1-3

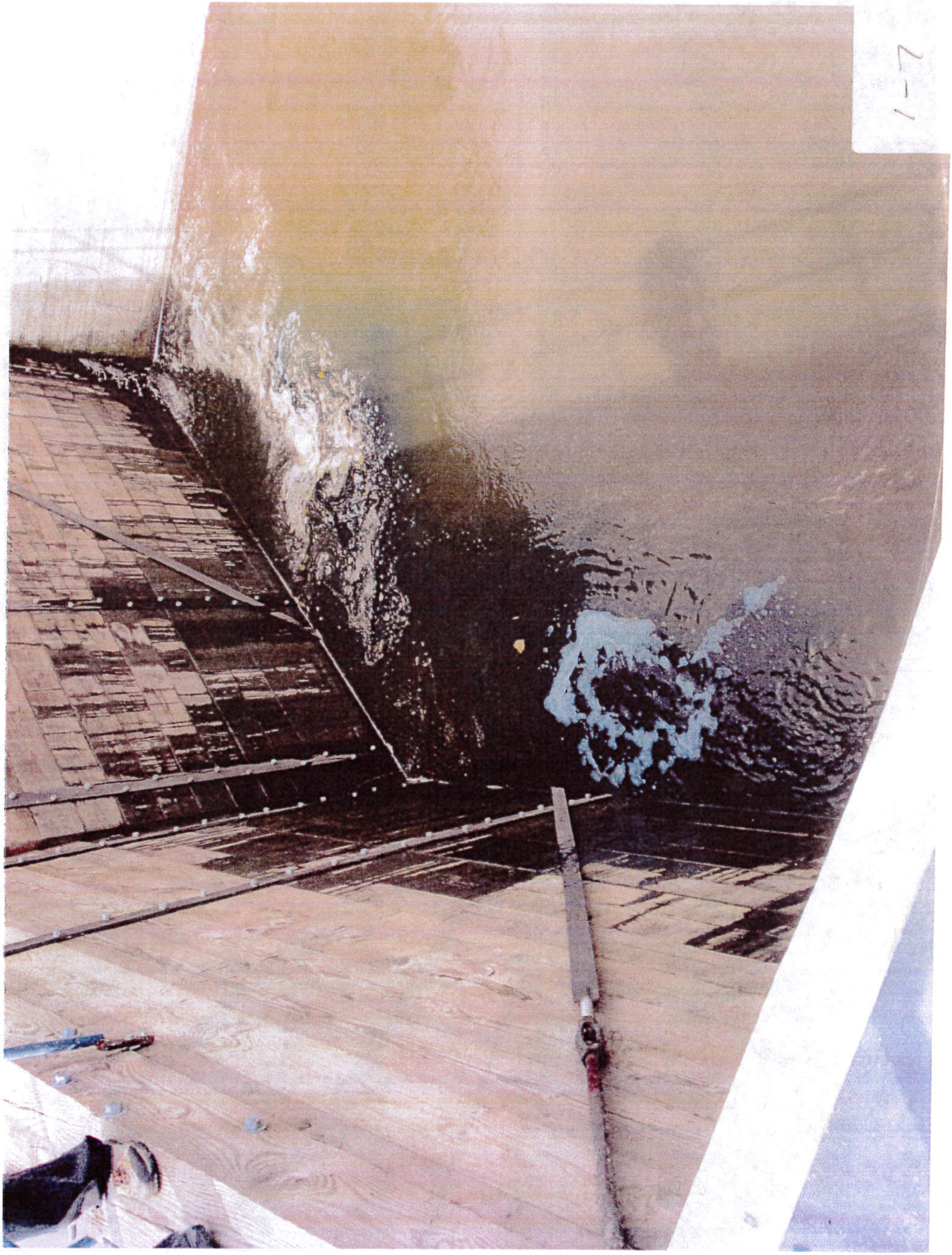




1-5



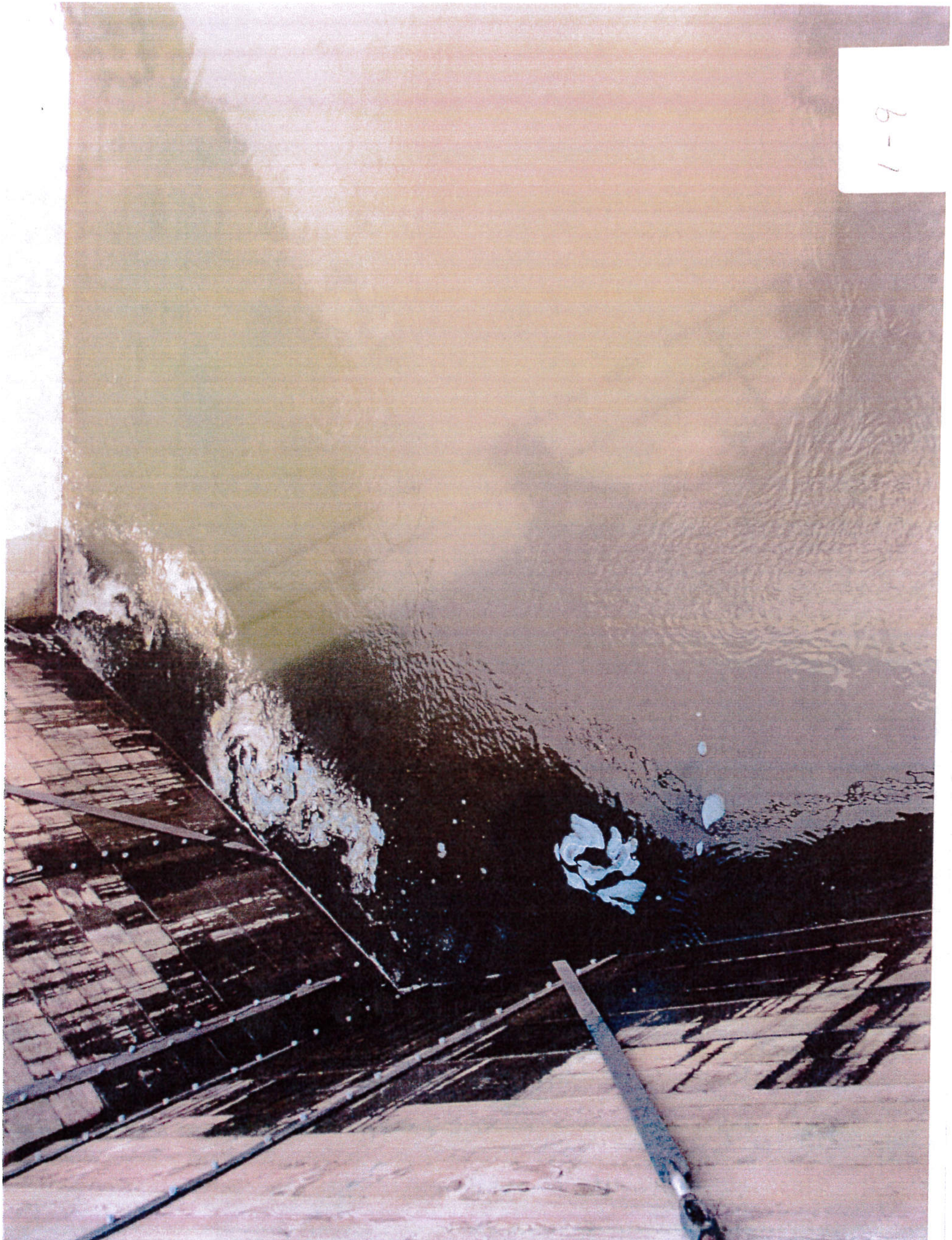
#1-4



1-7

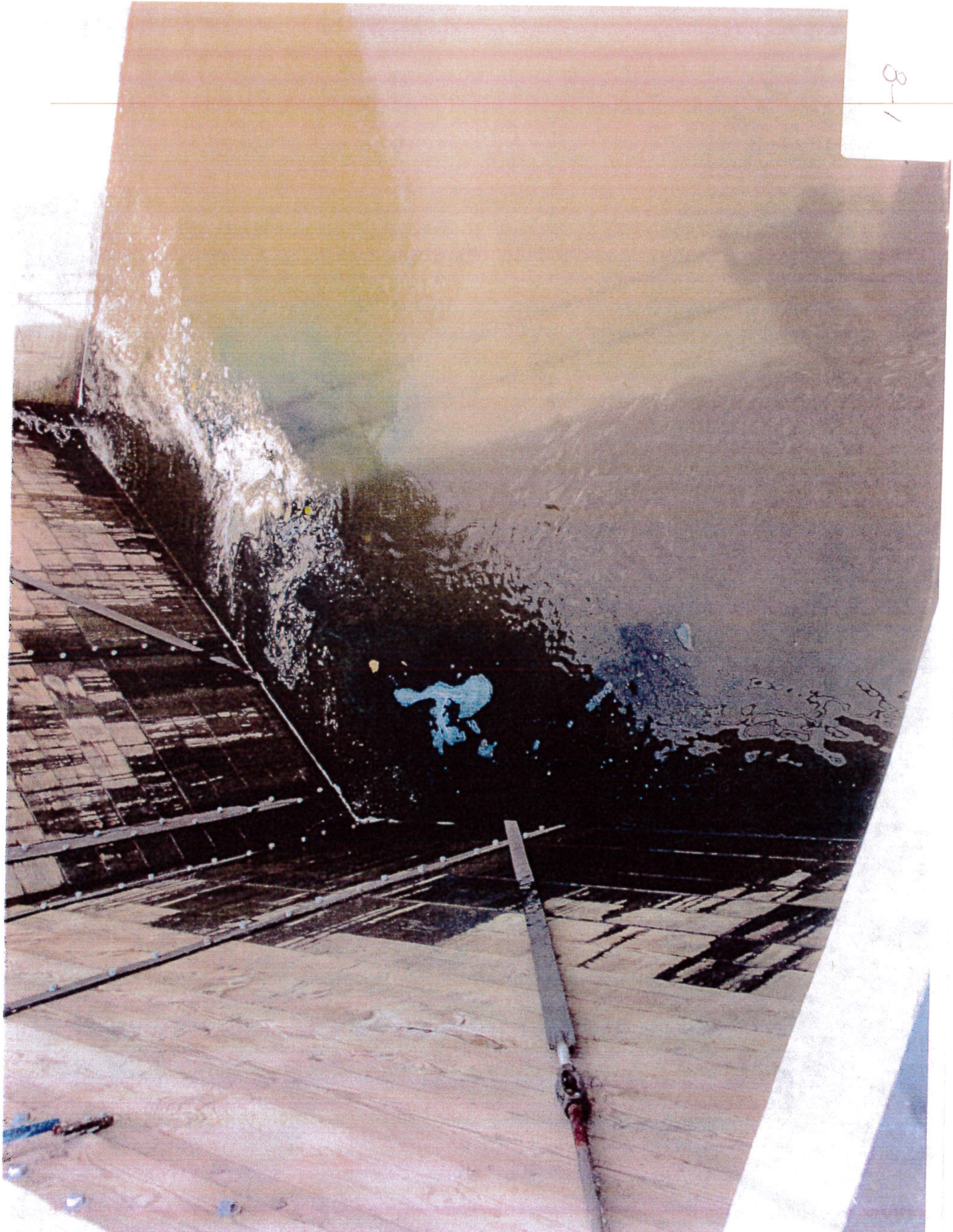
1-6

#6



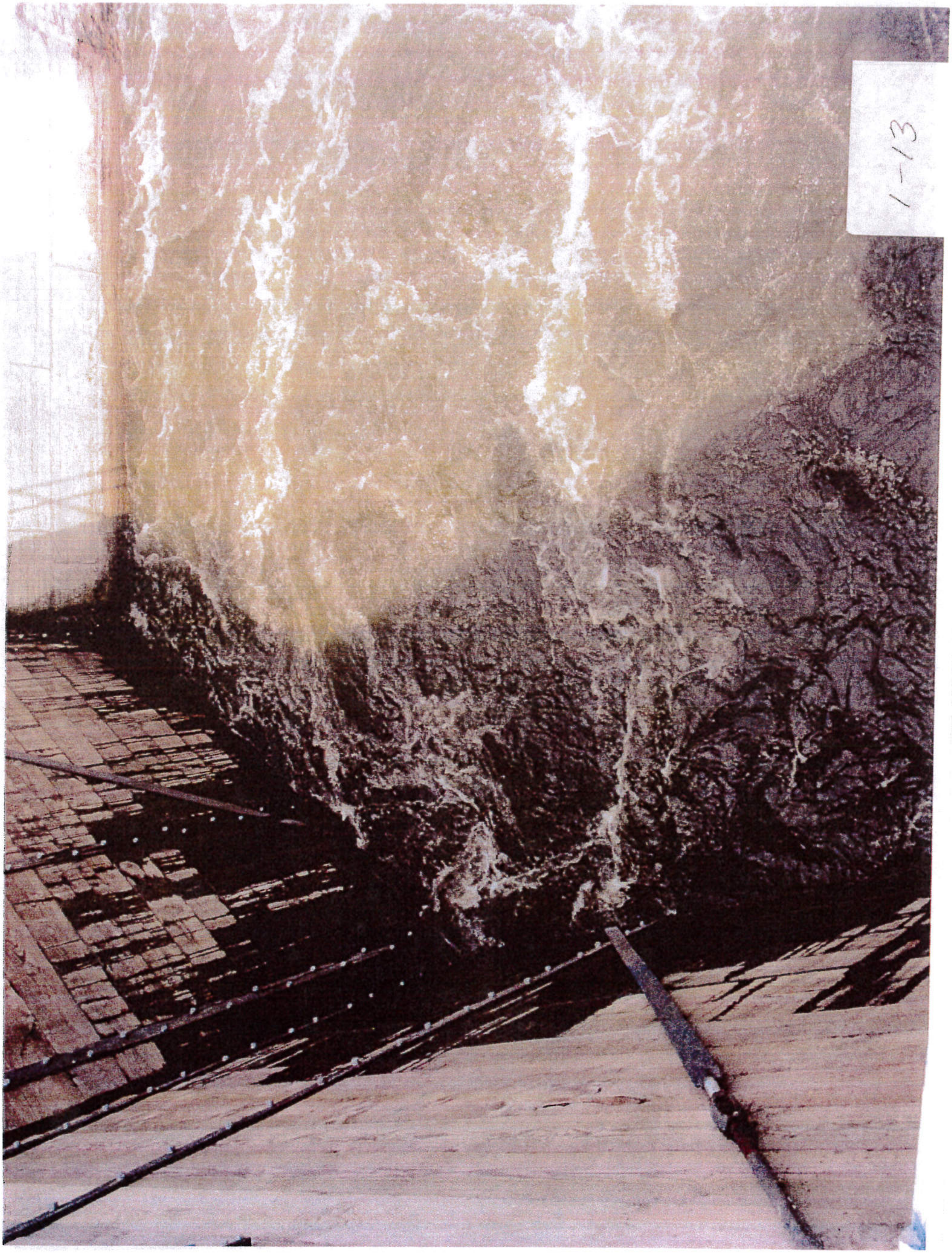
1-9

8-1



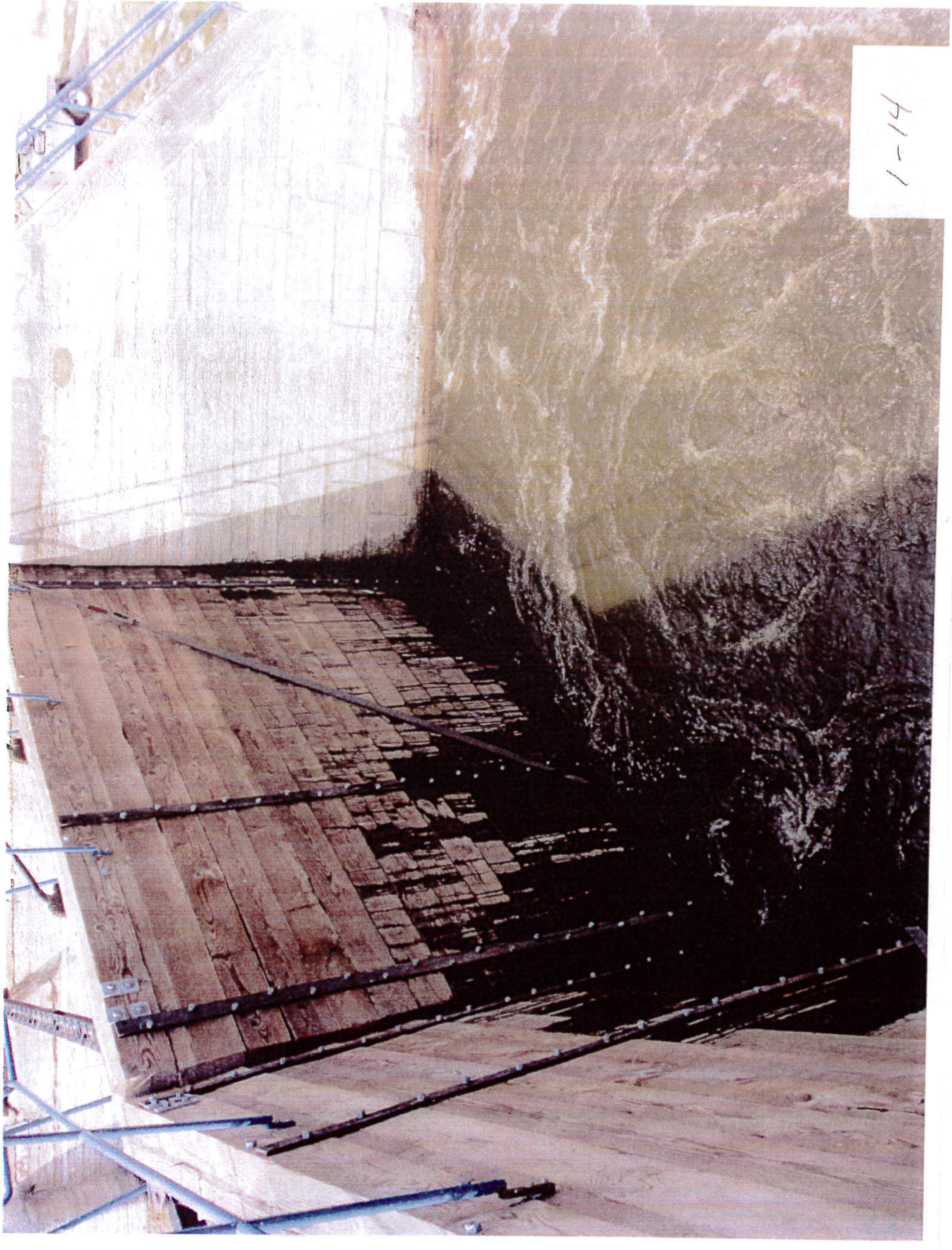
11-1


1-10


1-13

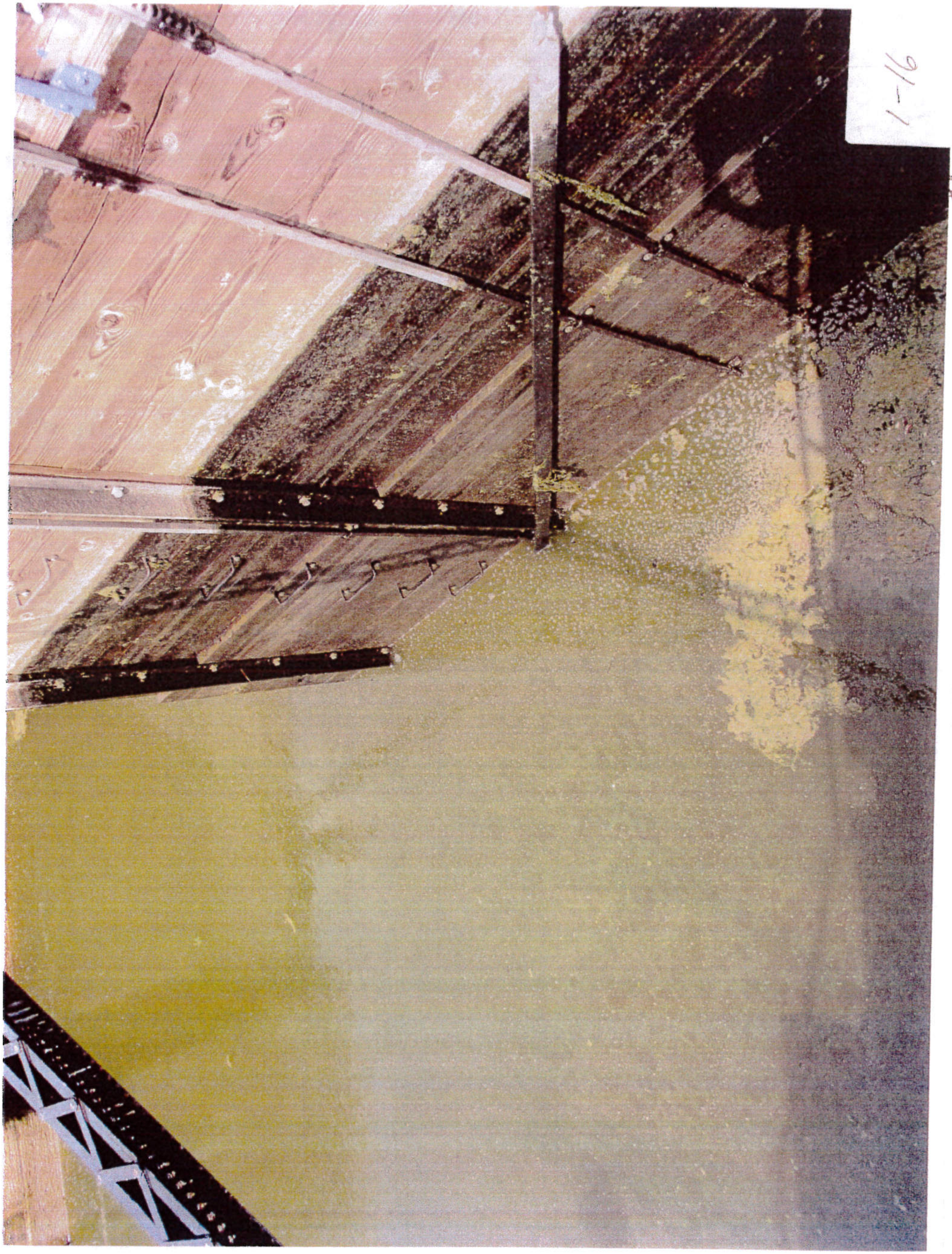
1-12

1-15


1-14

1-17

#11



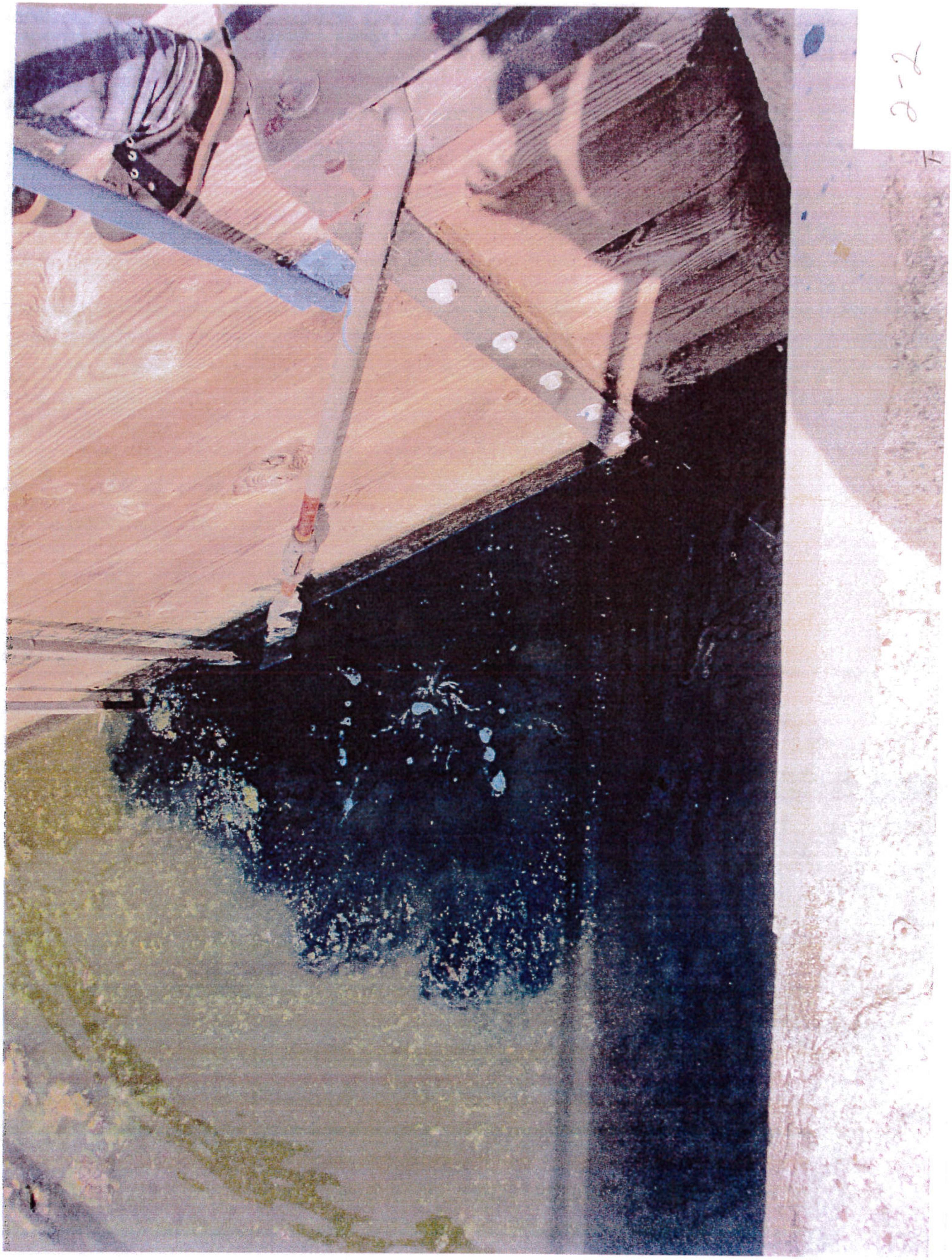
1-16

#4

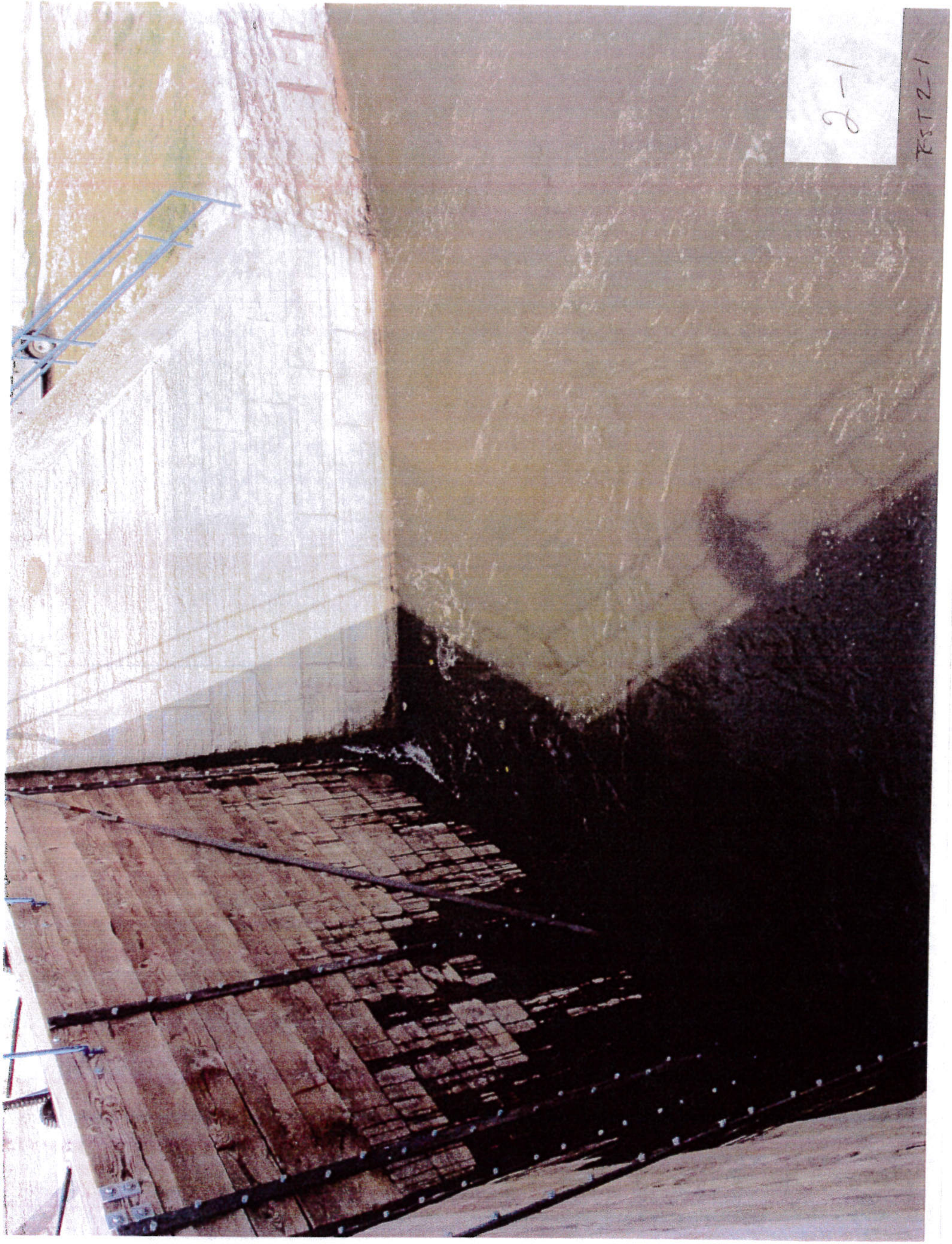
1-19

1-18

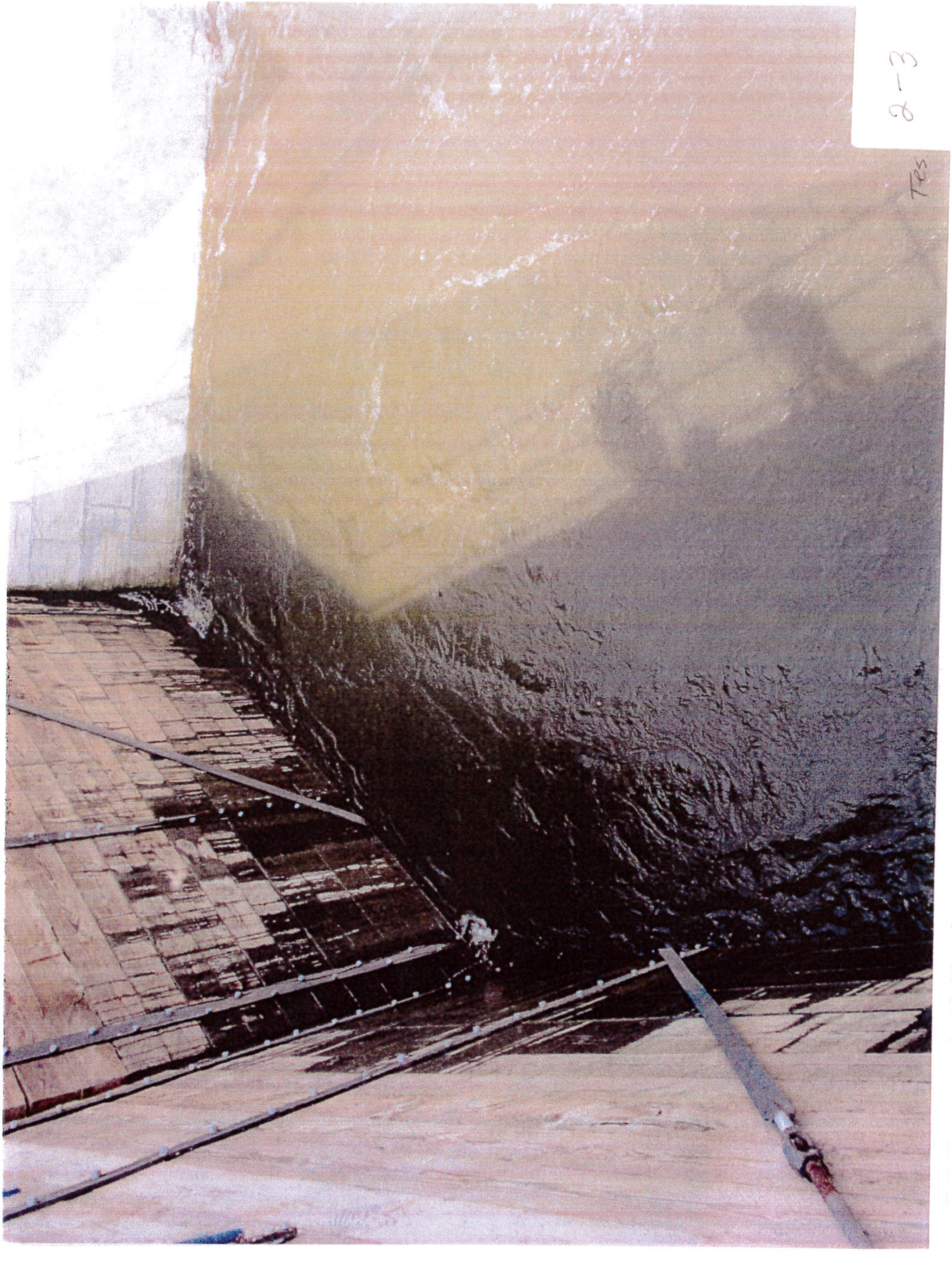
#18



2-2


2-1
TST 2-1

2-4

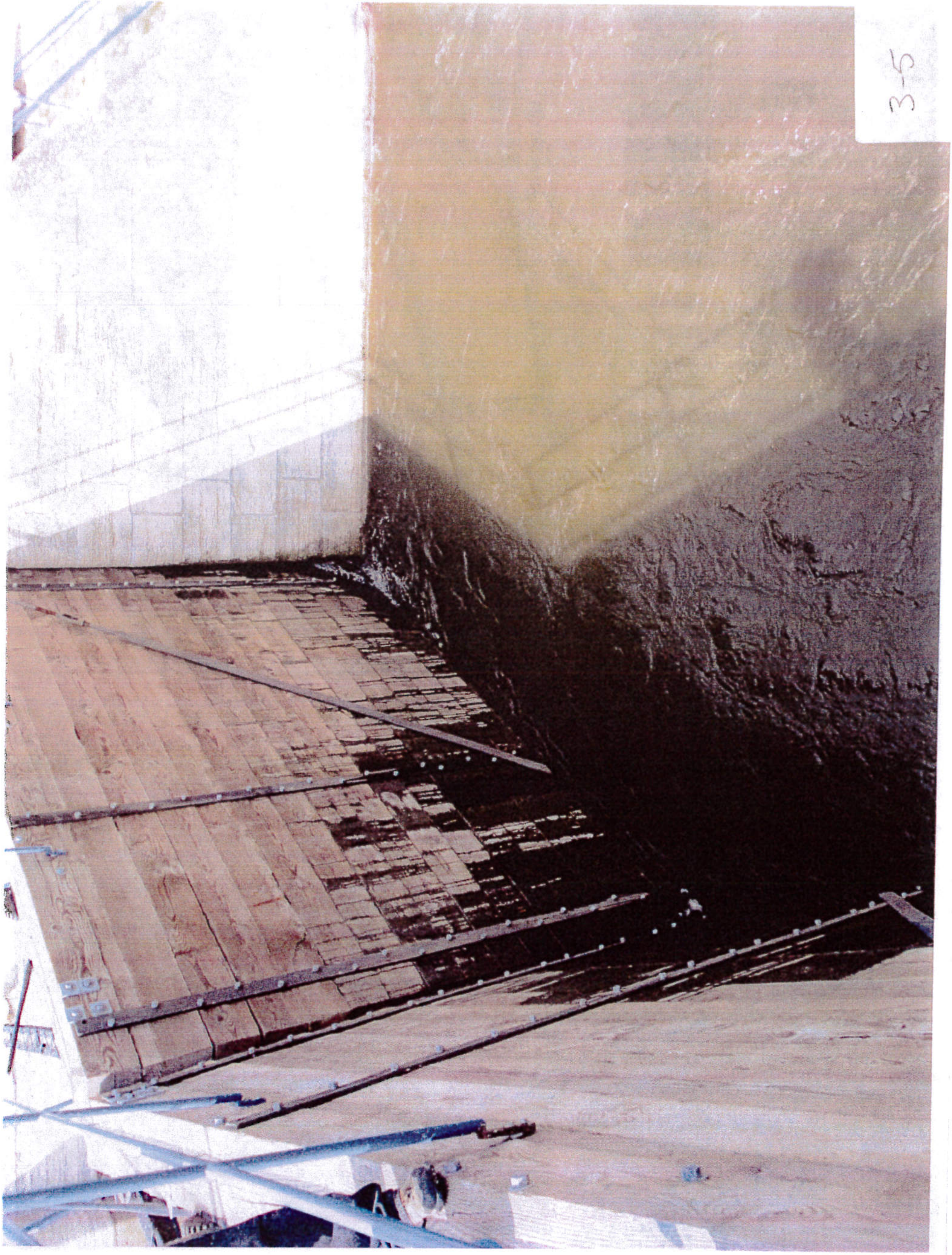


8-3

4-3

4-2

3-5

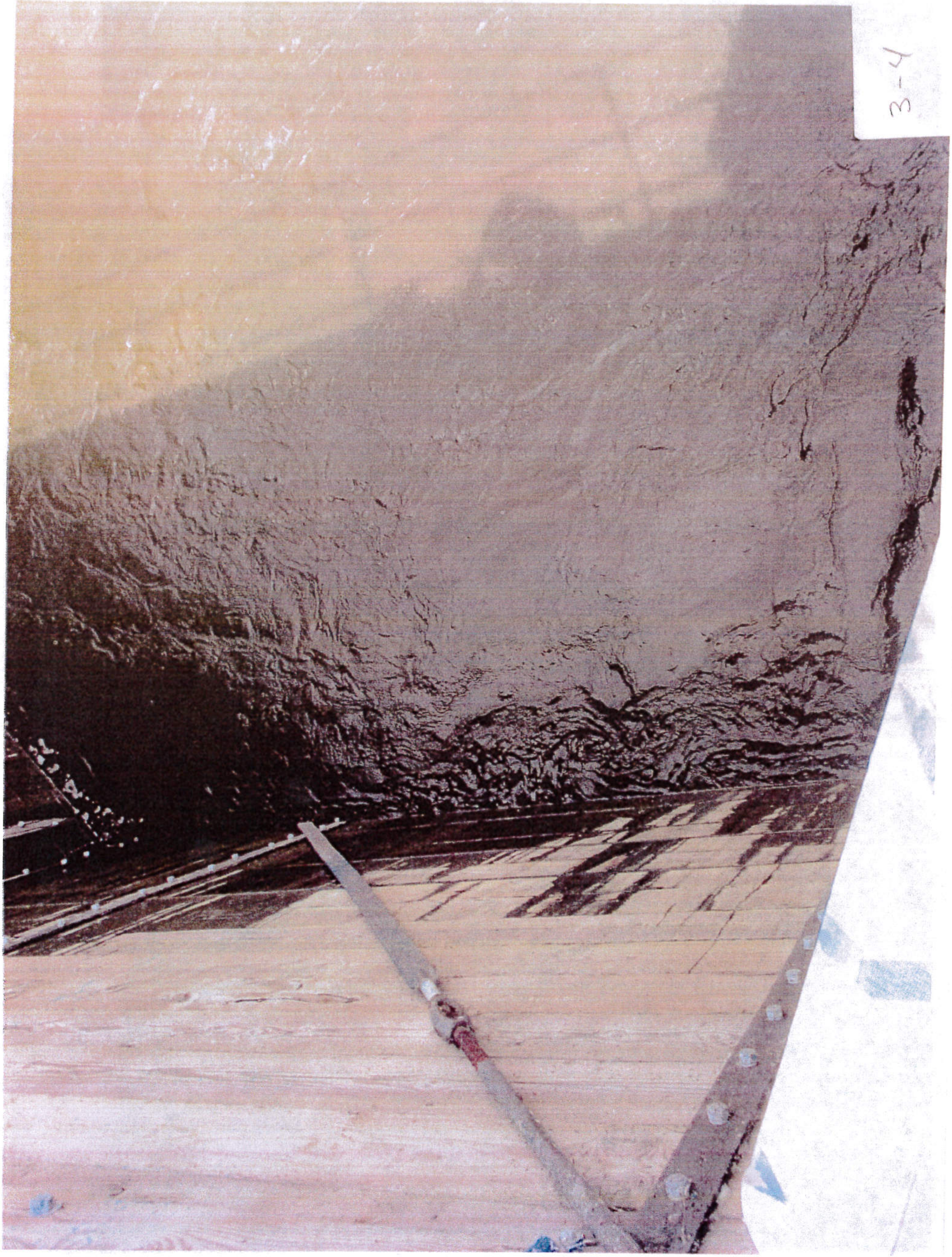


4-1

TEST 4

3-2

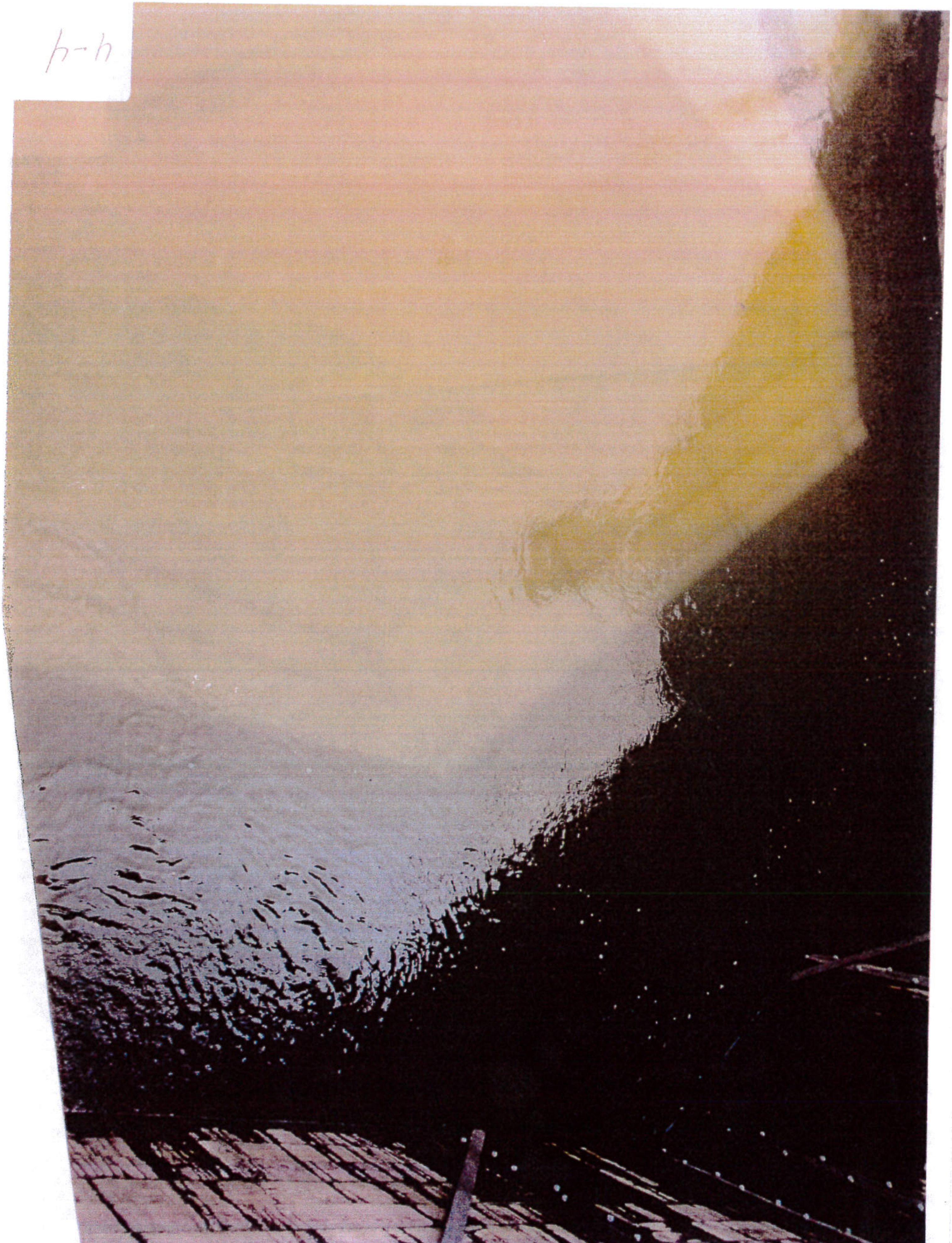

3-1

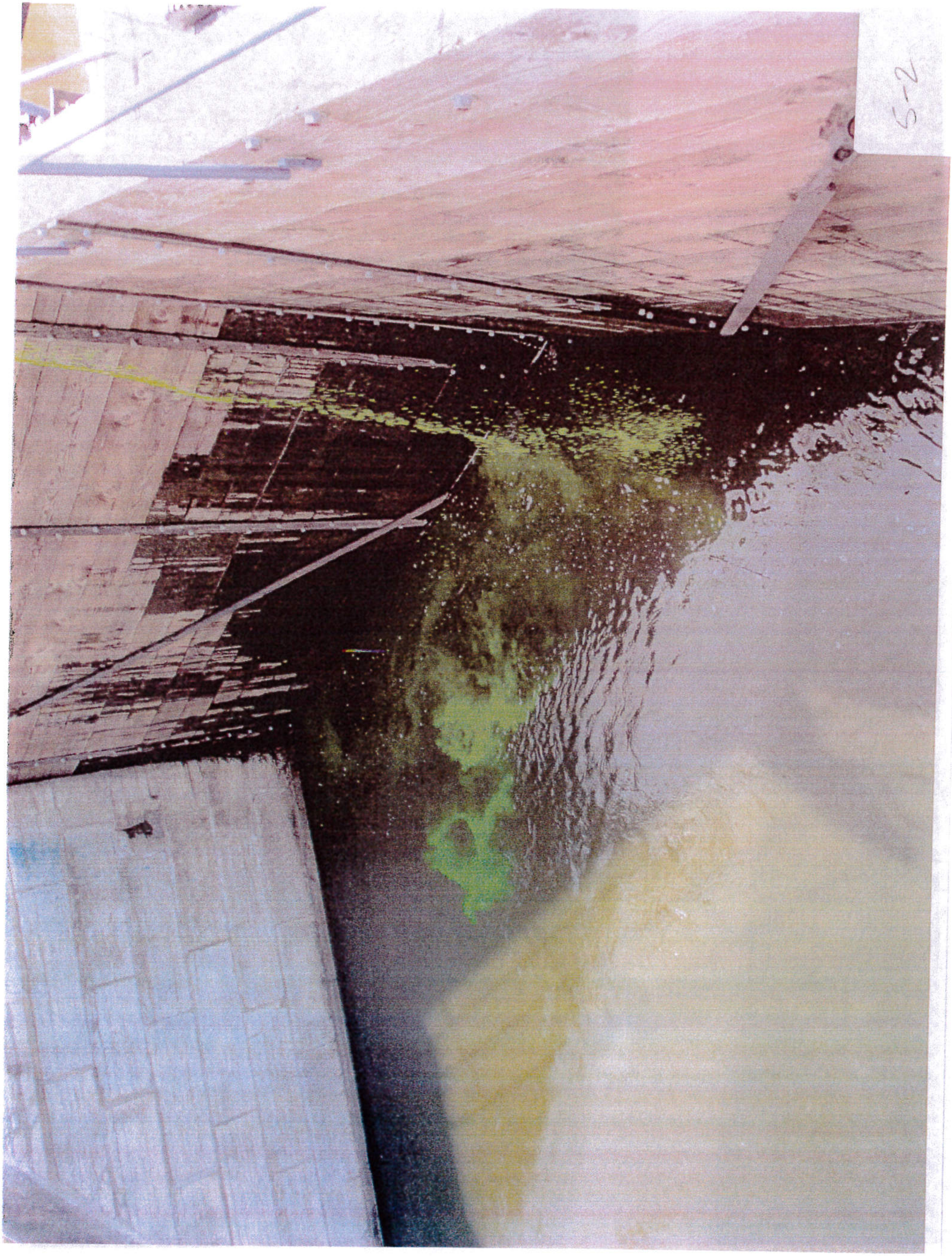


3-4

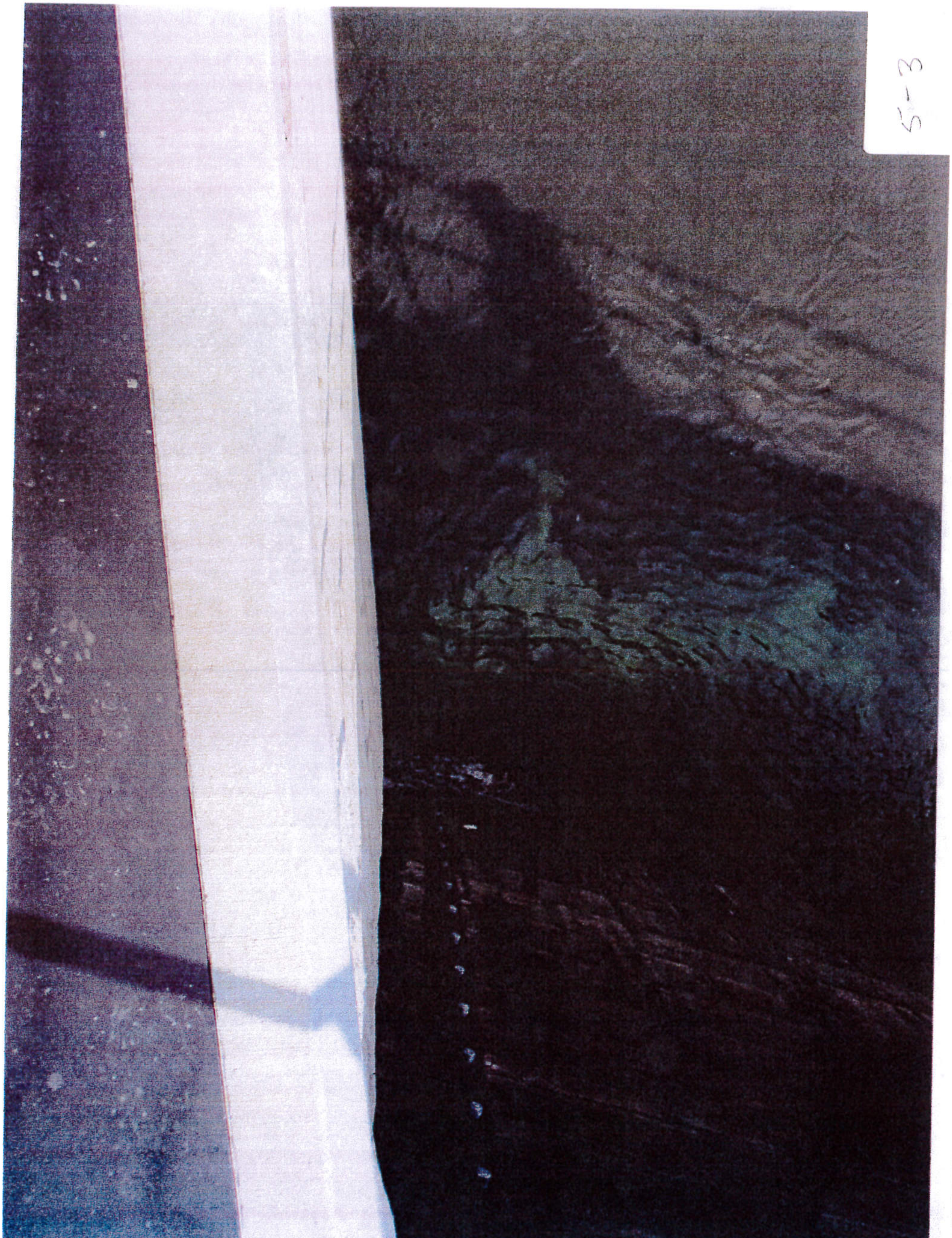
3-3

5-1

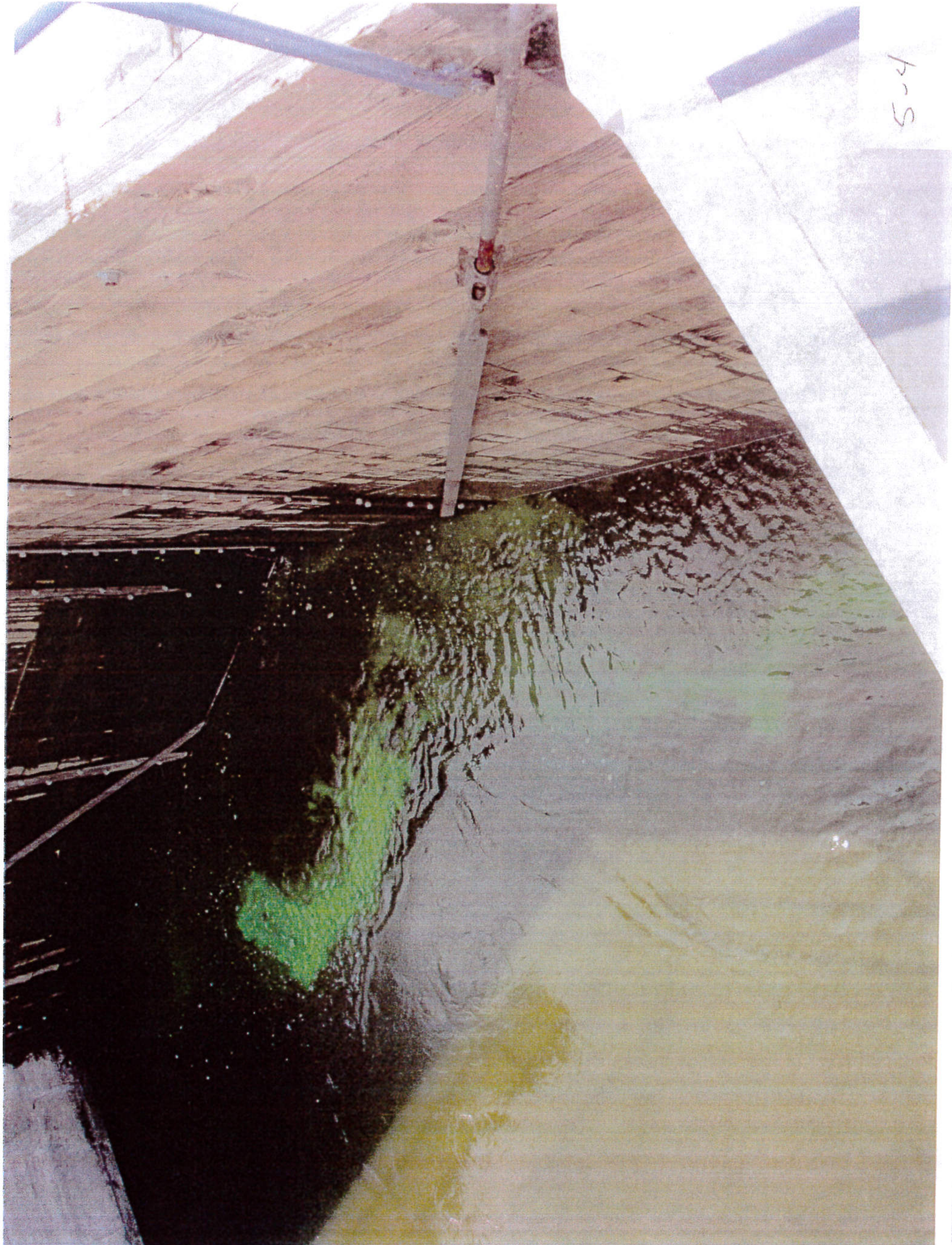




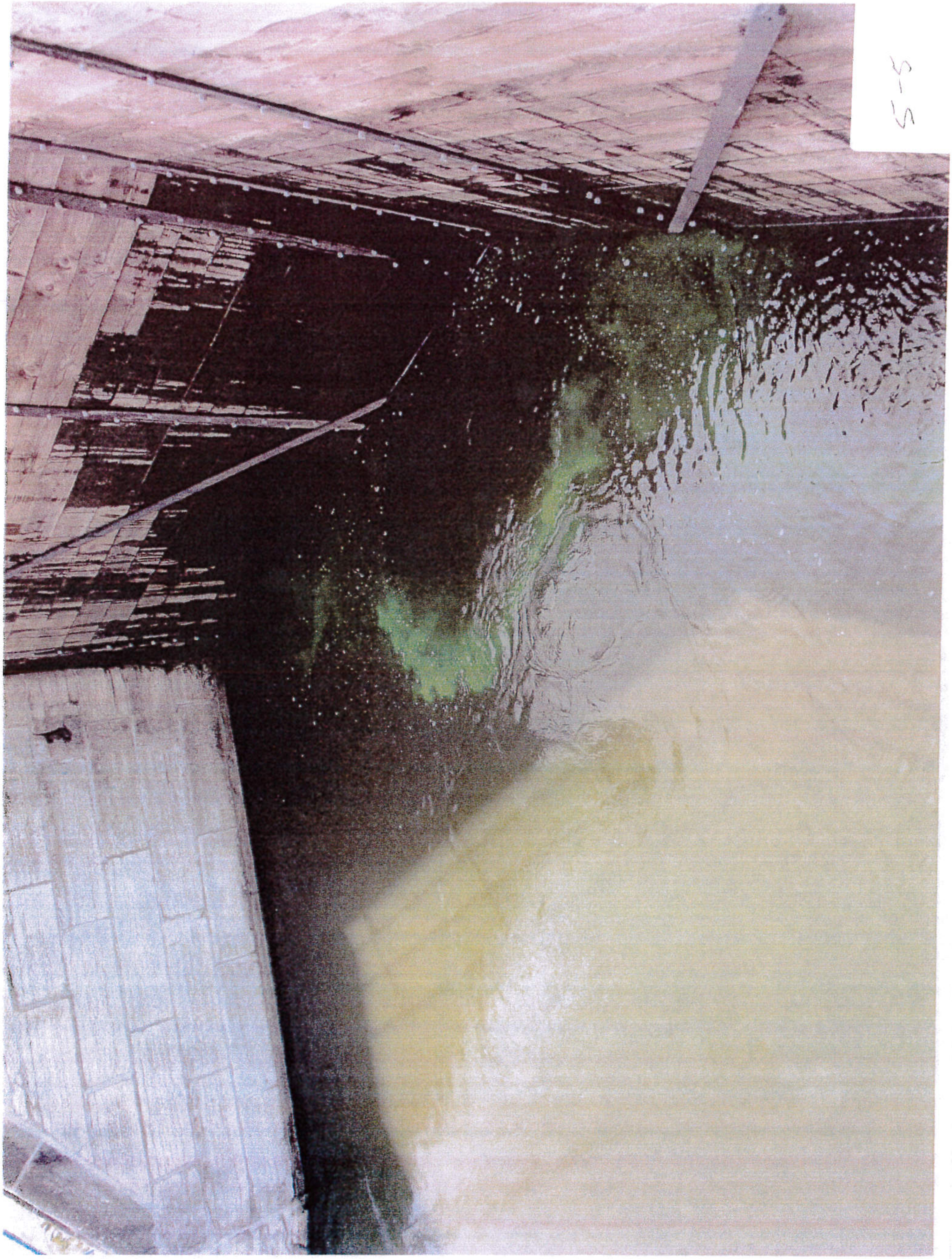
5-2



5-3


5-4

5-5

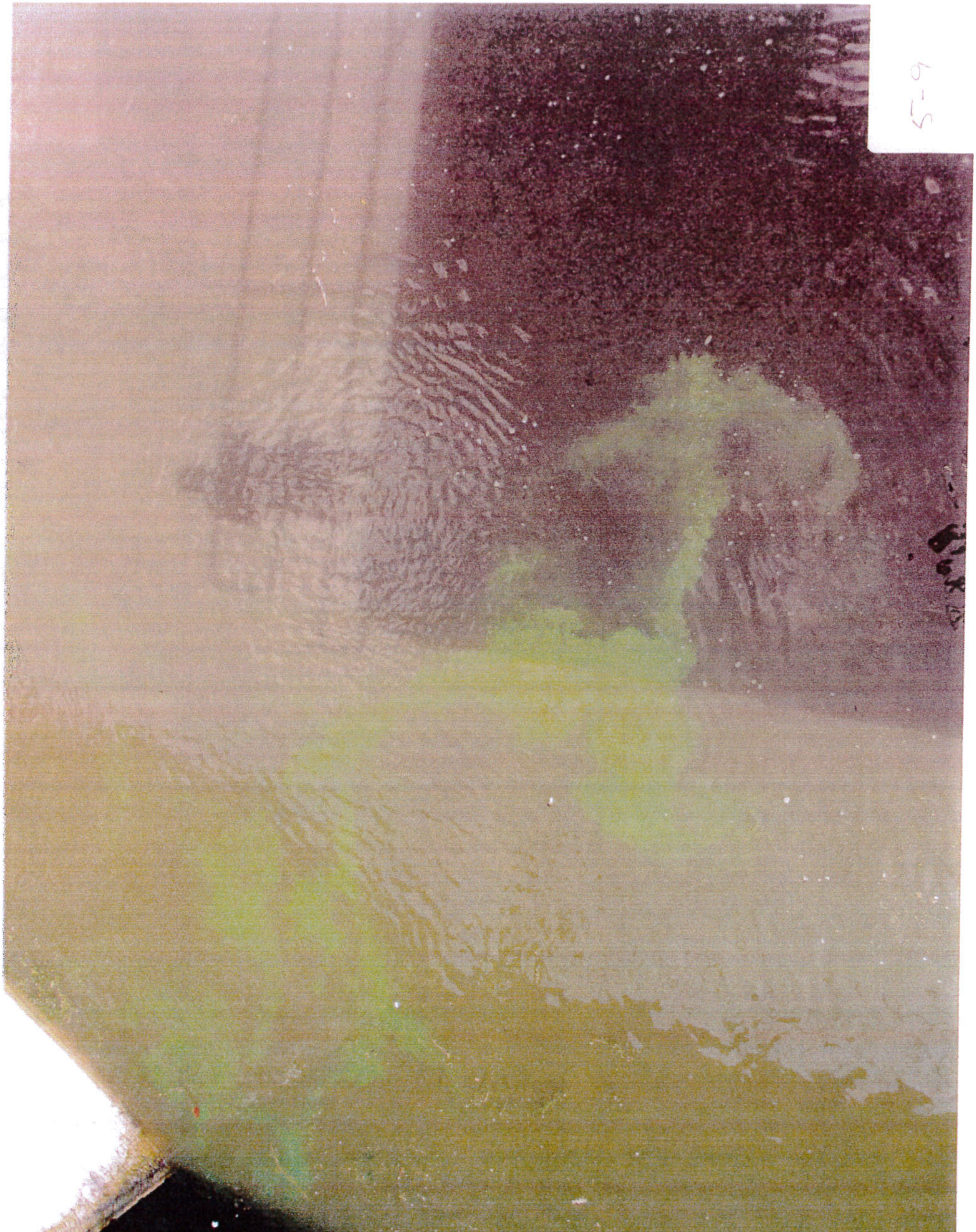


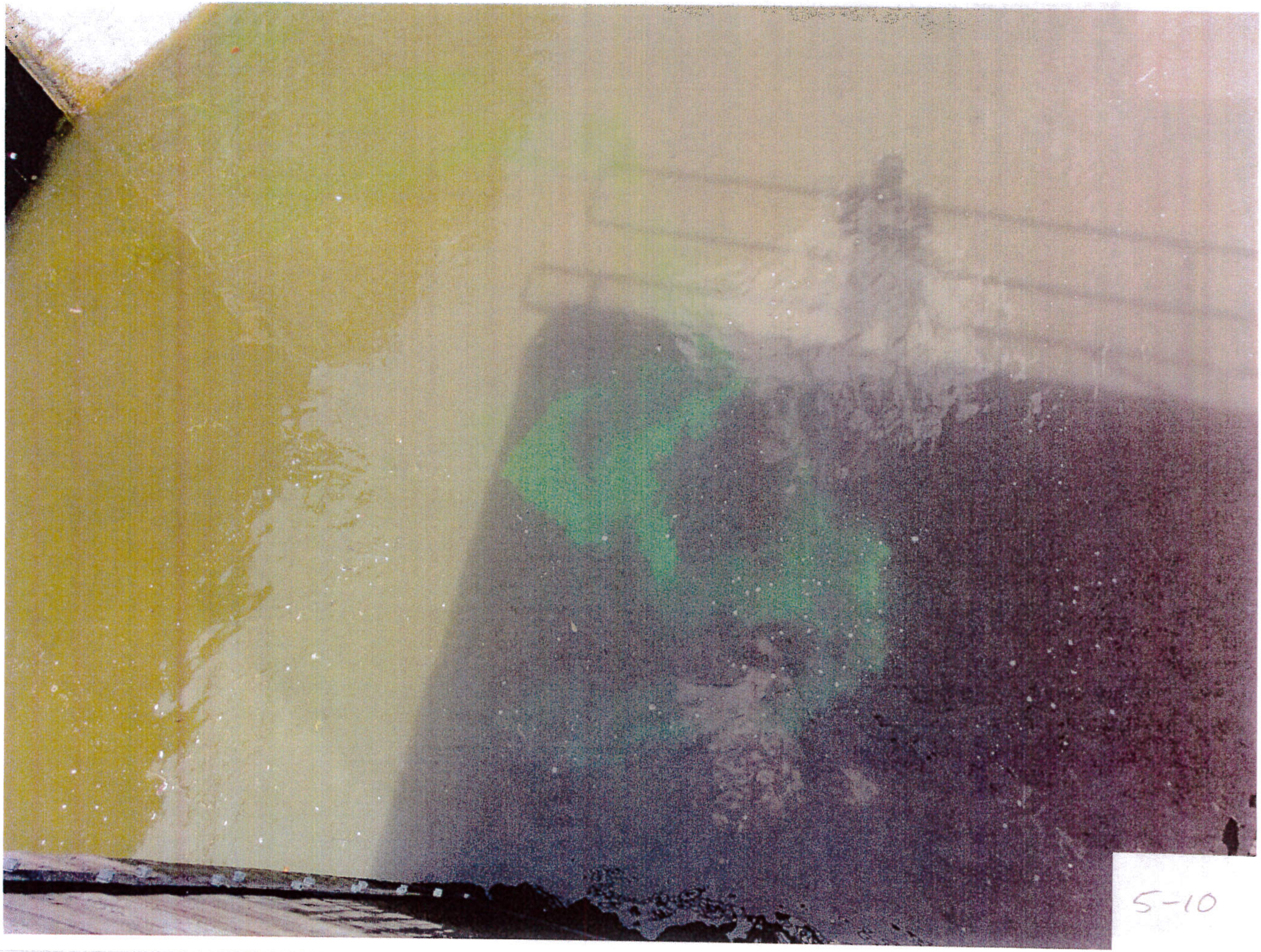
5-6

5-7

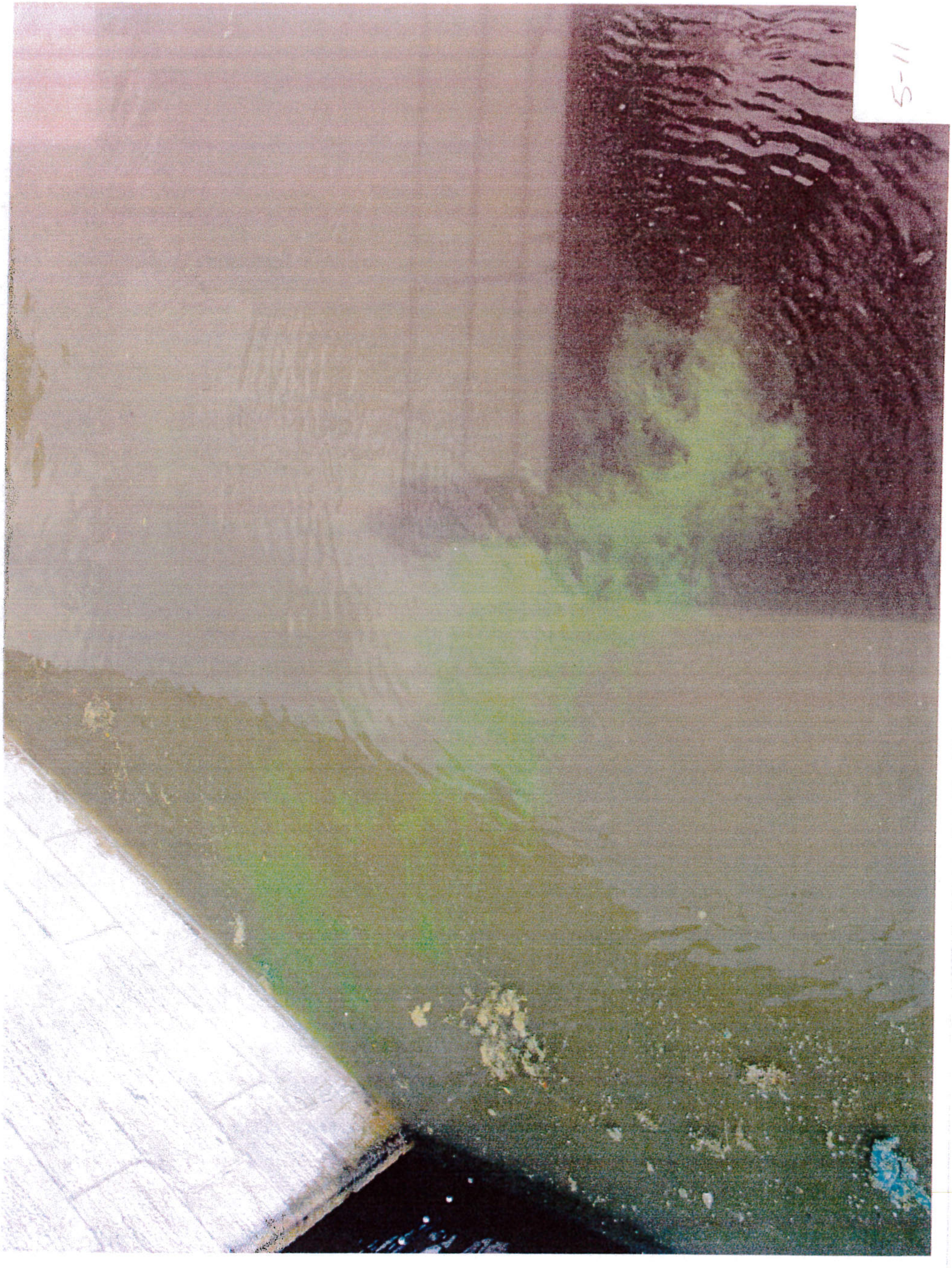

5-8

5-9



