Tuolumne River Fine Sediment Management Project: Chinook Salmon Survival to Emergence Study

Prepared for
The Tuolumne River Technical Advisory Committee
Turlock and Modesto Irrigation Districts
California Bay Delta Authority
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1 INTRODUCTION

Past studies have attributed low salmonid survival-to-emergence rates in the lower Tuolumne River to poor spawning gravel quality, which has resulted from the deposition of fine sediment in the gravel substrate (TID/MID 1992a,b). Gravel quality is a key factor influencing the success of incubation and emergence of salmonid eggs and alevins (Chapman 1988). In 1987 and 1988, the Turlock and Modesto Irrigation Districts ("Districts") assessed the effects of fine sediment on survival-to-emergence of fall Chinook salmon in the lower Tuolumne River (TID/MID 1992b). Based in part on these studies, improvement of spawning gravel conditions was identified as a key need for increasing Chinook salmon spawning success. Several measures, including gravel augmentation, riffle cleaning and increasing flood flows to increase the frequency of gravel transport and bed scour, have been proposed to improve spawning substrate conditions in the Tuolumne River (TID/MID 1997, McBain & Trush 2000).

One of the goals of the Tuolumne River Fine Sediment Management Project (CALFED #2001-C208) is to improve substrate quality within the spawning reach of the river near La Grange (RM 50). The purpose of this study within the context of fine sediment management is to quantify the *in-situ* relationship between gravel quality and Chinook salmon survival-to-emergence. The study described in this report tests whether gravel permeability and other measures of intragravel flow can be used as accurate and efficient field-based predictors of Chinook salmon (*Oncorhynchus tshawytscha*) egg incubation and emergence success.

Historically, monitoring of gravel quality has relied upon bulk gravel samples and various descriptors or indices of gravel size composition. This approach, however, is expensive, time consuming, and disruptive to the streambed. In addition, size distribution of gravel is only a proxy for gravel permeability. The delivery rate of dissolved oxygen (DO), which affects egg survival, is a function of DO concentration and intragravel water flow. Intragravel water flow is determined by hydraulic head and may generally be represented as an apparent velocity across a particular gravel cross-section using Darcy's (1856) Law:

$$V = -K\ (\Delta h/\Delta l) \qquad (1)$$

where K is the proportionality constant (i.e., permeability) between the hydraulic gradient ($\Delta h/\Delta l$) and the apparent velocity (V) to the gravel cross-section (Dunne and Leopold 1978).

Gravel permeability was selected as an *in-situ* measurement of spawning gravel quality because (1) it is known to directly affect intragravel flow and salmonid survival during egg incubation through fry emergence, and (2) it is directly affected by fine sediment deposition (McNeil 1966, Cooper 1965, McCuddin 1977, Platts 1979). Measuring gravel permeability directly is relatively inexpensive and quick and the data are immediately available without need for laboratory processing. In comparison to the use of bulk sediment characteristics (e.g., Tappel and Bjornn 1983), however, relating permeability to ecological processes (e.g., survival-to-emergence) is less common (Tagart 1976, McCuddin 1977). More data are needed to be able to use gravel permeability monitoring as an efficient and cost-effective technique for targeting restoration efforts and directly monitoring restoration success.

2 APPROACH

The objective of this study was to test the hypothesis that gravel permeability is directly correlated with survival-to-emergence of Chinook salmon eggs and can be used as an accurate and efficient field-based predictor of incubation and emergence success. To test this hypothesis we experimentally manipulated gravel quality in 14 artificially constructed Chinook salmon redds and attempted to identify relationships between intragravel permeability, dissolved oxygen, temperature and egg survival-to-emergence.

The advantages of using artificial redds included: (1) the ability to test a range of gravel quality and permeability, (2) a known number of eggs to accurately estimate incubation and emergence success as a proportion of the total eggs deposited, (3) control on the size and shape of the redds, and (4) minimal disturbance of the developing eggs by installing all permeability monitoring standpipes during redd construction.

3 METHODS

3.1 Site Selection and Redd Excavation

Riffle 4A (RM 48.2–48.8) in the lower Tuolumne River was selected as the site for the emergence study. Riffle 4A is located 3.2 miles downstream of La Grange Dam, is the largest spawning riffle in the river, and was the site of prior emergence trapping at natural Chinook salmon redds. In addition, this location served as the site for other studies over the past 20 years including gravel permeability, redd superimposition, and macroinvertebrate population investigations (TID/MID 2005). Riffle 4A is approximately 275 m (900 ft) long, and at 175 cfs (the flow during the emergence study) has an average width of 30.5–36.5 m (100–120 ft) and an average depth of 0.6 m (2 ft).