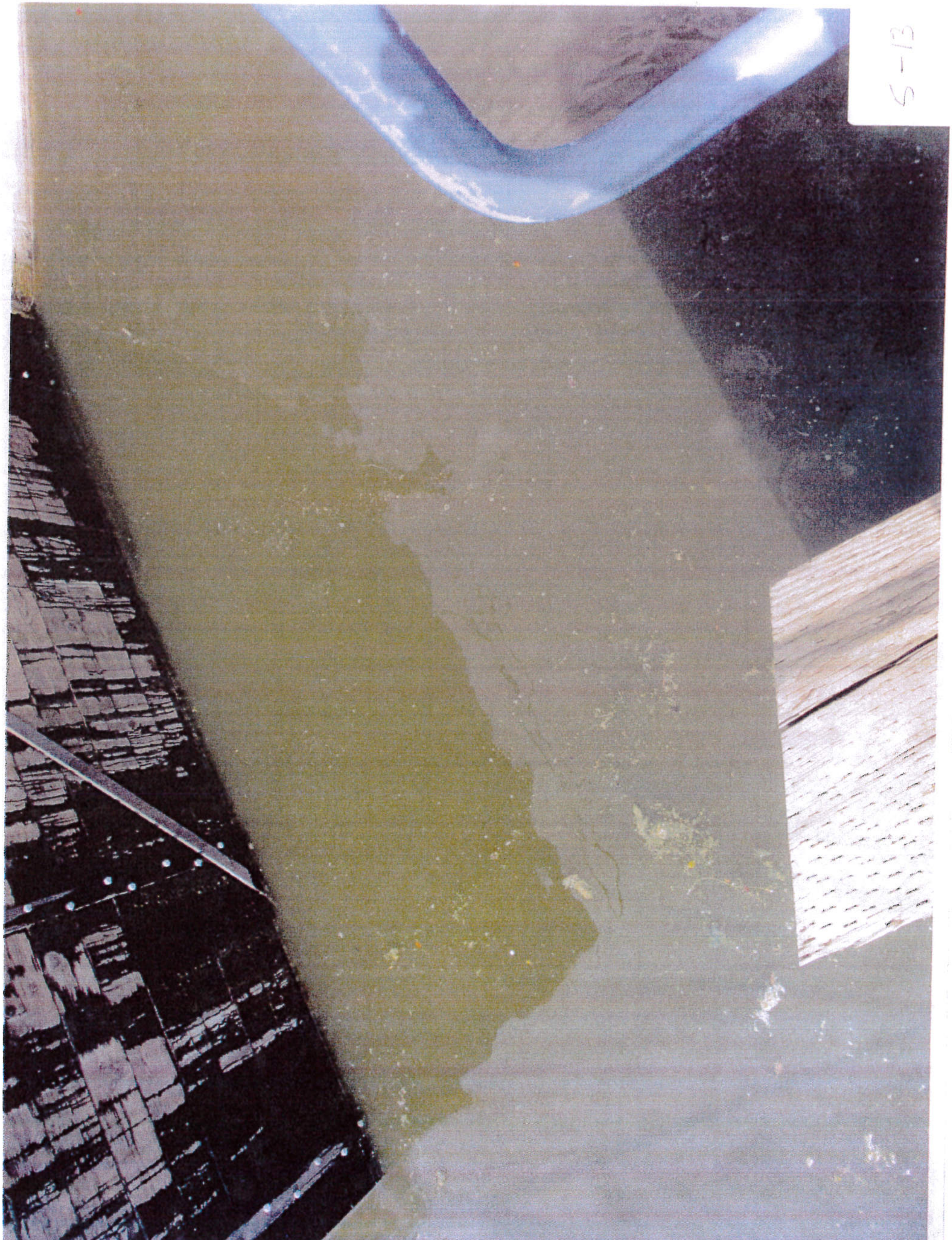


5-10



5-11

5-12



5-13

Lock Discharge Flow and Velocity Measurements

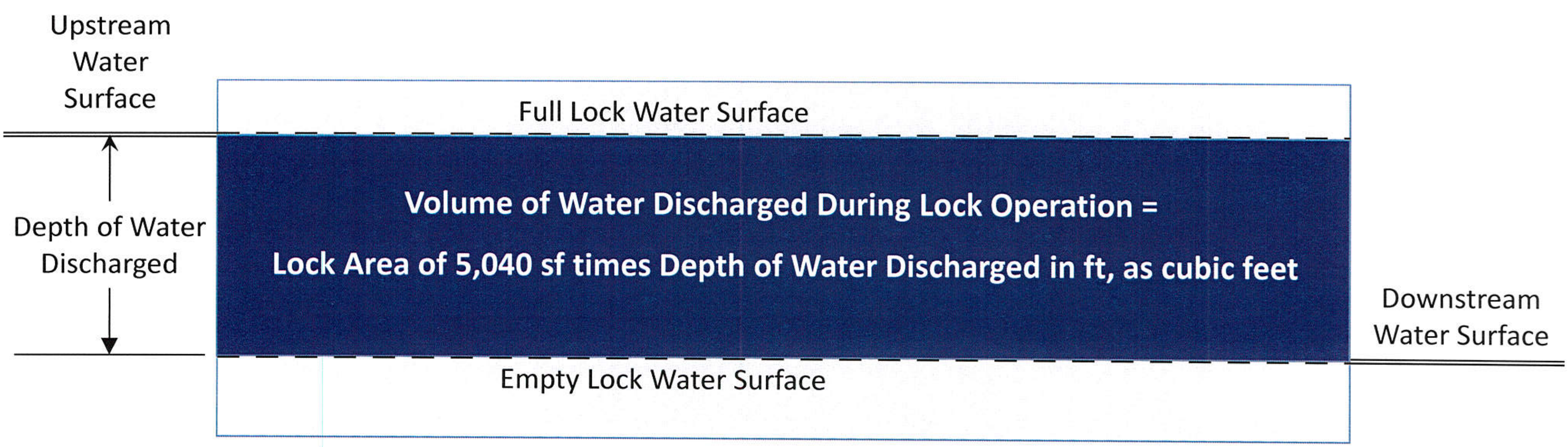
July 2018

Jeff Mazanec, PE
Sr. Consultant
Jeff.Mazanec@raSmith.com
(920) 843-5734

raSmith

Lock Water Elevations and Volume

Second, measure the **depth** of water in the lock, in feet



raSmith

Lock Discharge Flow Rate

$$\textbf{Discharge Flow Rate}\ (\text{cfs}) = \frac{\text{Volume Discharged}\ (\text{ft}^3)}{\text{Time of Discharge}\ (\text{seconds})}$$

Process for Determining Flow Rate

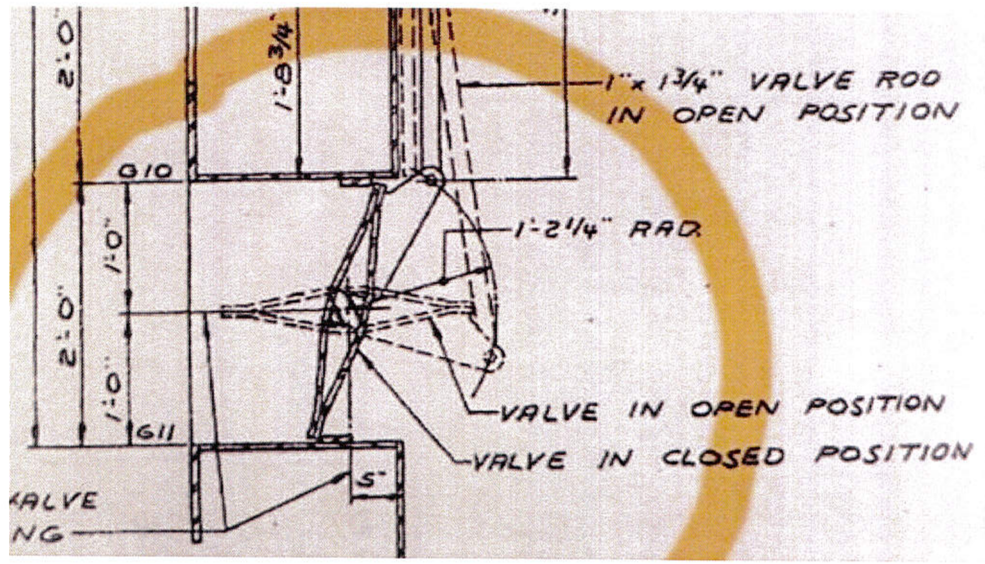
1. Measure depth to water surface before emptying lock
2. Empty lock, recording time of discharge
3. Measure depth to water surface of emptied lock
4. Subtract measurements to determine depth of water discharged
5. Multiply lock area times depth of water discharged to determine discharge volume, in cubic feet
6. Divide discharge volume by time of discharge to determine flow rate, in cubic feet per second

Lock Discharge Flow Rate and Velocity

$$\text{Velocity (fps)} = \frac{\text{Discharge Flow Rate (cfs)}}{\text{Area of Flow (sf)}}$$

Discharge Velocity Calculation

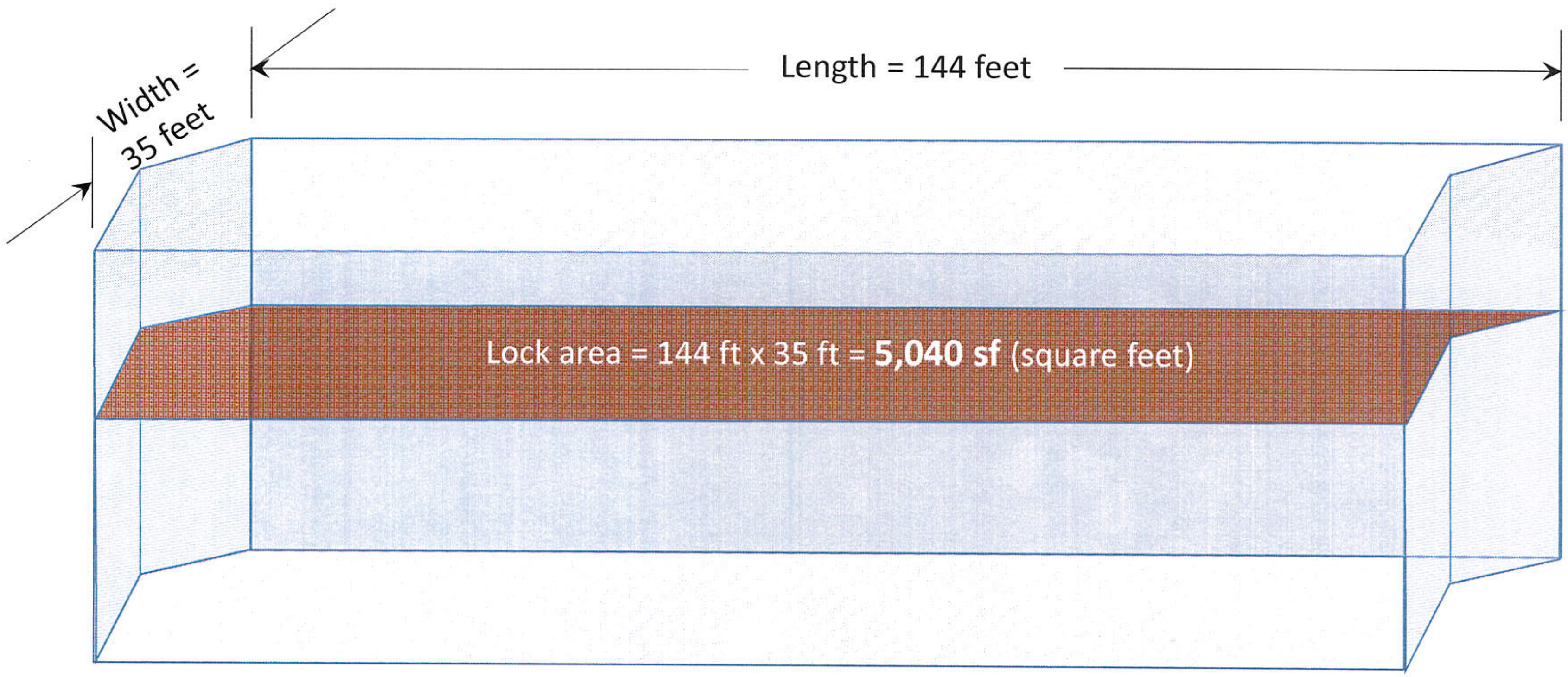
1. Determine area of discharge through butterfly valves in lock doors
   a) 2 doors; 3 butterfly valves per door = 6 openings
   b) Butterfly valve open area measures 20 inches by 47 inches, or 6.53 sf
   c) Total discharge area = 6 x 6.53 sf = 39.17 sf
2. Divide flow rate by discharge area to determine discharge velocity in feet per second



raSmith

Lock Volume Measurement

First, calculate the **area** of the lock, in sf (square feet)



Measurement Results – De Pere Lock

Lock Name: De Pere Lock

Lock Length: 146 ft

Lock Width: 36 ft

Lock Area: 5,256 sq ft

Date: 7/10/2018

Recorded By: J Mazanec/ J Cords

Measurement: 1

Start Time:

Average Velocity = 6.2 fps

Lock discharge measurements and calculations.

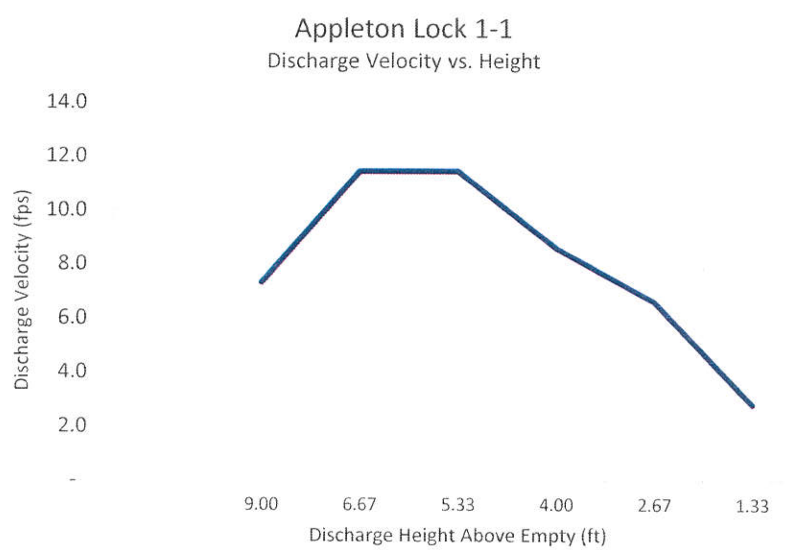
Water Level Description	Measurement to Water Surface		Incremental Depth and Volume Calculation		Total/Incremental Discharge Time		Discharge Flow Rate	Discharge Velocity