Artificial redd construction began in mid-December 2001, near the end of the typical spawning period for Tuolumne River fall Chinook salmon, which occurs from mid-October–December (**Figure 1**) (Ideally, artificial redd construction should occur earlier, before the peak spawning, but delays in acquiring permits necessitated a mid-December start). During redd excavation, numerous spawning Chinook salmon were observed at the study site, confirming that the study period coincided with at least the end of the spawning period of wild salmon.

Locations for artificial redds were chosen to conform as close as possible to the preferred ranges in depth (≥24 cm), velocity (30–91 cm s^{-1}), and substrate size (D_{50} 40–70 mm) observed for Chinook salmon (Thompson 1972, Hunter 1973, Kondolf and Wolman 1993), and were limited to sites that had not already been used by spawning wild salmon. Access pathways to each artificial redd location were marked on the riverbed in order to avoid disturbing natural redds, and artificial redd locations were marked with rebar stakes and colored flags.

Redd locations were excavated to a depth of approximately one foot with hand tools, and substrate was transferred to 5-gallon plastic buckets and transported to shore. Rocks ≥ 150 mm (6 in) are generally too large to be removed from the redd pit by a spawning female salmon (Kondolf and Wolman 1993) and if present in a naturally constructed redd, often remain as “centrum” rocks in the bottom of the pit (Burner 1951, Vronskiy 1972, Chapman 1988). When present, several of these large rocks were retained for use as centrum rocks, but the rest were not included in the materials used to reconstruct the redds. All remaining materials from each redd location were sorted into “coarse” (> 44.5 mm [1.75 in]) and “medium” (1.2–44.5 mm [0.047–1.75 in]) size categories by passing these materials sequentially through two wooden rocker boxes with 44.5 mm (1.75 in) and 1.2 mm (0.048 in) stainless steel wire mesh, respectively. Materials passing the 1.2 mm screen were retained by a standard testing sieve (No. 100) with a 150 µm (0.0059 in) opening.

Final constructed redd dimensions as well as the location, depth, and size of the egg pocket was based on an earlier redd delineation and excavation study conducted at Riffle 4A in 1989 (TID/MID 1992b). Saving time and effort in excavation and construction of artificial redds required that the designed artificial redd dimensions (**Figure 2**) be on the lower end of the size ranges found in the earlier study (**Figure 3**).

3.2 Gravel Mixtures

After the excavated substrate was separated by size, it was placed in 5-gallon plastic buckets and weighed with a hanging scale. The total weight of substrate in each size category (<1.2 mm, 1.2–

44.5 mm, and 44.5–150 mm) from each redd was recorded and then recombined into six gravel and fine sediment mixtures corresponding to the permeability levels shown in **Table 1**.

Table 1. Treatment mixtures by weight of gravel and fine sediment and predicted permeability for the 2001–2002 lower Tuolumne River survival-to-emergence study.

Mixture by weight (gravel: fines)	Predicted permeability (cm/hr)	Predicted survival-to-emergence	# of Redds receiving treatment
1:0	82,122	86%	4
20:1	20,221	65%	4
6:1	5,017	44%	2
2:1	1,250	24%	2
1:1	604	13%	1
1:3	284	2%	1

The permeability[1] of each mixture (**Equation 2**) was calculated using the Fair-Hatch formula (Bear 1988), which accounts for grain size distribution in estimating the proportionality between hydraulic gradient and apparent velocity in Darcy's Law for saturated flow (**Equation 1**):

$$K = \frac{\rho g}{\mu} \frac{\eta^3}{(1-\eta)^2} \frac{1}{mC^2} \left[\left(\sum_i \frac{p_i}{d_i} \right)^{-1} \right]^2 \tag{2}$$

where:

K is the permeability
ρ, μ, g are physical constants (the density and viscosity of water, and the acceleration of gravity, respectively)
η is the porosity of the sample (ranges from 0.1–0.4, but 0.25 used)
m is a "packing factor" (taken to be 5, consistent with standard practice)
C is a "shape factor" (taken to be 6 assuming near spherical grains)
d_i is the geometric-mean of the sieve-diameters of sieves i and $i+1$
p_i is the fraction of the sample (by weight) between sieves i and $i+1$

The gravel mixtures with the greatest amount of fine sediment were intended to have low permeability and low survival-to-emergence. Conversely, mixtures containing little or no fine

[1] Our use of the term 'permeability' (expressed in units of length/time), is consistent with the established convention in fisheries biology, but the property being measured is more accurately termed hydraulic conductivity, which depends on the temperature and viscosity of the fluid as well as the size of the pores (Nazaroff and Alvarez-Cohen 2001).

sediment were expected to have high permeability and high predicted survival-to-emergence (**Figure 4**). Redd substrates were recombined to the same ratio, by weight, of coarse to medium gravel fractions observed in the excavated substrate, and the total weight of substrate used to construct each artificial redd was equal to the total weight of substrate excavated from that location. Mixtures with high ratios of coarse to fine sediment (1:0, 20:1, 6:1, and 2:1) were replicated several times in the experimental design. Mixtures with the lowest ratios of coarse to fine sediment (1:1 and 1:3) were replicated only once (**Table 1**), due to limitations on the amount of fine sediment that could be obtained.