	Inches	Feet	Feet	cu. Ft.	Seconds		cfs	fps
Lock Full	49	4.08						
Empty Lock	131.75	10.98	6.90	36,244.50	150	150	241.6	6.2
Total Discharge			6.90	36,244.50		150	241.6	**6.2**

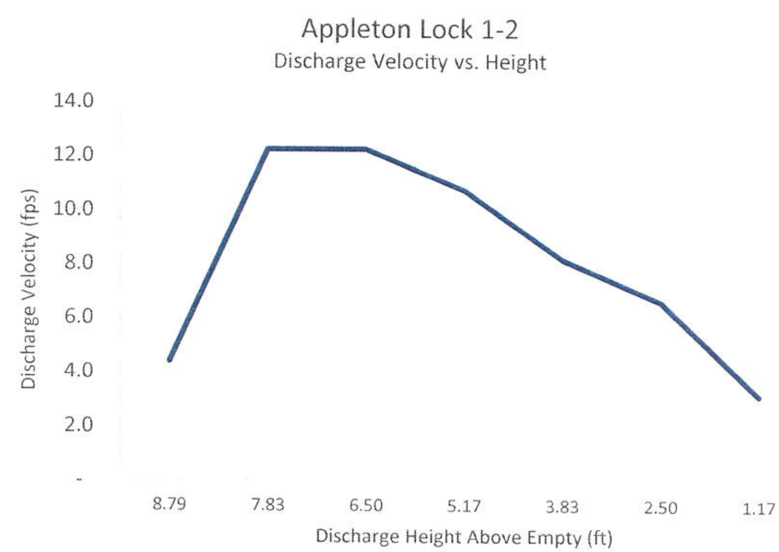
Total Discharge Gate Area 39.17 sf

raSmith

Lock Steps for Partial Discharge Measurement

Measurement Results – Appleton Lock 1



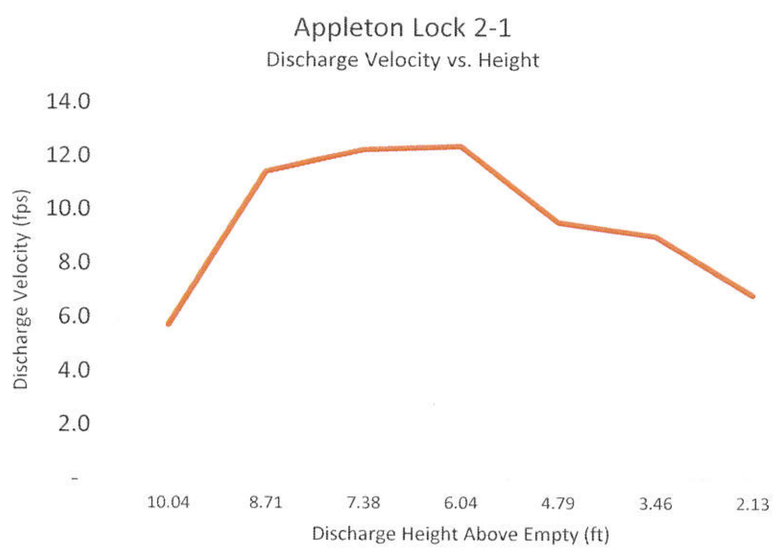


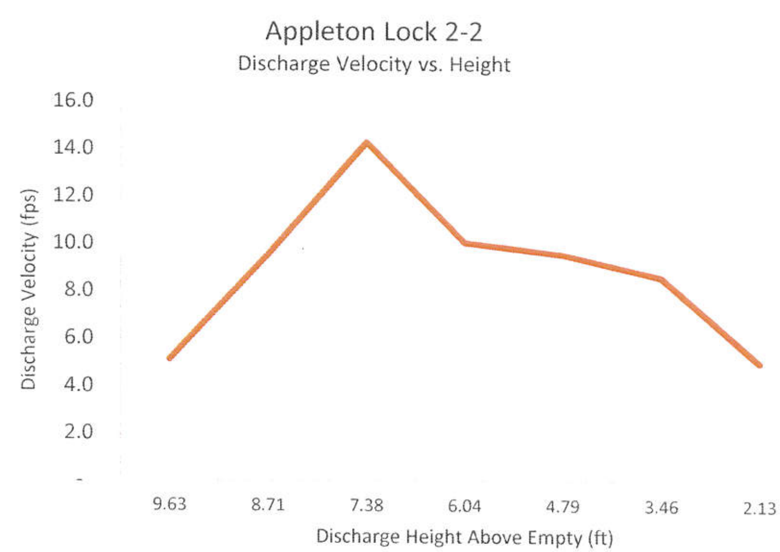
Two drawdown measurements, using steps:

- Peak Velocities = 11.4 and 12.3 fps
- Average Velocities = 6.5 and 6.8 fps

raSmith

Measurement Results – Appleton Lock 2





Two drawdown measurements, using steps:

- Peak Velocities = 12.4 and 14.3 fps
- Average Velocities = 7.6 and 8.7 fps

raSmith

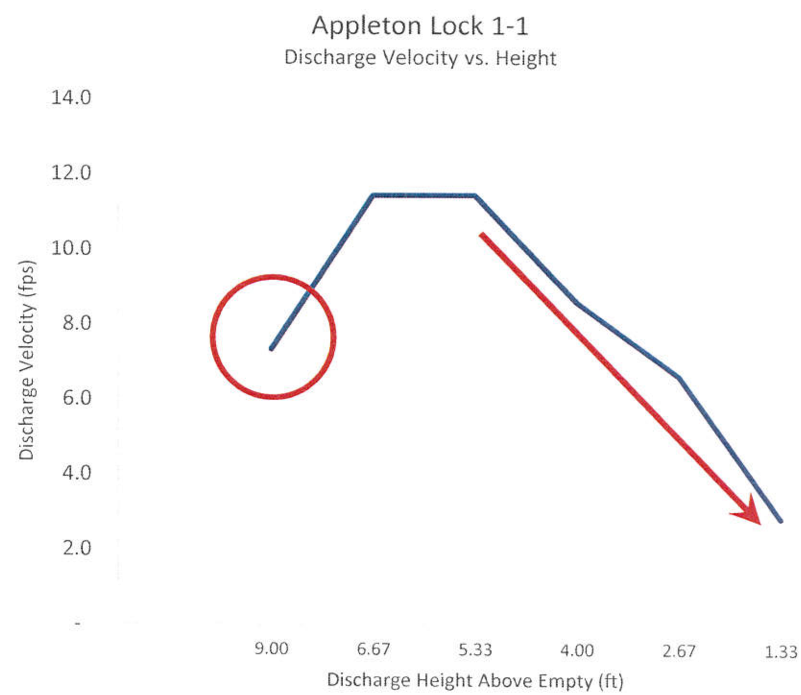
Questions from Graphics

1. **Why is first velocity low?**

   Six valves are opened sequentially, but timer started when the first gate opened. Velocity was calculated using full discharge area, so the lower initial velocity is incorrect.

2. **Why does velocity decline?**

   Height of water, or head, decreases as lock empties and reduces the pressure pushing the water out of the valves.



3. **Other Questions?**

Aquatic Invasive Species Monitoring Project

Year 2017 Report

To the

Fox River Navigational System Authority

By

Bart De Stasio, Ph.D.

Department of Biology
Lawrence University
Appleton, WI 54911

December 8, 2017

Objectives

The Aquatic Invasive Species (AIS) Control and Monitoring Plan of the Fox River Navigational System Authority (FRNSA, 2009 update) has the stated objective to "Monitor the presence and map the distribution of fish and invertebrate AIS in the Fox River three navigation pools immediately up and downstream of the Rapide Croche Lock." Under the supervision of Dr. Bart De Stasio, Ph.D., Lawrence University, three students (Chris Lee, Amanda Thomas, and Nabor Vazquez) were employed during the summer of 2017 to carry out the investigations. Cherise John was supported by an Advanced Opportunities Small Grant from the Wisconsin Louis Stokes Alliance for Minority Participation (WiscAMP) program funded through the National Science Foundation.

Sampling Design

Monitoring occurred at five of the standard six sites along the lower Fox River, WI during the summer of 2017 (Table 1, Figure 1). Each sampling site designated a general area for sampling efforts, and was further separated into mid-channel versus near-shore sampling locations, depending on the type of sampling performed. We conducted 16 different sampling trips during the summer (Table 2). We could not sample site FR-3 due to inability to gain access to a boat ramp. Sites were sampled three or four times over the course of the summer. Separate boats were employed upstream and downstream of the Rapide Croche dam site on each date, and all nets and equipment were sanitized thoroughly using bleach prior to the next sampling event according to the protocols established by the WI DNR to prevent the spread of AIS (http://dnr.wi.gov/topic/fishing/documents/vhs/disinfection_protocols.pdf).

Table 1. Latitude and Longitude coordinates of the sites sampled along the lower Fox River, WI during summers 2008-2017.

Location	Latitude	Longitude
Upstream of Rapide Croche		
FR-A (above Cedar lock)	N 44° 16.562	W 88° 20.541
FR-B (above Kaukauna Guard lock)	N 44° 16.665	W 88° 17.042
FR-3 (above Rapid Croche lock)	N 44° 19.077	W 88° 11.962
Downstream of Rapide Croche		
FR-4 (below Rapid Croche lock)	N 44° 18.947	W 88° 11.413
FR-C (above DePere dam)	N 44° 25.813	W 88° 04.273
FR-D (below DePere dam)	N 44° 27.742	W 88° 03.354

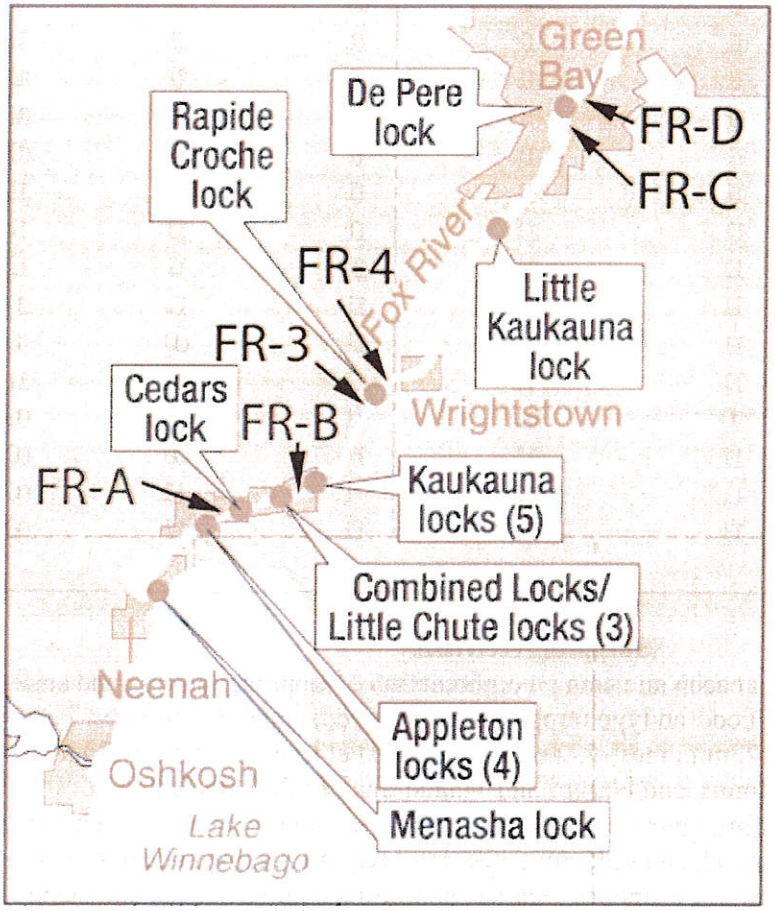


Figure 1. Map of sampling locations along the lower Fox River, WI.

Table 2. Sampling effort upstream and downstream of the Rapide Croche dam on the lower Fox River, WI during summer 2017. Dates on which sampling was performed at each site are indicated for each type of sampling effort.

Date and Site	Dip Net	Plankton Tow	Benthic Grab	Seine Netting	Fish Trap
FR-A 6/23/2017	1	1	1	1	0
FR-D 6/29/2017	1	0	0	1	0
FR-B 7/6/2017	1	1	1	1	0
FR-4 7/18/2017	1	1	1	1	0
FR-C 7/21/2017	1	1	1	0	0
FR-D 7/21/2017	1	1	1	1	0
FR-A 7/24/2017	1	1	1	1	1
FR-B 7/25/2017	1	1	1	1	1
FR-D 8/2/17	1	1	1	1	1
FR-A 8/7/2017	1	1	1	1	0
FR-C 8/8/2017	1	1	1	0	0
FR-4 8/14/2017	1	1	1	1	1
FR-D 8/15/17	0	1	1	0	0
FR-C 8/15/17	1	1	1	0	0
FR-B 8/22/17	1	1	1	1	0
FR-4 8/23/17	1	1	1	1	0

Sampling Activities

Fish: Fish were sampled at each site using a combination of trapping, netting and seining techniques. Three sizes of cod-end type traps were employed; standard "minnow" traps (length=0.42m, opening=22mm, mesh=6.4mm), elongated eel traps (length=0.78m, opening=40mm, mesh=6.4mm), and larger hand-made traps of the same design (length=2m, opening=125mm, mesh= 12.5mm). Traps were deployed without bait for a maximum of 24 hours, emptied, and redeployed during July and August at each site (see Table 2). Netting included mid-channel as well as shoreline locations at each site using standard hoop nets (2ft diameter, 10ft length, 1in square mesh) either unbaited or using frozen cod as bait. We also conducted at least three (and up to five) beach seine hauls at each shoreline location on each sampling day (1/4 inch mesh, 4 foot height, 20 foot length). If possible, fish were identified in the field to the species level and then released. Specimens of new species compared to existing records, non-native species, or specimens difficult to identify in the field were saved live for later identification in the laboratory. Specimens were transported to Lawrence University in accordance with WI Administrative Code NR 40 and all applicable permitting requirements under a WI Scientific Collector's permit (SCP-NER-148). Upon return to the laboratory specimens were frozen for disposal or transferred to ethyl alcohol (70%) for long-term preservation. Specimens were identified to the species level when possible, using Hubbs and Lagler (2004), Lyons *et al.* (2000), and the Wisconsin Fish ID software (2005).

Benthic invertebrates: Mid-channel areas were sampled using a standard Ekman grab sampler (0.15m X 0.15m box size). Replicate grab samples were collected at each site and filtered through a wash bucket with mesh bottom (mesh size=500um). Shoreline areas at each site were sampled with a combination of dip netting and beach seining techniques (generally until no new taxa were obtained). Animals captured were washed into sorting trays, picked into sealed containers and later preserved with 80% ethyl alcohol. Specimens were identified in the laboratory to the genus or species level, when possible, using the references listed above for plankton identifications as well as Pecharsky *et al.* (1990), Merritt *et al.* (2008) and Hilsenhoff (1995).

Plankton: On each sampling date oblique tows were performed at the mid-channel location of each site using a Wisconsin-type plankton net with retaining collar (mouth diameter=0.13m, mesh size=63 um). Samples were preserved in 80% ethyl alcohol and examined in the laboratory using 10X to 400X magnification. All zooplankton in the samples were identified to the species level, when possible, using Edmonson (1965), Balcer *et al.* (1984), Pennak (1989), Hopkins (1990), and Thorp and Covich (1991). Abundances in samples were not enumerated, but entire samples were examined to determine presence of each species.

Results

Fish:

A total of 22 species of fish were collected from the five sites during the summer of 2017 (Table 3). Sixteen species of fish were observed downstream of the Rapide Croche barrier, while 13 of the total 22 species were found upstream of Rapide Croche. As in the previous year, only one invasive fish species, the round goby (*Neogobius melanostomus*), was documented during the summer. Round goby was found at all sites sampled below Rapide Croche, and was not observed at any of the sites above the barrier (which extends upstream to the pool above the Cedar Lock).

Table 3. Fish species presence documented in the lower Fox River, WI upstream and downstream of the Rapide Croche dam during summer 2017. A value of one indicates presence. Sites FR-A, and FR-B are upstream, with FR-4, FR-C and FR–D downstream of Rapide Croche dam. The round goby (highlighted) was the only invasive fish species observed.

Fish	FR-A	FR-B	FR-3	FR-4	FR-C	FR-D
Aplodinotus grunniens (Freshwater drum)		1				
Ambloplites rupestris (Rock Bass)		1				
Covesius plumbeus (Lake chub)				1		
Dorosoma cepedianum (Gizzard Shad)						1
Esox lucius (Northern pike)		1				
Labidesthes sicculus (Brook silverside)				1		
Lepisosteus osseus (Longnose Gar)		1				
Lepomis cyanellus (green sunfish)	1			1		
Lepomis gibbosus (Pumpkin seed)				1		
Lepomis humilis (orange spotted sunfish)	1			1		
Lepomis macrochirus (Bluegill)	1	1		1		1
Micropterus dolomieu (Smallmouth bass)				1		1
Micropterus salmoides (Largemouth bass)	1	1		1		
Neogobius melanostomus (Round goby)				1		1
Notropis atherinoides (Emerald Shiner)				1		1
Notropis heterolepis (Blacknose Shiner)						
Notropis hudsonius (Spottail Shiner)	1			1		1
Luxilus cornutus (Common Shiner)	1					1
Pimphales notatus (Bluntnose minnow)		1		1		1
Perca flavescens (Yellow Perch)		1		1		1
Pomoxis annularis (White Crappie)	1					
Rhinichthys cataractae (longnose dace)				1		
TOTAL	**7**	**8**	**0**	**14**	**0**	**9**

Benthic Invertebrates:

There were 85 groups of benthic invertebrates observed during the summer of 2017 (Table 4). Zebra mussels were observed at all sites both above and below Rapide Croche. Rusty crayfish were found at one site above the Rapide Croche. Two invasive amphipod species ("side-swimmers") were observed, one at FR-A and FR-B and another at FR-D.

Table 4. Benthic invertebrate taxa documented upstream and downstream of the Rapide Croche dam during summer 2016 (value of 1 indicates presence). Highlighted groups are considered "invasive" species.

Macroinvertebrates	**FR-A**	**FR-B**	**FR-3**	**FR-4**	**FR-C**	**FR-D**
Hydra	1	1				1
(alderfly) Sialis sp.		1				
(amphipod) Crangonyx pseudogracilis	1	1				
(amphipod) Crangonyx spp.	1	1				
(amphipod) Gammarus sp.	1	1				
(amphipod) Crangonyctidae crangonyx		1				
(amphipod) Echinogammarus ischnus						1
(amphipod) Hyalella azteca	1	1		1	1	1
(amphipod) Monoporeia sp.		1				
(aquatic snail) Menetus	1	1				
(aquatic snail) Amnicola genus	1			1		
(aquatic snail, disc-shaped) Gyraulus sp.	1	1		1		1
(aquatic snail, left handed pond) Physella sp.	1	1				
(aquatic snail, right handed) Pleurocera sp.	1	1		1		
(aquatic snail) Helisoma sp.	1					
(aquatic snail) Fossaria	1					
(aquatic snail) Viviparus sp.	1					
(caddisfly) Helicopsyche	1	1				
(caddisfly) Brachycentrus	1					
(caddisfly) Cheumatopsyche		1				
(caddisfly) Hydropsychidae sp.	1	1			1	
(caddisfly) Hydroptilidae	1	1				
(caddisfly) Polycentropodidae sp.		1				
(caddisfly) Trichoptera order		1				
(caddisfly larvae)	1	1				1
(Asian clam) Corbicula fluminea	1					
(fingernail clam) Sphaeriidae sp.	1	1		1	1	
(damselfly) Amphiagrion sp.	1					1
(damselfly) Argia		1				
(damselfly) Palaemnema	1					

Table 4 (continued)

Macroinvertebrates	**FR-A**	**FR-B**	**FR-3**	**FR-4**	**FR-C**	**FR-D**
(damselfly) Anisoptera	1					
(damselfly) Calopterygidae				1		
(damselfly) Coenagrion sp.	1	1				
(damselfly) Enallagma sp.	1					
(damselfly) Nehalennia sp.	1	1		1		1
(damselfly) Odonata lestidae		1				
(damselfly) Zygoptera suborder		1				
(decollate snail) Bulimus genus	1					
(dragonfly) Neurocordulia	1					
(hoverfly) Syrphidae	1					
(isopod) Asellidae caecidotea		1				
(isopod) Caecidotea sp.		1				
(leech) Glossiphoniidae sp.	1	1				
(mayfly) Anthopotomus						1
(mayfly) Baetis hiemalis		1				
(mayfly) Caenidae, cercobrachys	1	1			1	1
(mayfly) Caenis sp.	1	1		1		1
(mayfly) Callibaetis sp.	1					
(mayfly) Cloeon genus		1				
(mayfly) Danella sp.	1					
(mayfly) Ephemerellidae sp.	1			1		
(mayfly) Lestidae archilestes	1	1		1		
(mayfly) Lestidae lestes	1	1		1		1
(mayfly) Stenacron	1					
(mayfly) Stenonema	1	1				1
(mayfly) Paracloeodes	1	1				
(mayfly larvae)	1	1		1		1
(mayfly) Ameletidae ameletus		1				
(stonefly) Chauliodes	1					
(midge) Brachycera		1		1		1

Table 4 (continued)

Macroinvertebrates	FR-A	FR-B	FR-3	FR-4	FR-C	FR-D
(midge) Chironomidae family	1	1		1	1	1
(midge, biting) Ceratopogonidae sp.		1				
(midge) Chrysogaster	1	1				
(midge) Dasyhelea	1					
(midge) Dolichopodidae		1				
(midge) Tanypodinae sp.		1				
(midge) Hesperoconopa						1
(mollusk) Campeloma				1		
(mollusk) Goniobasis	1					
(rusty crayfish) Orconectes rusticus		1				
(crayfish) Orconectes limosus		1				
(Virile crayfish) Orconectes virilis	1					
(threadworm) Oligochaeta sp.		1				
(water mite) Hydrachna sp.		1				1
Water Mite	1	1		1	1	1
(water scorpion) Ranatra sp.				1		
(waterboatman) Chymatia	1	1				
(waterboatman) Corixidae	1	1		1		1
(waterboatman) Sigara sp.	1	1		1		
(waterboatman) Trichocorixica sp.	1	1				1
(worm/bloodworm) Glycera	1	1		1	1	1
(worm) Naididae/Tubificidae		1				
(worm) Tubifex		1				
Zebra Mussel Veliger	1	1		1	1	1
(zebra mussel) Dreissena polymorpha	1	1		1	1	1
TOTAL	**55**	**58**	**0**	**22**	**9**	**23**

Plankton:

A total of 25 taxa of zooplankton were recorded in 2017, with 23 occurring upstream of the barrier and 21 below (Table 5). The invasive spiny water flea, *Bythotrephes longimanus,* was collected on 24 July 2017 at FR-A (a single individual was found in an Ekman grab sample). More extensive sampling with a larger net (0.5m diam, 250um mesh) did not show any spiny water fleas at this site. Examination of

Table 5. Zooplankton documented from sites upstream and downstream of the Rapide Croche dam during Summer 2017. A value of one indicates presence. The spiny water flea *Bythotrephes longimanus* (highlighted) was the only invasive species observed.

Zooplankton	**FR-A**	**FR-B**	**FR-3**	**FR-4**	**FR-C**	**FR-D**
Acanthocyclops vernalis	1	1		1	1	1
Alonella	1	1		1		
Alona Sp.	1	1		1		1
Alonopsis elongata	1	1		1	1	1
Bosmina longirostris	1	1		1	1	1
(spiny waterflea) Bythotrephes longimanus	1					
Ceriodaphnia	1	1		1	1	1
Chydorus sp.	1	1		1	1	1
Daphnia mendotae	1			1		
Daphnia pulex	1					
Daphnia pulicaria	1			1	1	1
Dapnia retrocurva	1	1		1		1
Daphnia schodleri		1				
Diaphanosoma birgei	1	1		1	1	1
Eubosmina coregoni	1	1		1	1	1
Eurycercus lamellatus	1	1				
Leptodiaptomus siciloides	1	1		1	1	1
Leptodora kindti	1	1		1	1	1
Leydigia sp.				1		
Pleuroxus		1				1
Mesocyclops edax	1	1		1	1	1
Scapholeberis						1
Sida crystallina		1		1		1
Simocephalus serrulatus		1		1		
Skistodiaptomus oregonesis	1	1		1	1	1
TOTAL	**19**	**19**	**0**	**19**	**12**	**17**

additional Ekman grab samples on did not result in any tail spines or individuals. Based on these data it appears that the spiny water flea had not established a reproducing population at this site. The presence of spiny water fleas in the samples on 24 July may be due to local contamination near the public boat ramp at Sunset Park near FR-A.

References Cited

Balcer, M.D., N.L. Korda, and S.I. Dodson. 1984. Zooplankton of the Great Lakes: A Guide to the Identification and Ecology of the Common Crustacean Species. The University of Wisconsin Press, Madison, WI.

Edmonson, W.T. (ed.) 1965. Fresh-water Biology, 2nd edit. John Wiley and Sons, Inc. New York, NY.

Fox River Navigational System Authority. 2009. AIS Control and Monitoring Plan for the Rapide Croche Boat Transfer Station, Appendix B: Aquatic Invasive Species Control and Monitoring Plan. (June 2009).

Hilsenhoff, W.L. 1995. Aquatic Insects of Wisconsin. Natural History Museums Council, University of Wisconsin Press, Madison, WI.

Hopkins, G.J. 1990. The Zebra Mussel, *Dreissena polymorpha*: A Photographic Guide to the Identification of Microscopic Veligers. Queen's Printer for Ontario, Canada.

Hubbs, C.L. and K.F. Lagler. 2004. Fishes of the Great Lakes Region, Revised Edition (Revised by G.R. Smith). University of Michigan Press, Ann Arbor, MI.

Lyons, J., P.A. Cochran, and D. Fago. 2000. Wisconsin Fishes 2000: Status and Distribution, University of Wisconsin Press, Sea Grant Institute, Madison, WI.

Merritt, R.W., K.W. Cummins, and M.B. Berg. 2008. An Introduction to the Aquatic Insects of North America, 4th edit. Kendall/Hunt Publishing, Iowa.

Pecharsky, B.L., P.R. Fraissinet, M.A. Penton and D.J. Conklin 1990. Freshwater macroinvertebrates of northeastern North America. Cornell University Press, Ithaca.

Pennak, R.W. 1989. Fresh-water Invertebrates of the United States: Protozoa to Mollusca, 3rd edit. John Wiley and Sons, Inc. New York, NY.

Thorp, J.H. and A.P. Covich (eds.) 1991. Ecology and Classification of North American Freshwater Invertebrates. Academic Press, Inc. San Diego, CA.

Wisconsin Fish ID Software. 2005. Software for Identifying Fishes of Wisconsin. University of Wisconsin Center for Limnology, Sea Grant Institute, and Wisconsin Department of Natural Resources. http://www.wiscfish.org/fishid/.

Spiny Water Flea (*Bythotrephes longimanus*) and Round Goby (*Neogobius melanostomus*) Monitoring in Southern Green Bay, Lake Michigan, Lower Fox River, and Lake Winnebago During 2017

Bart De Stasio
Biology Department
Lawrence University
Appleton, WI 54911

December 8, 2017

Abstract

The spiny water flea (*Bythotrephes longimanus*) is an invertebrate aquatic invasive species (AIS) in the Great Lakes that competes with native fish species for smaller crustacean prey. The species can lay two types of eggs, resting eggs and immediately hatching eggs. Resting eggs are tolerant to harsh conditions, allowing them to be rapidly distributed when attached to fishing and other recreational gear and boats. One goal of this project was to determine spiny water flea population dynamics in southern Green Bay, the lower Fox River and Lake Winnebago, including when they produce resting eggs. Six sites along the lower Fox River, two sites in southern Green Bay and two sites in Lake Winnebago were sampled with oblique net tows approximately biweekly from early June to late Septemeber 2017 to determine the abundance of juvenile and adult stages of the spiny water flea, including the type of eggs being produced by adult females. No spiny water fleas were collected from Lake Winnebago during 2017. Spiny water fleas were observed in the lower Fox River at a single site on a single date in July. In southern Green Bay juvenile and female spiny water fleas were first observed 7 June and individuals were observed continuously until at least late September when sampling ceased. Peak population abundances occurred in Sept at both sites in southern Green Bay. Females produced both types of eggs as early as 19 July. Females continued to produce resting eggs at least into late September.

Round goby were sampled along shorelines near the outflows of Lake Winnebago and at the six locations established along the lower Fox River for monitoring by the Fox River Navigational System Authority. No round goby were collected from Lake Winnebago. In the lower Fox River, round goby were observed only at sites below the Rapide Croche barrier.

Introduction

The spiny water flea, *Bythotrephes longimanus* (formerly known as *B. cederstroemii),* is an aquatic invasive species (AIS) of the zooplankton that has spread throughout the Great Lakes, and was first observed in Lake Michigan in 1986 (Lehman 1987). This invasion has resulted in changes to the food web dynamics in Lake Michigan (Lehman & Caceres 1993). It is a predatory cladoceran that competes with small fish and other native invertebrates for food such as smaller zooplankton like the water flea

Daphnia (Lehman 1991, Pothoven *et al.* 2003, Pothoven & Hook 2014). The rapid spread and success of this species throughout the Great Lakes and inland lakes in the region is due in large part to the production of a resistant stage that can survive harsh conditions during transport to new areas. The species can produce two types of offspring, either immediately hatching eggs or the resistant embryos called resting eggs. Resting eggs are in a dormant state and range from 0.4-0.5 mm in diameter with a golden brown color. The resting eggs are known to tolerate a wide range of conditions, including temporary drying and even passage through the guts of fish (Jarnagin *et al.* 2000, Branstrator *et al.* 2013).

This resistant resting stage and the fact that the tail spines of this species causes it to get caught on fishing line, fabric, anchor ropes, etc. has allowed the species to spread rapidly to new areas and become a successful invasive species. Spiny water fleas have been recorded in Green Bay since at least the late 1980s (Jin & Sprules 1990) and there is concern that it may spread up the lower Fox River and into the Lake Winnebago, Upper Fox River and Wolf River systems if boats and gear are allowed to navigate upstream without being properly cleaned. Some cleaning procedures will kill juveniles, adults and immediately hatching eggs but not resting eggs. Concern for this possibility is warranted based on the data on spiny water flea population dynamics collected in 2015 from southern Green Bay. Although spiny water fleas are not established in the lower Fox River, adult females were observed by late June and produced resting eggs from early July until at least early October. Peak population abundances occurred in September (De Stasio & Merkle 2016, Merkle & De Stasio, in review). Understanding the population dynamics and when the various stages occur in Green Bay and the lower Fox River is important to planning effective cleaning protocols and practices.

Another AIS of concern in northeastern Wisconsin is the round goby (*Neogobius melanostomus*). It is known to be established in Green Bay and the lower Fox River as far upstream as the invasive species barrier at Rapide Croche (Kornis & Vander Zanden 2010). Round goby have been shown to have important impacts on food webs and fisheries (Lederer *et al.* 2008, Kornis *et al.* 2012), and there is concern that spread of this AIS inland would do damage to the important sport fishery in Lake Winnebago, known to drive at least $234 million of the local economy (Cook & Neiswender 2007).

The goal of this study was to determine the spatial and temporal distribution of spiny water flea and round goby in Lake Winnebago, the lower Fox River and southern Green Bay during the main boating period of the year. In addition, the project was to provide documentation of the abundance of each life stage of the spiny water flea during the study period, with special attention paid to when resting eggs were being produced.

Methods

Field Collections - Samples for spiny water flea were collected from the lower Green Bay area from 7 June through 23 Sept 2017. Two sampling sites established during previous research on lower Green Bay were sampled (Table 1 & Fig. 1; De Stasio & Richman 1998, De Stasio *et al.* 2008, 2014). Oblique plankton tows from just above the sediment to near the surface were collected using a standard conical plankton net (0.50 m diameter opening, 200 cm length, 250 um mesh; Aquatic Research Instruments, Hope, ID). The net was towed at a constant speed of 2 mph for either 3 min or 1 min when plankton were abundant. Duplicate samples were collected to allow estimation of variability among samples. On the lower Fox River, samples were collected from mid-channel areas at six locations established and monitored since 2006 (Fig. 1; De Stasio 2016). Samples on Lake Winnebago were obtained with duplicate plankton tows conducted the same as for Green Bay but at two sites at the northern end of the lake (Fig. 1). Ekman grab sediment samples were also collected at the WIN-1 location. Samples were held live in closed 2-L containers and transported to the Lawrence University laboratory facility in accordance with WI Administrative Code NR 40 and all applicable permitting requirements. Animals and potentially contaminated water was maintained in the laboratory at Lawrence University, decontaminated and prevented from release into natural waterways or public water treatment system at all times.

Round goby were sampled along shorelines and shallow rocky reef areas in the outflow regions of Lake Winnebago during summer 2017 (Fig. 2). Shallow areas were sampled using a combination of trapping, dip netting, beach seining, and angling techniques, procedures we have found to be effective for many years for catching round goby in the lower Fox River. Two sizes of cod-end type traps were employed; elongated eel traps (length=0.78m, opening=40mm, mesh=6.4mm), and larger hand-made traps of the same design (length=2m, opening=125mm, mesh= 12.5mm). Traps were deployed with bait (e.g. previously frozen fish, cheese) for a maximum of 24 hours, emptied, and redeployed multiple times at each site. Multiple dip net sweeps (at least six at each site) were performed in each region, being sure to disrupt the bottom and force fish into the water for capture. Multiple beach seine hauls were conducted at shoreline locations (1/4 inch mesh, 4 foot height, 20 foot length). Hook & line angling was conducted in the sampling areas utilizing standard fishing gear; specifically, size #14 hooks, Berkley Gulp! Maggots bait, and no bobber. All fish caught were identified with the Wisconsin Fish ID program and/or Field Guide to Wisconsin Streams.

Laboratory Procedures – Samples were preserved in 70% denatured alcohol upon return to the laboratory. Either entire samples were enumerated, or samples were subsampled using a Folsom plankton splitter (Wildco Inc., Yulee, FL) using liquid dishwashing soap to eliminate surface trapping of specimens. Subsamples were counted at 10X – 40X using five categories for life stages of spiny water fleas: juveniles, males, females with no eggs, females with immediately hatching eggs, and females with resting eggs. Resting eggs are a golden brown color (Jarnagin *et al.* 2000) and this obvious visible trait allowed us to determine the production of resting eggs by females. Our work in 2015 and 2016 confirmed that these golden brown eggs are always resting eggs based on hatching tests performed on live females in the laboratory. Samples from the lower Fox River were not enumerated, but presence/absence was determined.

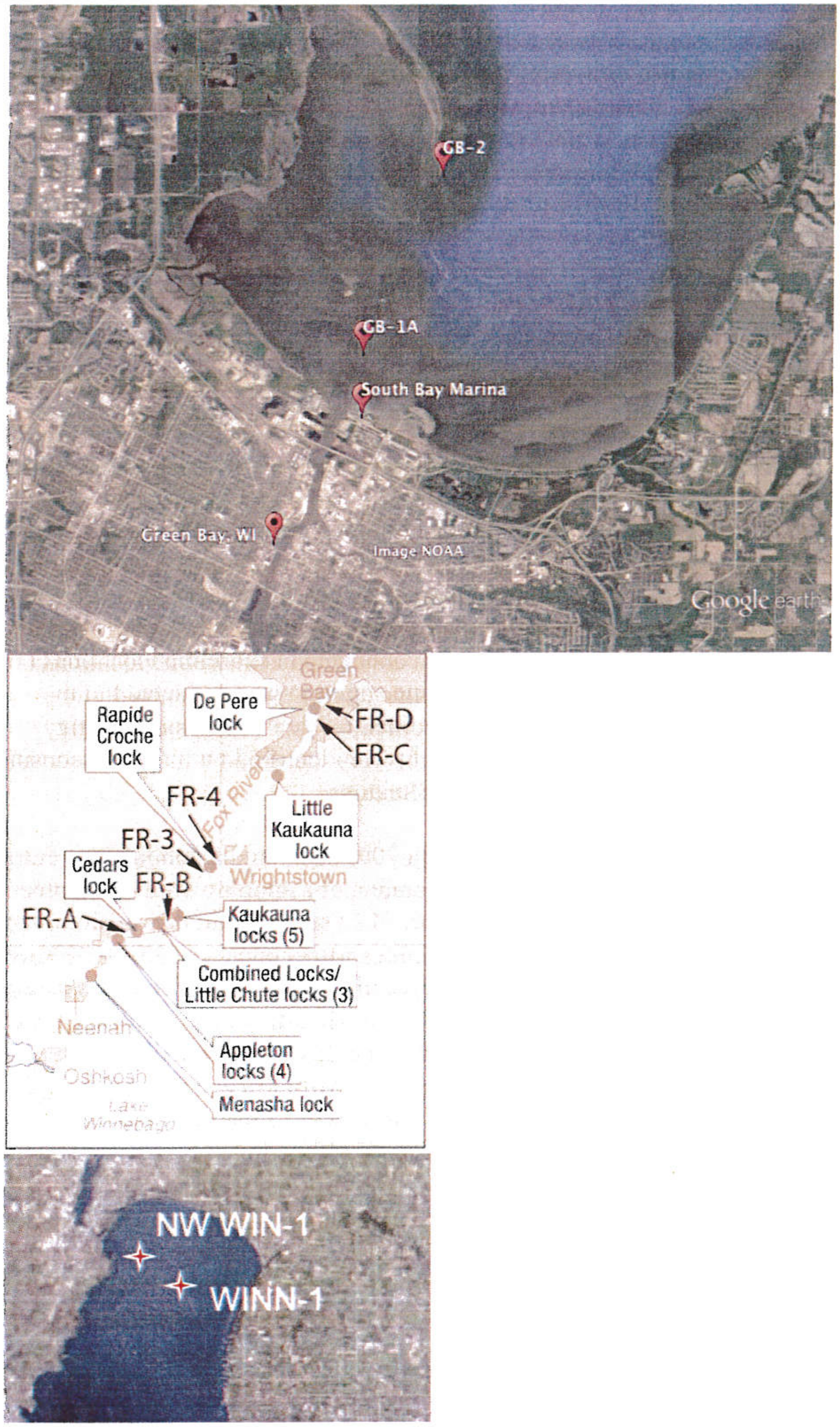


Figure 1. Map of sampling locations in 2017 in lower Green Bay (GB1A and GB2; top panel), lower Fox River, WI (FR-A, FR-B, FR-3, FR-4, FR-C, FR-D; middle panel), and Lake Winnebago (WIN-1, NW WIN-1; bottom panel).

Table 1. Latitude and Longitude coordinates of established sampling sites along the lower Fox River, WI (top section), lower Green Bay (middle section) and Lake Winnebago (bottom section). Sites GB-1A and GB-2 are established sampling locations from studies by De Stasio and colleagues (De Stasio *et al.* 2008, 2014).

Lower Fox River Locations	Latitude	Longitude
Upstream of Rapide Croche		
FR-A (above Cedar lock)	N 44° 16.562	W 88° 20.541
FR-B (above Kaukauna Guard lock)	N 44° 16.665	W 88° 17.042
FR-3 (above Rapid Croche lock)	N 44° 19.077	W 88° 11.962
Downstream of Rapide Croche		
FR-4 (below Rapid Croche lock)	N 44° 18.947	W 88° 11.413
FR-C (above DePere dam)	N 44° 25.813	W 88° 04.273
FR-D (below DePere dam)	N 44° 27.742	W 88° 03.354

Lower Green Bay Locations	Latitude	Longitude
GB-1A	N 44° 32.952	W 87° 59.890
GB-2	N 44° 34.817	W 87° 58.733

Lake Winnebago Locations	Latitude	Longitude
WINN-1	N 44° 11.22	W 88° 23.63
NW WIN-1	N 44° 11.82	W 88° 25.33

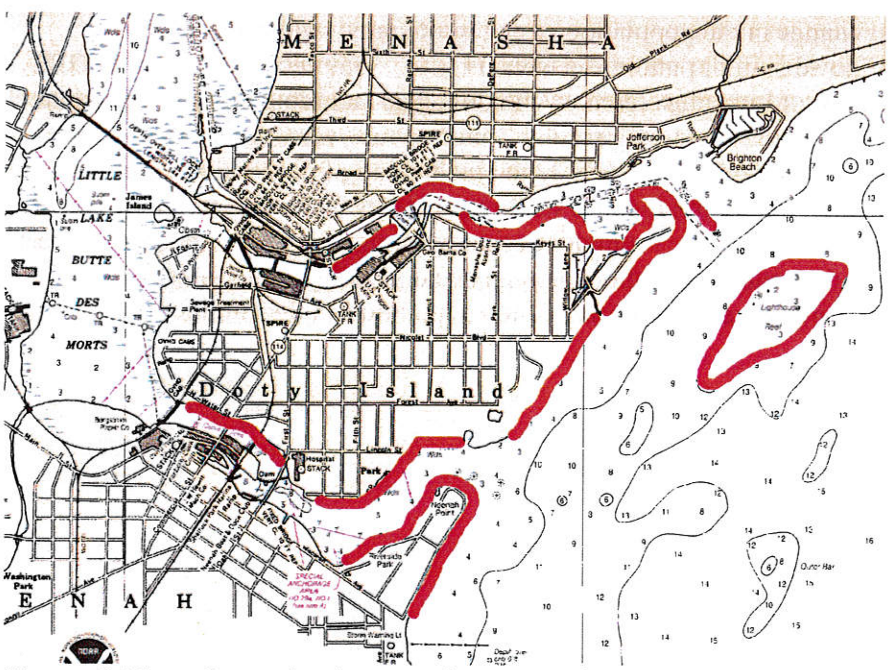


Figure 2. Map of round goby sampling areas for 2017 in Lake Winnebago, WI. Red highlighted areas are where round goby are most expected to occur (e.g. shallow, rocky areas, pipes).

Results

Round goby was not caught in Lake Winnebago in 2017. This was based on 386 hours of fish trapping at five locations, and 8.5 hours of angling at four locations, and dip netting and beach seining at four locations from 30 June to 16 August 2017 (Appendix A). On the lower Fox River round goby was found only at sites below the Rapide Croche invasive species barrier (FR4, FRD), and was not observed at any of the sampling sites above the barrier (which extends upstream to the pool above the Cedar Lock). Details of sampling on lower Fox River are reported in De Stasio (2017).

No spiny water fleas were collected from Lake Winnebago in 2017. Samples were collected from each sampling location biweekly from 15 June to 15 August 2017 (Appendix B). Spiny water fleas were absent from the lower Fox River except for a single individual collected in a sediment sample on 24 July at site FR-A. No additional animals were found in more extensive follow-up sampling, and none were collected by additional sampling conducted by the WI DNR focused on that location (Maureen Ferry, *personal communication).*

The overall dynamics of spiny water fleas in Green Bay were similar at the two sites from June to late September (Figure 3, bottom). The population was not present at GB-1A on the first sampling date (7 June 2017), but were already established at GB2 by that date. Juveniles as well as adults were found at both sites by 21 June (Fig. 4). Abundance at GB2 increased in June and then decreased in July. Population abundacne at both locations increased starting in August and continued to increase through September at GB2.

These dynamics were similar to those in 2015 and 2016 (Fig. 3, top and middle panels). There were population decreases in all years during the middle of the summer, followed by increased abundances in late August and September. The mid-summer decrease in 2017 occurred earlier than in 2015 or 2016.

Seasonal changes in the population structure of spiny water flea at the two sampling sites followed similar patterns as well (Fig. 4). Samples from 7 June at GB2 consisted of a mixture of juveniles, females without eggs, and females with immediately hatching eggs. This is consistent with results from previous years indicating that the population is initiated in late May or early June by hatching of individuals from resting eggs in the sediments. Males and females with resting eggs were observed by 19 July and were collected throughout the reminder of the sampling period. Females comprised from 20% to 80% of the total population abundance depending on the sampling date, with juveniles making a larger proportion of the population as the summer progressed.

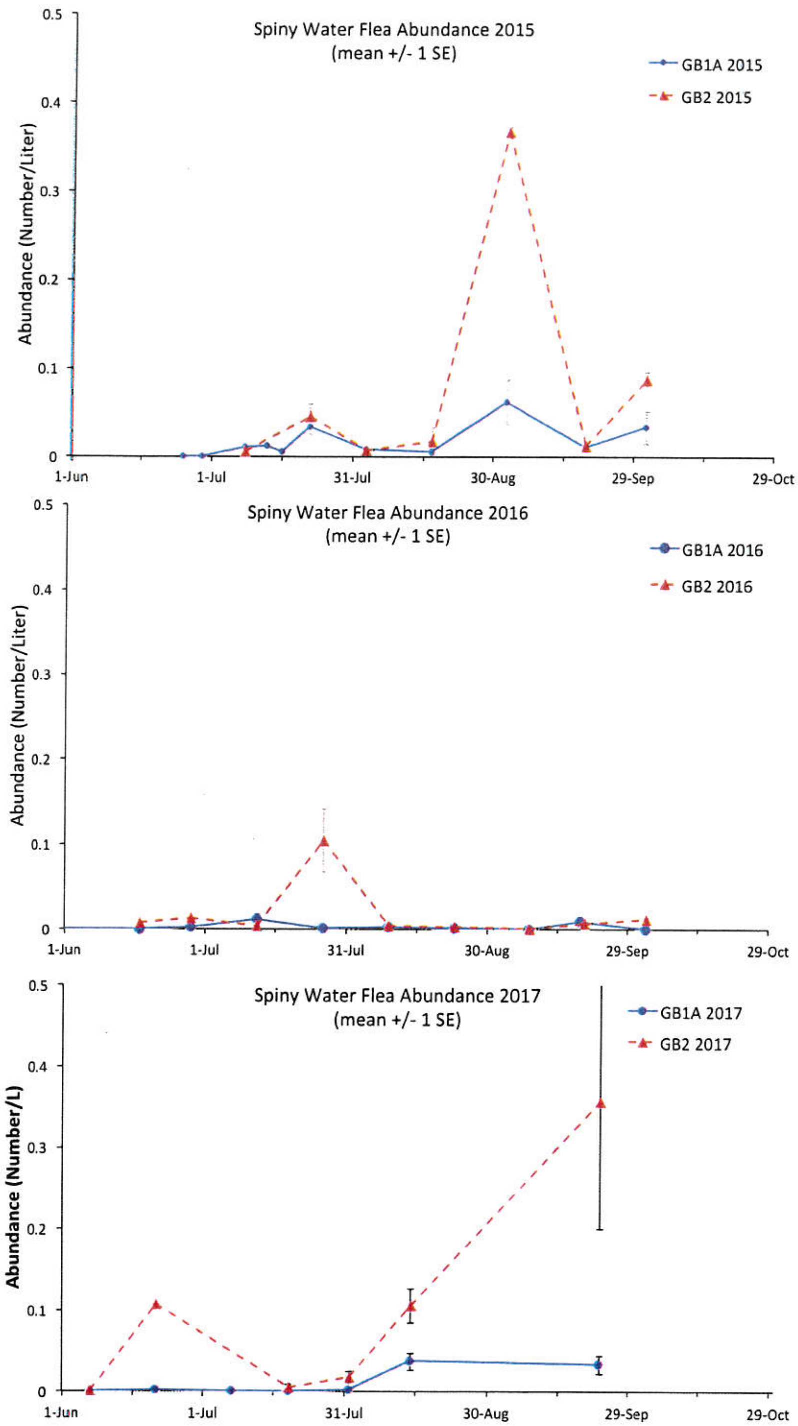


Figure 3. Total population abundance (mean +/- 1 standard error) of spiny water flea in southern Green Bay during 2015 (top panel), 2016 (middle panel) and 2017 (bottom panel).

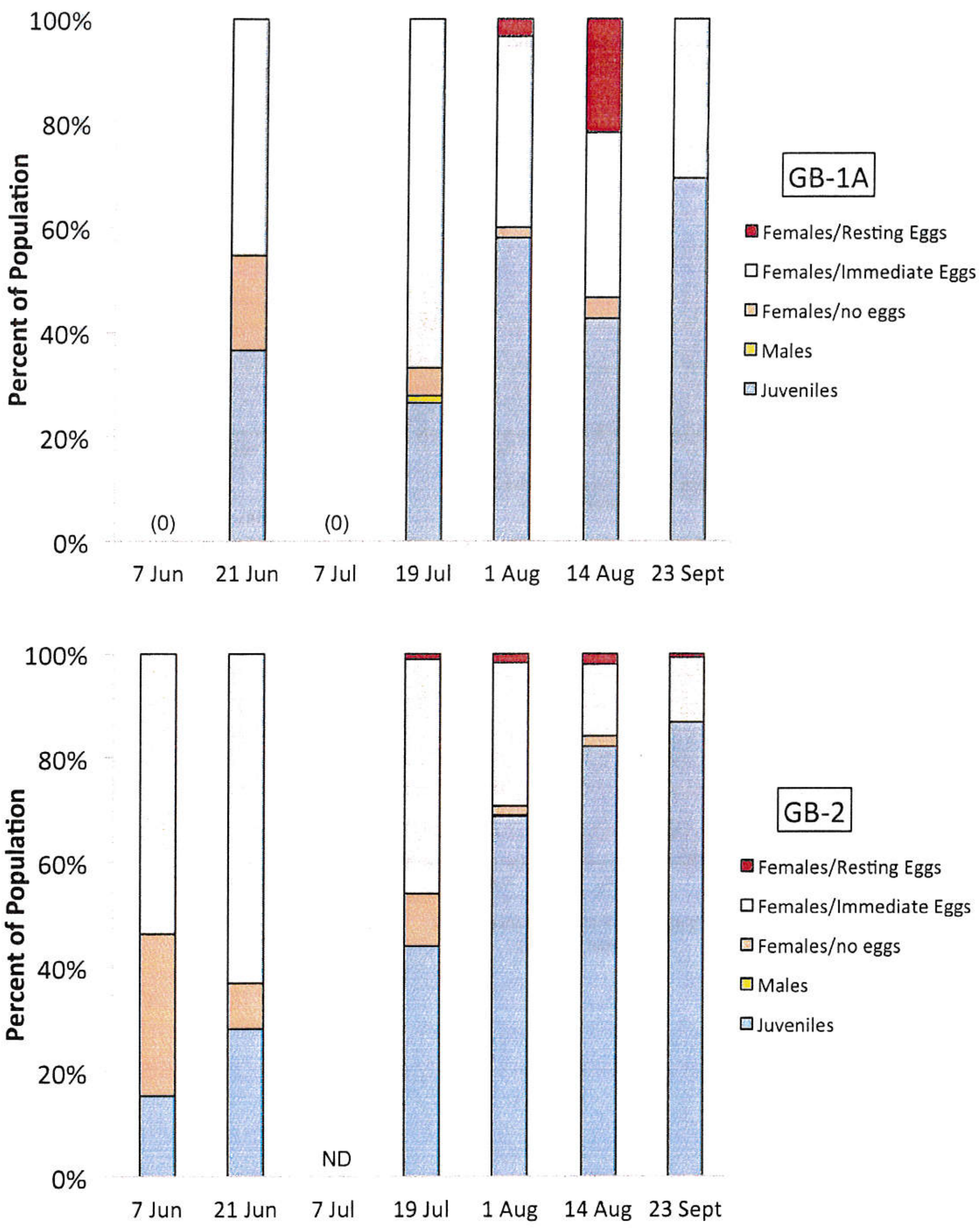


Figure 4. Percent of spiny water flea population in different life stages during 2017 for location GB-1A (top panel) and GB-2 (bottom panel). Note that samples were not collected from GB-2 on 7 July.

Discussion

No spiny water fleas were observed in Lake Winnebago and at only a single site on a single date in the lower Fox River. This indicates that spiny water flea was not established in the lower Fox River or Lake Winnebago. Spiny water fleas were recorded in southern Green Bay from 7 June through 23 September 2017. The population size of spiny water fleas at both locations in southern Green Bay was highest during August and September, and showed a mid-summer dip in abundance. Similar dynamics have been recorded in each of the last 3 years sampled. The population consisted of a mixture of all life stages as early as 7 June, with females making resting eggs by 19 July and continuing production until at least the end of September.

The population already included reproductive females in early June, similar to what occurred in previous years. This suggests that resting eggs most likely hatched in the middle of May. This pattern of resting egg hatching, juvenile maturation and subsequent production of eggs is consistent with previous studies in the Laurentian Great Lakes (e.g. Yurista 1992, 1997), inland lakes in North America (Yan *et al.* 2001, Brown & Branstrator 2005, 2011) as well as European lakes where the species is native (Herzig 1985, Rivier 1998, Straile & Hälbich 2000). Typically the newly hatched individuals from the resting eggs will mature and reproduce asexually (using parthenogenesis) to produce the next generation quickly. Some females switch to sexual reproduction at some point to produce resting eggs that are resistant to harsh conditions. This sexual reproduction requires males, so normally males will be observed in the population when females carrying resting eggs are found. During our sampling in 2017 males and females with resting eggs were first observed on 19 July, later than in the previous two years studied. The presence of females carrying resting eggs indicates that resistant resting eggs could be spread by boaters and other recreational users to new locations during the middle of the summer, when boating activity is highest. In 2015 and 2016 resting eggs were produced up to a month earlier than in 2017, extending concerns about dispersal upstream throughout the main boating season on the lower bay and lower Fox River.

In Fall 2015 reports were obtained by the Wisconsin Department of Natural Resources that round goby had been caught in Little Lake Butte des Morts just below the Menasha dam (Ebert 2015). This lead to concern that this AIS might be able to disperse through the boat lock at Menasha that was functioning at that time. The WI DNR decided to force the closure of the lock in Fall 2015 and increased sampling efforts in Lake Winnebago and encouraged the public to report any round goby caught in the area. During the sampling conducted for our study in 2017 round goby were observed only in the lower Fox River, at sampling locations below the Rapide Croche invasive species barrier. No round goby were caught in Lake Winnebago, despite sampling throughout the summer in shallow, rocky habitats known to be preferred by the fish. We used multiple methods that successfully catch round goby in the lower Fox River. These data support the conclusion that the round goby has not successfully established a population in Lake Winnebago at this time.

Acknowledgements

Funding and support were provided by the Fox River Navigational System Authority, Lawrence University and the Lawrence Excellence in Science Fund. Madison Murray and Alexander Timpe were hired as research assistants on this project. Additional assistance was provided by Chris Lee, Amanda Thomas and Nabor Vazquez.

Literature Cited

Branstrator, D. K., Shannon, L. J., Brown, M. E., & Kitson, M. T. (2013) Effects of chemical and physical conditions on hatching success of *Bythotrephes longimanus* resting eggs. *Limnology & Oceanography* 58(6): 2171-2184.

Brown, M. E., & Branstrator, D. K. (2005) Seasonal dynamics in *Bythotrephes* diapausing egg emergence and production, and the role of dormancy in range expansion. *Verh. Internat. Verein. Limnol.* 29: 174–178.

Brown, M. E., & Branstrator, D. K. (2011) Patterns in the abundance, phenology, and hatching of the resting egg stage of the invasive zooplankter *Bythotrephes longimanus*: implications for establishment. *Biological invasions* 13(11), 2547-2559.

Cook, C. & Neiswender, C. 2007. The Economic Impact of Angling on the Lake Winnebago System. University of Wisconsin-Extension Report. Accessed on 24 September 2016 at http://winnebago.uwex.edu/files/2010/09/Summary_4_page_version5.pdf.

De Stasio, B. T., & Richman, S. (1998) Phytoplankton spatial and temporal distributions in Green Bay, Lake Michigan, prior to colonization by the zebra mussel (*Dreissena polymorpha*). *Journal of Great Lakes Research* 24(3): 620-628.

De Stasio, B. T., Schrimpf, M. B., Beranek, A. E., & Daniels, W. C. (2008) Increased Chlorophyll a, phytoplankton abundance, and cyanobacteria occurrence following invasion of Green Bay, Lake Michigan by dreissenid mussels. *Aquatic Invasions* 3(1), 21-27.

De Stasio, B., Schrimpf, M. & Cornwell, B. 2014. Phytoplankton communities in Green Bay, Lake Michigan after invasion by dreissenid mussels: Increased dominance by cyanobacteria. *Diversity* 6:681-704.

De Stasio, B., Merkle, C. 2016. Spiny Water Flea (*Bythotrephes longimanus*) Monitoring in Southern Green Bay, Lake Michigan, Lower Fox River, and Lake Winnebago During 2015. Final Report to the Fox River Navigational System Authority. Lawrence University, Appleton, WI.

De Stasio, B. 2017. Aquatic Invasive Species Lower Fox River Monitoring Project. Year 2017 Final Report To the Fox River Navigational System Authority. Lawrence University, Appleton, WI.

Ebert, G. 2015. Menasha Lock Closes Indefinitely. Post-Crescent News, 3 September 2015. Appleton, WI.

Herzig, A. (1985) Resting eggs, a significant stage in the life cycle of crustaceans *Leptodora kindtii* and *Bythotrephes longimanus. Verh. Int. Ver. Theor. Angew. Limnol.* 22(3):3088-3098.

Jarnagin, S., Swan, B. & Kerfoot, W.C. (2000) Fish as vectors in the dispersal of *Bythotrephes cederstroemi*: Diapausing eggs survive passage through the gut. *Freshwater Biology* **43**: 579–589.

Jin, E.H. & Sprules, W.G. (1990) Distribution and abundance of *Bythotrephes cederstroemii* (Cladocera: Cercopagidae) in the St. Lawrence Great Lakes. *Verh. Int. Ver. Theor. Angew. Limnol.* 24: 383-385.

Kornis, M.S., Vander Zanden, M.J., 2010. Forecasting the distribution of the invasive round goby (*Neogobius melanostomus*) in Wisconsin tributaries to Lake Michigan. *Can. J. Fish. Aquat. Sci.* 67, 553-562.

Kornis, M.S., Mercado-Silva, N., Vander Zanden, M.J., 2012. Twenty years of invasion: a review of round goby *Neogobius melanostomus* biology, spread and ecological implications. *J. Fish Biology* 80, 235-285.

Lehman, J.T. (1987) Palearctic predator invades North American Great Lakes. *Oecologia* 74: 478–480.

Lehman, J.T. & Caceres, C.E. (1993) Food-web responses to species invasion by a predatory invertebrate: *Bythotrephes* in Lake Michigan. *Limnology & Oceanography* 38(4):879-891.

Lederer, A.M., Janssen, J., Reed, T., Wolf, A., 2008. Impacts of the Introduced Round Goby (*Apollonia melanostoma*) on Dreissenids (*Dreissena polymorpha* and *Dreissena bugensis*) and on Macroinvertebrate Community between 2003 and 2006 in the Littoral Zone of Green Bay, Lake Michigan. *J. Gt. Lakes Res.* 34, 690-697.

Merkle, C. and De Stasio, B.T. In review. *Bythotrephes longimanus* in shallow, nearshore waters: Interactions with *Leptodora kindtii*, impacts on zooplankton, and implications for secondary dispersal from southern Green Bay, Lake Michigan. Journal of Great Lakes Research.

Pothoven, S. A., Fahnenstiel, G. L. and Vanderploeg, H. A. (2003) Population characteristics of *Bythotrephes* in Lake Michigan. *J. Gt. Lakes Res.* 29: 145–156.

Pothoven, S. A., & Höök, T.O. (2014) Predatory demands of *Bythotrephes* and *Leptodora* in Saginaw Bay, Lake Huron. *J. Gt. Lakes Res. Supplement* 40: 106–112.

Rivier, I.K. (1998) The Predatory Cladocera (Onychopoda: Podonidae, Polyphemidae, Cercopagidae) and Leptodorida of the World. In: HJF Dumont (ed.), Guides to the identification of the microinvertebrates of the continental waters of the world. 13: 213 p. Backhuys Publishing, Leiden.

Straile, D. & Hälbich, A. (2000) Life history and multiple antipredator defenses of an invertebrate pelagic predator, *Bythotrephes longimanus*. *Ecology* 81, 150–163.

Yan, N. D., Blukacz, A., Sprules, W.G., Kindy, P.K., Hackett, D., Girard, R.E. & Clark, B.J. (2001) Changes in zooplankton and the phenology of the spiny water flea, *Bythotrephes*, following its invasion of Harp Lake, Ontario, Canada. *Can. J. Fish. Aquat. Sci.* 58: 2341–2350

Yurista, P.M. (1992) Embryonic and post-embryonic development of *Bythotrephes cederstroemii. Can. J. Fish. Aquat. Sci.* 49:**1**118-1 125.

Yurista, P. M. (1997) *Bythotrephes cederstroemi* diapausing egg distribution and abundance in Lake Michigan and the environmental cues for breaking diapause *J. Gt. Lakes Res.* 23(2), 202-209.

Appendix A: Sampling effort for round goby monitoring on Lake Winnebago and lower Fox River during 2017.

Site	Date	Sample Type	Time (hr)
Jefferson Park	6/30/17	Angling	1
Smith Park	6/30/17	Angling	1.5
Smith Park	7/5/17	Angling	3
Kimberly Point, Neenah	8/10/17	Angling	1.5
ThedaClark Hospital	8/10/17	Angling	1.5

Site	Date	Sample Type	Time (hr)
Jefferson Park	7/5/17	Traps	24
Smith Park	7/5/17	Traps	72
Jefferson Park	7/17/17	Traps	24
Smith Park	7/17/17	Traps	72
Kimberly Point, Neenah	8/10/17	Traps	98
Doty Park, Neenah	8/16/17	Traps	48
Nicolet Blvd Access	8/16/17	Traps	48

Appendix B: Sampling effort for spiny water flea monitoring on Green Bay and Lake Winnebago during 2017.

Site	Date
GB1A	6/7/17
GB1A	6/21/17
GB1A	7/7/17
GB1A	7/19/17
GB1A	8/1/17
GB1A	8/14/17
GB1A	8/21/17
GB1A	9/23/17
GB2	6/7/17
GB2	6/21/17
GB2	7/19/17
GB2	8/1/17
GB2	8/14/17
GB2	8/21/17
GB2	9/23/17
Win1	6/15/17
Win1	6/27/17
Win1	7/11/17
Win1	7/25/17
Win1	8/15/17
NW WIN-1	6/15/17
NW WIN-1	6/27/17
NW WIN-1	7/11/17
NW WIN-1	7/25/17
NW WIN-1	8/15/17

OSHKOSH

Business Success Center

The Economic Impact of the Fox Locks

Dr. David L. Fuller

Department of Economics
University of Wisconsin-Oshkosh

October 2017

The Economic Impact of the Fox Locks

Dr. David L. Fuller
Department of Economics
University of Wisconsin-Oshkosh

October 2017

Executive Summary

This report explores the economic impact of the Fox Locks system. Stretching from Menasha to DePere, the Fox Locks represents a system of 17 locks on the Fox River. Beginning in 2005, the Fox River Navigational System Authority (FRSNA) was authorized to begin a $14.5 million project to renovate the lock system. This report first evaluates the economic contribution of the completed work since 2005. Next, the report estimates the future economic impact of the locks under four different scenarios: (i) Menasha and Rapid Croche locks are closed (ii) Rapid Croche opens, Menasha is closed (iii) Rapid Croche is closed, Menasha opens, and (iv) All locks are fully operational. Summarizing the main findings:

- The work to date restoring the locks has contributed the following to the Fox Valley Regional economy from 2005-2015 (Menasha is closed Scenario):
  - $64.4 million in total output
  - $39.2 million in labor income
  - 1458 jobs
  - $22 million in business investment

- The ***additional*** economic impact of opening each of Menasha and Rapide Croche accumulated over a 10 year period starting in 2018:
  1. Menasha is opened, Rapide Croche is closed:
     - $42.9 million in *additional* total output accumulated over 10 years
     - $26 million in *additional* labor income accumulated over 10 years

  - 939 *additional* jobs accumulated over 10 years
  - $14.6 million in *additional* business investment accumulated over 10 years

2. Menasha is opened, Rapide Croche receives boat transfer station:
   - $210 million in *additional* total output accumulated over 10 years
   - $127.7 million in *additional* labor income accumulated over 10 years
   - 4,595 *additional* jobs accumulated over 10 years
   - $71.8 million in *additional* business investment accumulated over 10 years

3. Rapide Croche receives boat transfer station, Menasha is closed:
   - $167.7 million in *additional* total output accumulated over 10 years
   - $102 million in *additional* labor income accumulated over 10 years
   - 3,669 *additional* jobs accumulated over 10 years
   - $57.3 million in *additional* business investment accumulated over 10 years

- Over the next 10 years, the proposed Visitors' Center has a potential economic impact of:
  - $79.7 million in *additional* total output accumulated over 10 years
  - $48.5 million in *additional* labor income accumulated over 10 years
  - 1,744 *additional* jobs accumulated over 10 years
  - $27.2 million in *additional* business investment accumulated over 10 years

- In total, a fully functioning Lock system, including the visitors' center has a 10 year potential economic impact of:
  - $290 million in *additional* total output accumulated over 10 years
  - $176 million in *additional* labor income accumulated over 10 years
  - 6,339 *additional* jobs accumulated over 10 years
  - $99 million in *additional* business investment accumulated over 10 years

1 Introduction and Overview

Stretching from Menasha to DePere, the Fox Locks represents a system of 17 locks on the Fox River. Figure 1 provides a map of the Lock system. Beginning in 2005, the Fox River Navigational System Authority (FRSNA) was authorized to begin a $14.5 million project to renovate the lock system. Currently, 16 of the 17 locks have been restored and are potentially fully operational; however, due to concerns regarding an aquatic invasive species (AIS), the Menasha lock is closed (it was open from 2005-2015 and was closed in September of 2015). Similarly, the lock at Rapid Croche is closed, although the FRNSA has a proposed plan to make the lock operational via a boat transfer and cleaning station.

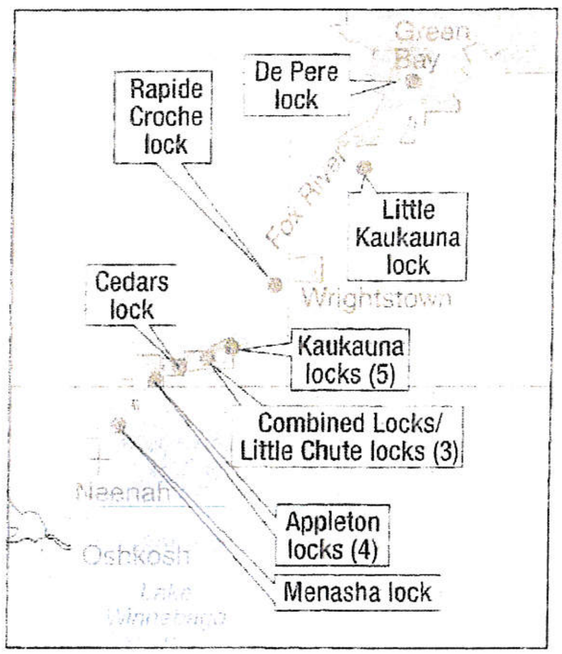


Figure 1: Map of Lock System

This report has two primary objectives: 1) Evaluate the economic impact of the locks and their restoration work, and 2) evaluate the future economic impact of differing levels of lock functionality, depending on what combinations of locks currently closed are opened and usable. While the details are described below in Section 2, the amount and timing of restorations and maintenance to the Locks represents the key starting point for the analysis.

Since 2005, restoration on the existing locks occurred at the following dates:[1]

- 2005: Little Chute
- 2006: Appleton 1-4
- 2007: Cedars
- 2008: Little Chute
- 2009: Combined Locks
- 2011: Kaukauna 4
- 2012: Kaukauna 3 and 5
- 2013: Kaukauna 2
- 2014: DePere, Kaukauna 1, and Menasha

Over this period of time, $14.5 million was invested in the Fox Valley Regional economy. Section 3 of this economic impact analysis examines the contribution of this previous work. In Section 4, the potential future impact of the Locks system is evaluated under several different scenarios. As discussed above, two locks are currently closed. The lock at Rapide Croche is closed indefinitely to help prevent transmission of aquatic invasive species (AIS) from the Great Lakes to Lake Winnebago. Similarly, the Menasha lock is closed since September 2015 due to AIS concerns (round goby). Thus, there exist four different scenarios to analyze:

1. Current system, Menasha and Rapide Croche stay closed
2. Menasha lock re-opened, Rapide Croche stays closed
3. Rapide Croche opened, Menasha stays closed
4. Both Rapide Croche and Menasha open

Water sports and related activities represent an important component of the Wisconsin economy, and this is especially true of the Fox Valley Region. With two large lakes, the Fox River, and access to Lake Michigan, the water sport possibilities are significant. Indeed boating, fishing, and other related water activities have a large economic impact on the Fox Valley Regional economy. According to data from the National Marine Manufactures Association (NMMA), in 2015 recreational boating had an estimated total economic impact of $603.5 million and $742.8 million in Congressional Districts 6 and 8, respectively (which

[1] See `http://www.foxlocks.org/the-locks/lock-system-overview/`

includes the region defined for the Locks contribution).[2] Thus, recreational boating contributes \$1.3 billion annually to the Fox Valley Regional economy, representing nearly 12% of total output (GDP) in the Fox Valley Regional economy. Similarly, a 2006 Economic Impact analysis of fishing activities on Lake Winnebago found a total economic impact of \$234 million annually. Adjusted for inflation, this is equivalent to an annual economic impact of \$275 million in 2016.

These studies show the importance of water-sports and activities to the Fox Valley Regional economy. Although these previous studies are not used in the analysis below, they are presented here simply to show the importance of water-sports and related activities to the local economy. The Locks represent a key component of the interconnected waterways supporting this economic activity. The goal of this analysis is to estimate the past and potential future impact of the Locks on the Fox Valley Regional economy.

It is also worth noting that the analysis in this report characterizes the potential gains from different levels of functionality of the Locks, assuming the necessary AIS protections are in place. In this regard, this report focuses only on characterizing the potential economic gains; as a result, it is not a cost-benefit analysis. A full cost-benefit analysis would require estimating models to quantify the varying probabilities of AIS issues potentially propagated by the Locks, as well as estimating their potential economic costs. While AIS protections may utilized, as with all bodies of water, there exists some risk of potential AIS issues. The economic impact numbers presented in this report should be considered relative to these potential future costs.

Within each combination of lock openings/closures, different scenarios are analyzed to estimate the future impact of the Locks on the Fox Valley Regional economy over the next 10 years. The next section describes the details of the approach taken in this study, along with the data and methodology.

2 Methodology, Approach, and Data

The Locks have several ways to contribute to the Fox Valley Regional economy. Most immediately, the \$14.5 million spent on lock repairs and renovations directly contributes. Many industries are supported in this process. Of course, the impact stretches beyond the immediate impact of \$14.5 million. Specifically, there exist two other possibilities for evaluating the total economic impact.

[2] See https://www.nmma.org/statistics/publications/economic-impact-infographics

First, one could examine the additional spending created by a functioning Lock system. Since 2005, over 30,000 people and more than 6,000 boats have travelled through the locks system. When recreational boaters and other water craft (e.g. kayaks) use the locks, they spend money in the local economy. For example, on a trip through the locks, a group of 4 people in a boat eat lunch, purchase gasoline and other supplies for the boat, and may shop at local stores along the way. Traditional economic impact analyses (using an input-output model) focus on this injection of spending. This is referred to as an increase in final demand. To meet this increase in demand, local business produce more goods and services from other local businesses, causing the total impact to be a multiple of the initial injection of spending.

There are two reasons why examining additional spending by lock boaters is inappropriate to judge the economic impact of the Locks. First, to be valid, the spending by boaters would have to be from visitors to the area; that is, it must be truly *new* spending to the area. While indeed some users of the locks come from out of the area, many others do not. Lacking consistent data on the residence of Lock users, the spending approach becomes infeasible. Moreover, this approach requires one to estimate the number of additional visitors that can be directly attributable to the opening of the Locks, which again is difficult given currently available data.

Second, the economic impact of the Locks is potentially well beyond the additional spending by lock users. Specifically, a functioning lock system provides opportunities for expansion of local businesses. If lock users dock boats and explore local surroundings, the value of investing in expansions and new businesses increases. In addition, the Locks provide various educational opportunities for users and visitors of the locks. Indeed, the planned Visitor's Center in Appleton is intended to highlight and expand these educational opportunities. Viewed in this light, the lock restorations function similarly to investments in education. This second effect is not well captured, if at all, by a traditional input-output model based economic impact study.

2.1 Approach

To begin, consider how any additional spending or business investment affects a local economy. To understand this question, we must first break down how an economy operates. An economy produces goods/services that are referred to as **output**. To produce output, an economy needs three key ingredients: (i) Capital, (ii) Labor, and (iii) Infrastructure. Capital refers to the buildings, factories, machines, equipment, etc. that a business uses to produce its products/services. Labor refers to the workers a business employs, and infrastructure refers to **Public Capital**, which is roads, bridges, power supplies, schools, etc. that facilitate business activity.

For example, consider a restaurant. To produce meals for customers, the restaurant needs a building and cooking equipment (ovens, refrigerators, etc.). This represents the restaurant's Capital. In addition, the restaurant will need employees to operate the equipment, prepare the food, and serve customers. This represents the restaurant's Labor. Finally, the restaurant needs functioning roads/railways/waterways to transport the raw materials it uses and to allow customers and workers to access their establishments, as well as a school system to educate its owners and workers. This represents the Infrastructure.

The value of infrastructure, or public capital, on economic activity has been well established in existing research.[3] Consider the restaurant example. Suppose that initially access to the restaurant's location was somewhat restricted. If the area invests in infrastructure improvements that increase access to the restaurant, the restaurant becomes more productive. They will produce more meals and services, and hire more workers. The restaurant will likely also have to purchase additional capital, referred to as business investment. Moreover, with improved access and expansion of this particular restaurant, and as the increased incomes of employees leads to more spending in the area, other businesses may decide to locate nearby. Thus, the initial increase in infrastructure investment increases overall economic activity by a multiple of the initial investment.

A similar scenario is true with respect to the Locks. Functioning locks increase the infrastructure value of the Fox river and nearby lakes. For example, consider the recent riverfront development in Appleton. Local housing, a coffee shop (Temptest), restaurant (Mr. Brews Taphouse), and hotel (Marriot) have all been built along the waterfront. Indeed, the water access represents a key component of the profitability of these investments for local businesses. While the functioning locks that increase access to this area do not represent the sole reason for this increased economic activity, it does represent a crucial improvement/investment in the infrastructure that supports this economic activity. The analysis presented in this report estimates the economic impact of the Lock system via its value as infrastructure.

[3]See for example Glomm and Ravikumar (1997) and Seung and Kraybill (2001) among many others.

2.2 Methodology

Defining the relevant local economics potentially impacted represents an important first step in the analysis. Again, the economic impact of the Locks stems from its value as infrastructure for local economies; therefore, the lakes and waterways used by the locks, or accessible via the locks, represent areas of potential impact. Given this, the Fox Valley Regional economy is defined from Green Bay to Fond du Lac. This represents Brown, Calumet, Outagamie, Winnebago, and Fond du Lac counties.

To estimate the economic impact of the infrastructure investments represented by the Locks, a model of the local economy is developed. Estimating the relationship between output, labor, capital, and infrastructure in the local economy represents a key foundation. Towards this end, a *production function* must be estimated for the Fox Valley Regional economy. An attached Technical Appendix describes the details of the specification of this production function and its estimation.

Having estimated a production function, with data on actual output, employment, capital, and public capital (infrastructure), a model is specified that describes local business investment decisions (how much capital to use) and employment decisions (how much labor to hire and at what wages), taking as given the level of infrastructure. This model is then fitted to existing data on the Fox Valley Regional economy as a benchmark. From this benchmark, the desired "experiments" are conducted, varying the available infrastructure based on different levels of Locks functionality.

2.3 Data

As discussed above, estimating a production function and fitting the model require data for the Fox Valley Regional economy. Regional economic data is available from the U.S. Department of Commerce via the Bureau of Economic Analysis (BEA).[4] For some necessary data series, regional availability is given by Metropolitan Statistical Areas (MSA). Given the aforementioned definition of the Fox Valley Regional economy, the appropriate MSAs are: Green Bay, Appleton, Oshkosh-Neenah, and Fond du Lac.[5]

To estimate the model, data on Real GDP (Gross Domestic Product), Employment, and Public Capital (Infrastructure) is needed. Real GDP and Employment data were obtained from the BEA. Data on Public Capital is not readily available and thus must be constructed.

[4] This data was obtained at `https://www.bea.gov/regional/index.htm`.

[5] MSAs are defined and determined by the Office of Management and Budget, `https://www.whitehouse.gov/omb`.

In this study, estimates of public capital for the State of Wisconsin were obtained from two sources, Holtz-Eakin (1993) and Fisher and Wassmer (2013). From these sources, the stock of public capital is estimated at 2.89% of real GDP and is nearly constant across the relevant years. Thus, the stock of public capital is calculated based on this fraction of Real GDP for the Fox Valley Regional economy. The remaining details of the estimating procedure and data benchmarks is discussed in the Technical Appendix.

3 Economic Impact of the Locks: 2005-2015

The analysis begins by estimating the total economic impact of the Locks over the course of their renovations and repairs, namely from 2005-2015. This is accomplished by using the model of the Fox Valley Regional economy to predict what *would* have occurred had none of the Locks been restored. That is, decrease the actual stock of public capital in a particular year by the amount of work done on Locks in that year. Given this counterfactual level of infrastructure, what would GDP, employment, investment, and wages be? The difference between the actual data and this counterfactual outcome gives the economic impact of the Locks renovations.

Table 1: Economic Impact of Locks: 2005-2015

Variable	Contribution of Locks
GDP	$64, 421, 074
Labor Income	$39, 168, 013
Investment	$22, 047, 490
Employment	1,458

Table 1 displays the cumulative economic impact of the Locks from 2005-2015. In terms of total output, the Locks contributed $64.4 million in additional GDP to the Fox Valley Regional economy. The Locks also contributed an additional $39 million in Labor Income, stemming in part from the additional 1, 458 jobs attributable to the Locks, and from an increase in wages paid by firms. Wages increase primarily due to the increase in the capital stock attributable to the Locks. When capital increases, workers become more productive and earn higher wages. Combined with the increase in employment, total Labor Income increased. Finally, investment increased by a cumulative sum of $22, 047, 490, which is calculated as the difference in capital income in the baseline case (data) and the counterfactual economy (with no Locks renovations).

In Table 1, the results apply only to the direct impact of the Locks renovations. That is, in each year a lock is renovated, the appropriate amount of infrastructure is removed from the economy in that specific period; however, the cumulative effect of removing the infrastructure is not calculated. To examine the full impact of the renovations, one must consider the cumulative effect of removing the infrastructure. Consider the following example.

Suppose that each lock involves an infrastructure investment of $1 million. In year 1 one lock is renovated. 1 is renovated in year 2, and 3 are renovated in year 3. This implies a total investment of 5 locks or $5 million. In Table 1, the observed stock of public capital is reduced by $1 million in year 1, $1 million, year 2, and then $3 million in year 3. This gives the economic impact of each lock individually, but does not cumulate the total impact of having none of the locks renovated. The total cumulative impact is represented by reducing the stock of public capital by $1 million in year 1, $2 million in year 2, and then $5 million in year 3. The total cumulative impact of the Locks on the Fox Valley Regional economy is presented in Table 2.

Table 2: Total Cumulative Impact of the Locks: 2005-2015

Year	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
2005	2,541,511	1,545,239	-	870,596
2006	13,121,962	7,978,153	18	4,489,106
2007	17,343,479	10,544,835	109	5,932,899
2008	21,739,819	13,217,810	216	7,436,369
2009	26,616,553	16,182,865	341	9,104,207
2010	29,312,554	17,822,033	486	10,026,271
2011	34,571,717	21,019,604	630	11,824,942
2012	42,748,471	25,991,070	790	14,621,411
2013	48,447,602	29,456,142	985	16,570,465
2014	60,567,592	36,825,096	1,203	20,715,558
2015	65,925,986	40,083,000	1,474	22,548,198
Total	362,937,247	220,665,846	6,252	124,140,021

Imagine the following counterfactual: none of the Locks were renovated, and thus none are usable. Taking the difference between predictions with no locks and what actually occurred calculates the value of the entire lock system. Table 2 presents these results. From 2005-2015 the Lock system contributed a total of nearly $363 million in real GDP (output), $220.7 million in labor income, 6,252 additional jobs, and $124 million in capital investments. This amounts to an average of $33 million each year from 2005-2015 in total additional economic activity. This cumulative look at the value of the Locks further underscores its importance to the Fox Valley Regional economy. If the locks are all closed at some point in the future, the last row of Table 2 displays what impact this would have on the local economy over a 10 year period.

4 Economic Impact of Rapide Croche and Menasha Locks

This section analyzes the economic value of both the Menasha and Rapide Croche locks. As both locks currently are closed, a baseline predicted path for the economy must be established. The projected future path of the key economic variables for the Fox Valley Regional economy are first estimated using a linear time-trend specification. Having estimated a specification for each of real GDP, employment, and population growth, the remaining variables can similarly be computed/imputed from the model economy. This exercise then predicts levels for real GDP. employment, labor income, and investment for the next 10 years.[6] Once the benchmark future economy is established, the counterfactual cases may be analyzed. Each case is now discussed.

4.1 Menasha is opened and Rapide Croche is closed

If the Menasha lock is opened, this increases the value of existing infrastructure. The lock has already been restored and had been operational, so opening the lock also restores the infrastructure value. If the Rapide Croche lock remains closed, however, there is no change to the baseline level of public capital. Thus, the first experiment increases infrastructure by the value of the Menasha lock, and recomputes the levels for real GDP, employment, labor income, and investment for the next 10 years. The value of the Menasha lock is assumed as a baseline to be equal to the average infrastructure value of 1 lock, which is equivalent to distributing the $14.5 million investment equally across the locks repaired. This assumption almost certainly understates the full impact of the Menasha lock, as this lock was the most used in the system, acting as a gateway to Lake Winnebago; as a result, Menasha is likely significantly more valuable than average.

[6]The levels predicted for the baseline economy do not affect the results presented here. Since the production function exhibits constant returns to scale (i.e. homogeneous of degree 1), any level changes in real GDP result in proportionate changes in capital, labor, and public capital. Assuming that real GDP grows somewhere approximately close to trend in the future, the estimates presented here will not vary significantly if real GDP varies mildly from its predicted value.

Table 3: Economic Impact of Menasha Lock over 10 years

Year	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
1	2,865,331	1,742,121	18	978,447
2	3,187,099	1,937,756	35	1,088,479
3	3,507,351	2,132,469	52	1,197,992
4	3,825,816	2,326,096	70	1,306,893
5	4,142,230	2,518,476	86	1,415,093
6	4,456,328	2,709,448	103	1,522,502
7	4,767,856	2,898,856	120	1,629,031
8	5,076,560	3,086,548	136	1,734,594
9	5,382,194	3,272,374	152	1,839,108
10	5,684,518	3,456,187	167	1,942,489
Total	42,895,282	26,080,332	939	14,654,628

Table 3 displays the effect of opening the Menasha lock over the next 10 years. In total over the next 10 years, the Menasha lock has the potential to bring an additional $43 million in total output, $26 million in labor income, and additional 939 jobs, and increases capital investment by a total of $14.6 million. In addition, notice that the annual impact of opening the Menasha lock, *adjusted for inflation*, grows each year. This occurs as the additional infrastructure generates more investment, increasing the capital stock, and generating more employment. These affects accumulate over time. This represents the economic growth potential of the infrastructure value of the Locks.[7]

Table 4: Economic Impact of Opening Both Menasha and Rapide Croche

Year	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
1	14,030,819	8,530,738	86	4,797,044
2	15,607,474	9,489,344	172	5,336,247
3	17,176,710	10,443,440	257	5,872,912
4	18,737,205	11,392,221	340	6,406,588
5	20,287,655	12,334,895	423	6,936,829
6	21,826,781	13,270,683	505	7,463,197
7	23,353,325	14,198,822	585	7,985,261
8	24,866,054	15,118,561	665	8,502,601
9	26,363,764	16,029,169	743	9,014,805
10	27,845,279	16,929,930	820	9,521,469
Total	210,095,067	127,737,801	4,595	71,836,954

[7]See Glomm and Ravikumar (1997), Rioja (2003), Gibson and Rioja (2017), among others for discussion of the economic growth potential on infrastructure investments.

4.2 Menasha is opened, Rapide Croche receives boat transfer station

In this scenario, in addition to the infrastructure impact of the Menasha lock described in Section 4.1, the planned boat transfer and cleaning facility is completed at Rapide Croche, making this lock also fully operational. The boat transfer and cleaning facility is estimated to cost $3.8 million and would be potentially operational by 2018 (the start date does not impact the estimated economic impact). Based on these scenarios, Table 4 shows the economic impact on Real GDP, Labor Income, Employment, and Investment over the next 10 years. In total, over the next 10 years a fully functional lock system has the potential to add an additional $210 million in output, $127.7 million in labor income, nearly 5,000 jobs, and an additional $71.8 million in capital investments. On average, this represents an additional $21 million annually to the Fox Valley Regional economy.

4.3 Rapide Croche receives boat transfer station, Menasha Lock is closed

Assuming Rapide Croche receives the boat transfer and cleaning station while Menasha is closed represents the final Lock scenario to analyze. As discussed above, the proposed boat transfer and cleaning facility is estimated to cost $3.8 million. ?? displays the 10 year impact of increasing the level of infrastructure in the Fox Valley Regional economy by this amount.

Table 5: Economic Impact of Rapid Croche Boat Transfer, Menasha is closed

Year	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
1	11,202,308	6,811,003	69	3,829,694
2	12,460,889	7,576,220	137	4,260,115
3	13,713,542	8,337,833	205	4,688,509
4	14,959,212	9,095,201	272	5,114,515
5	16,196,858	9,847,690	338	5,537,776
6	17,425,458	10,594,679	403	5,957,944
7	18,644,008	11,335,557	467	6,374,675
8	19,851,523	12,069,726	531	6,787,632
9	21,047,042	12,796,601	593	7,196,486
10	22,229,624	13,515,611	655	7,600,915
Total	167,730,464	101,980,122	3,669	57,348,260

From Table 5, in total, a functional lock at Rapide Croche has a potential economic impact of $167.7 million of additional output, $101.9 million in labor income, and additional 3,700 jobs, and an additional $57.3 million in capital investments. Annualized this is equivalent to an additional $16.7 million of total economic activity per year.

4.4 Appleton Visitors' Center

Finally, this section examines the potential economic impact of completing the proposed Appleton Visitors' Center. As discussed above, the proposal is for a $1.8 million Visitor's Center located at Appleton Lock 3 (see `http://foxlocks.org/visitor-center/` for more details).

Table 6: Economic Impact of Appleton Visitors' Center over 10 years

Year	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
1	5,324,628	3,237,374	33	1,819,527
2	5,922,633	3,600,961	65	2,024,031
3	6,517,818	3,962,834	97	2,227,571
4	7,109,683	4,322,687	129	2,429,976
5	7,697,731	4,680,220	161	2,631,075
6	8,281,476	5,035,137	192	2,830,702
7	8,860,441	5,387,148	222	3,028,695
8	9,434,157	5,735,968	252	3,224,892
9	10,002,168	6,081,318	282	3,419,139
10	10,564,027	6,422,928	311	3,611,281
Total	79,714,760	48,466,574	1,744	27,246,889

Table 6 displays the potential economic impact each year over the next 10 years. As previously discussed, the potential economic impact of the Visitors' Center is significant as it may be viewed similarly to an investment in education. Indeed, Table 6 confirms this, showing a total potential impact of an additional $79.7 million of output, $48.5 million in labor income, 1,744 additional jobs, and $27.2 million in additional capital investments. On average, this represents a potential $7.9 million per year of additional economic activity. As with the other cases examined, the economic impact of the visitors' center increases over time (after adjusting for inflation), reflecting the economic growth potential of such investments in the infrastructure in the Fox Valley Regional economy.

5 Total Potential Impact of the Locks and the Economic Impact of Related Activities

This section cumulates the total impact of the Locks under each scenario above. To begin, first combine the future potential impact of each lock opening/closing scenario with the economic impact of the Visitors' Center, which occurs in each scenario. Table 7 presents the total 10 year impact on the relevant economic variables, and Table 8 displays the average annual contribution in each variable under each scenario. From Table 8, on average, having both the Menasha and Rapide Croche locks open has the potential to contribute $29 million in total output, $17.6 million in additional Labor Income, $634 additional jobs, and $99 million in additional capital investment, *each year* for the next 10 years.

As a matter of comparison, consider the economic impact of the EAA AirVenture event on the Fox Valley Regional Economy. Based on a recent study of its economic impact, in 2017 it contributed a total of $\$170 million$ in additional economic activity, including around $2,000$ additional jobs.[8] Thus, the potential contribution of the Locks represents on average about 20% of the total contribution of AirVenture to the Fox Valley Regional economy.

Next, consider the total 20 year impact of each Lock opening scenario. In this case, we want to include the 2005-2015 impact of the Locks, and add to it the potential additional future impact. To do so, one adds the impact of the appropriate variable from Table 1 to the same variable under each scenario in Table 7. Table 9 displays this total economic impact.

Finally, again considering the full 20 year impact, Table 10 adds the cumulative contribution of the Locks from 2005-2015 to the appropriate variable under each scenario in Table 7, giving the full cumulative impact of the Locks over a 20 year period. Table 11 presents the average annual impacts of this case.

Table 7: Total 10 year Impact including Visitors' Center

Scenario	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
Menasha Open	122,610,042	74,546,906	2,683	41,901,517
Rapide Croche Open	247,445,224	150,446,696	5,413	84,595,149
Both Open	289,809,827	176,204,375	6,339	99,083,844

[8] https://www.eaa.org/en/eaa/eaa-news-and-aviation-news/news/09-21-2017-airventure-contributes-more-

Table 8: Average annual impact of Table 7 scenarios

Scenario	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
Menasha Open	12,261,004	7,454,691	268	4,190,152
Rapide Croche Open	24,744,522	15,044,670	541	8,459,515
Both Open	28,980,983	17,620,437	634	9,908,384

Table 9: Total Impact of Each Scenario, Including 2005-2015 Individual Impacts

Scenario	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
Menasha Open	187,031,116	113,714,919	4,141	63,949,007
Rapide Croche Open	311,866,298	189,614,709	6,871	106,642,639
Both Open	354,230,901	215,372,388	7,797	121,131,334

6 Conclusion

The analysis presented above estimates the economic impact of the Locks system on the Fox Valley Regional economy. To date the Locks have already had a significant economic impact on the Fox Valley Regional economy. Including the visitors' center, having a fully functioning lock system has the potential to generate an additional $290 million in economic activity over the next 10 years, supporting over $6,300$ additional jobs. This underscores the great value the Locks add to the Fox River in an area where water sports and related activities represent a key part of the economy.

Table 10: Total Impact of Each Scenario, Including 2005-2015 Cumulative Impact

Scenario	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
Menasha Open	528,442,571	321,293,083	9,874	180,696,166
Rapide Croche Open	610,382,471	371,112,542	11,665	208,735,170
Both Open	652,747,074	396,870,221	12,591	223,223,864

Table 11: Average Annual Impact of Scenarios from Table 10

Scenario	Real GDP ($'s)	Labor Income ($'s)	Employment	Investment ($'s)
Menasha Open	25,163,932	15,299,671	470	8,604,579
Rapide Croche Open	29,065,832	17,672,026	555	9,939,770
Both Open	31,083,194	18,898,582	600	10,629,708

References

Costa, J. d. S., R. W. Ellson, and R. C. Martin (1987): "Public capital, regional output, and development: some empirical evidence," *Journal of Regional Science*, 27(3), 419–437.

Fisher, R., and R. Wassmer (2013): "Differences in state and local government, public capital expenditure before, during and after the Great Recession: Did the Federal stimulus matter," *Seattle, WA: Western Economic Association.*

Garcia-Mila, T., T. J. McGuire, and R. H. Porter (1996): "The effect of public capital in state-level production functions reconsidered," *The review of economics and statistics*, pp. 177–180.

Gibson, J., and F. Rioja (2017): "Public Infrastructure Maintenance and the Distribution of Wealth," *Economic Inquiry*, 55(1), 175–186.

Glomm, G., and B. Ravikumar (1997): "Productive government expenditures and long-run growth," *Journal of Economic Dynamics and Control*, 21(1), 183 – 204.

Holtz-Eakin, D. (1993): "State-specific estimates of state and local government capital," *Regional science and urban economics*, 23(2), 185–209.

Plaut, T. R. (1981): "An econometric model for forecasting regional population growth," *International Regional Science Review*, 6(1), 53–70.

Rioja, F. K. (2003): "Filling potholes: macroeconomic effects of maintenance versus new investments in public infrastructure," *Journal of Public Economics*, 87(9), 2281–2304.

Seung, C. K., and D. S. Kraybill (2001): "The Effects of Infrastructure Investment: A Two-Sector Dynamic Computable General Equilibrium Analysis for Ohio," *International Regional Science Review*, 24(2), 261–281.

A Model of the Local Economy

This technical appendix describes the model used in the analysis above. Towards this end, the production function describing the relationship between the capital stock, labor stock, and public capital stock to total output (real GDP) must be specified. Following Glomm and Ravikumar (1997) and Seung and Kraybill (2001) , a constant returns to scale production function in the Cobb-Douglas class is specified. The production function for the Fox Valley Regional economy is:

$$Y_t = z_t K_t^{\alpha(1-\varepsilon)} L_t^{(1-\alpha)(1-\varepsilon)} G_t^{\varepsilon} \tag{1}$$

where Y_t, K_t, L_t, and G_t represent output, capital stock, labor stock, and public capital stock in period t, respectively. The parameters z_t, α, and ε must be determined based on existing data, which is described below.

This function describes how the economy combines the inputs of capital, labor, and infrastructure and produces output. We assume that firms in the economy operate under perfect competition and make decisions to maximize profits. Under these assumptions, the market prices for capital and labor are determined by:

$$w_t = \frac{\partial Y_t}{\partial L_t} = (1-\alpha)(1-\varepsilon) z_t K_t^{\alpha(1-\varepsilon)} L_t^{(1-\alpha)(1-\varepsilon)-1} G_t^{\varepsilon} \tag{2}$$

$$r_t = \frac{\partial Y_t}{\partial K_t} = \alpha(1-\varepsilon) z_t K_t^{\alpha(1-\varepsilon)-1} L_t^{(1-\alpha)(1-\varepsilon)} G_t^{\varepsilon} \tag{3}$$

where w_t represents the real wage in period t, and r_t is the return to capital in period t. Thus, the price of labor, w_t, and capital, r_t, are determined by their respective marginal products.

A.1 Determination of Employment and Investment

Workers are assumed to supply labor inelastically. The stock of potential labor is taken as the current level of employment. Then, employment evolves as workers either migrate to the Fox Valley Region, or current workers exit (either to work in another location, to enter unemployment, or if they leave the labor force). Specifically, following, employment evolves according to:

$$L_t = L_{t-1}(1+g) + M_{t-1} \tag{4}$$

where L_t is the employment level in period t, g is the population growth rate, and M_t is the net-migration of workers to the Fox Valley Region. Following Seung and Kraybill (2001) net migration is determined by:

$$M_t = L_t\Big[(\frac{w_t}{\bar{w}_t})^{\mu} - 1\Big] \tag{5}$$

where $\bar{w}_t$ represents the ROW (rest of world wage), or the outside option for a worker employed in the region in period t. From Equation (5), workers in-migrate to the region if wages are higher than the outside option, and out-migrate if the ROW wage remains higher. The parameter μ measures the elasticity of labor migration with respect to this relative wage.

Investment depends on two factors: (i) depreciation and (ii) expected future profitability of capital. Letting δ_k denote the depreciation rate of capital, capital evolves according to:

$$K_t = (1-\delta)K_{t-1} + I_t \tag{6}$$

where K_t is the capital stock in period t and I_t denotes investment in new capital. To determine the level of investment, I set $K_t = K_t^*$, where K_t^d represents capital demand and is given by solving Equation (3) for K_t:

$$K_t^d = \Big[\frac{r_t}{\alpha(1-\varepsilon)z_t(L_t)^{(1-\alpha)(1-\varepsilon)}G_t^{\varepsilon}}\Big]^{\frac{1}{\alpha(1-\varepsilon)-1}} \tag{7}$$

Thus, we have

$$I_t = K_t^d - (1-\delta)K_{t-1} \tag{8}$$

B Calibration and Simulation of Counterfactuals

This section describes the calibration of the baseline model and simulation of the counterfactual cases. To begin, several of the baseline parameters are readily available in the existing literature. Table 12 lists these parameters, their values, and the source of the data/values. Capital share of income is determined by α (see Equation (1)), which is set at the standard value determined by the NIPA (National Income and Product Accounts). The depreciation rate of capital is set to 0.04, following Seung and Kraybill (2001), while μ, the elasticity of labor mobility is set to 0.137 according to Plaut (1981). Finally, the elasticity of output with respect to public capital, ε is set to 0.05, following Costa, Ellson, and Martin (1987). This value represents the lowest value found in the existing literature. Garcia-Mila, McGuire, and

Porter (1996) finds a value of 0.20, and Seung and Kraybill (2001) use a value of 0.10 as a baseline. Generally, the higher the value of ε, the stronger the effect of the locks estimated above will become; as a result, it was prudent to error on the side of underestimating the impact by using the lowest estimated value of ε.

Table 12: Parameterization from existing estimates

Variable	Description	Value	Source
α	Capital Share	0.36	NIPA
ε	Elasticity of public capital	0.05	Costa, Ellson, and Martin (1987)
δ_k	Depreciation rate, Capital	0.04	Seung and Kraybill (2001)
μ	Elasticity of Labor Mobility	0.137	Plaut (1981)

Given the parameters in Table 12, the remaining parameters are estimated to fit the model's predictions to existing data from the 2005-2016 time period. The data utilized are as follows. First, output in the model is estimated to match total Real GDP in the Fox Valley Regional Economy. The Fox Valley Regional economy is defined as Brown, Calumet, Outagamie, Winnegabo, and Fond du Lac counties. Data on Real GDP was obtained from the Bureau of Economic Analysis (BEA) for the metropolitan areas of Green Bay, Appleton, Oshkosh-Neenah, and Fond du Lac (which comprises the aforementioned counties; see the definitions of these MSAs). Similarly, both employment and population data was obtained from the same source.

Once the model is estimated and fitted to the 2005-2016 period, the counterfactual experiments are performed. For the future 10 year predictions, the baseline levels must be established. The model then predicts the additional economic activity based on different scenarios. For the future 10 year levels, time trend models were estimated on each of the aforementioned data series. Although forecasting at longer horizons involves increasingly large confidence intervals, the ability of these time trend models to predict does not affect the estimated impact of the Locks. The impact of the Locks is *relative* to current GDP, employment, and investment; the time trend predictions simply provide the most informed estimate of the baseline scenario in the future.