3.3 Chinook Salmon Eggs

Chinook salmon eggs were obtained from the California Department of Fish and Game's (CDFG) Merced River Fish Facility (Snelling, CA), placed in moist cheesecloth bags, and transported by car approximately 32 km (20 mi) to the field site for placement in the redds. Eggs were transported in insulated coolers and kept out of direct sunlight to minimize light and temperature stress. Although all eggs were from the same hatchery egg lot, initial redd construction using "green" eggs was abandoned after construction of two high permeability redds because all eggs were observed to be opaque and premature mortality was suspected to have occurred. All remaining redd construction used eggs from the same lot that were in the "1/4-eyed" stage of development, approximately 16 days post-fertilization. At the time the eggs were planted in the artificial redds, the eggs had accumulated 184 °C-days (accumulated thermal units [ATUs]). As a control for the health of the egg lot and handling conditions, a group of 1,000 eggs from the same egg lot was subjected to the same handling and transport procedures as the eggs to be placed in the artificial redds, and then returned to the hatchery for rearing. Thus, the travel time for the control group was twice as long as the experimental group. The control group was monitored by CDFG staff at the hatchery. Incubation conditions (e.g., water temperature) experienced by the control group were recorded continuously until hatching and the hatching success (number of live alevins) was recorded.

3.4 Redd Construction

Prior to egg placement and redd construction, four perforated plastic (PVC) standpipes were held vertically in place within each excavated pit: one in the egg pocket area to sample dissolved oxygen and water temperature, and three surrounding the egg pocket (upstream, downstream, and left) to sample permeability (**Figure 2**). Two thermographs (Optic Stowaway TidbiT, Onset

Computer Corp, Bourne, MA) were affixed to each standpipe; one near the bottom and the other above the redd surface to continuously monitor incubation and water column temperature.

One thousand fertilized Chinook salmon eggs were placed in the egg pocket alongside the centrum rocks. Redds were then constructed by covering the egg pocket and lower portions of the standpipes with one of the six sediment mixtures and then contoured to mimic the bed surface profiles of natural Chinook salmon redds observed at this and other locations in 1988 and 1989 (**Figure 5**). Following construction, an emergence trap frame, was placed over each artificial redd without a cover for several weeks to deter spawning attempts by adult salmon.

3.5 Emergence Traps

Emergence trap covers were placed on the trap frames at each redd approximately 10 days prior to the predicted date of emergence, which was during the week of February 3, 2002. The covers, which included a skirt, sleeve and collection bottle, were constructed of heavy nylon sail cloth and 0.13 in (0.32 cm) inch nylon mesh (**Figure 6**). The skirt extended vertically from the trap frame perimeter down into the stream bed surrounding the artificial redd, and was buried to a depth of 1 ft (30 cm) to prevent lateral escape of alevins or fry. Water flowing into the sleeve directed newly emerged fry into the collection bottle at the downstream end. After the covers were affixed to the frames, rebar stakes were driven into the bed around the perimeter of each frame through metal grommets in the cover skirt. The trap was attached to the stakes using metal washers secured by nylon zip ties.

3.6 Apparent Velocity

Hydraulic gradient measurements were used to indicate differences in intragravel flow between various mixtures of gravel and fine sediment used in the artificial redds. Flow through the redd is a function of both permeability and hydraulic gradient, as demonstrated by dye studies by Cooper (1965) (**Figures 7 and 8**) and explained by Darcy's Law (**Equation 1**). Changes in the bed profile, across individual redds or riffle features, cause changes in the direction and magnitude of water velocity over the leading and trailing faces of these features due to conservation of momentum of the flowing water (i.e., Bernoulli effect). For a redd structure, these velocity changes are accompanied by a differential hydraulic head across the redd length that promotes downwelling through the leading face of the redd to allow and high water exchange rates in the vicinity of the egg pocket (Cooper 1965, Milhouse 1982). Due to the difficulty of measuring the hydraulic gradient of each artificial redd over the relatively short distance between upstream and downstream standpipes (**Figure 2**), we used diel patterns in temperature differences and time-lag between maximum and minimum temperature in the egg pocket and the overlying water column (as recorded by thermographs) to estimate apparent velocity (**Appendix B**).

3.7 Incubation and Emergence Monitoring

Water temperature data from the hatchery and Riffle 4A were used within a degree-day model (**Equation 3**) to predict the approximate dates of hatching and fry emergence:

$$ATU = \exp(-6.4 - 9 * 10^{-4} W + 0.93 \ln T) \quad (3)$$

where ATUs (i.e,. degree-days) are predicted from the initial egg weight W (mg) and the mean incubation temperature T (ºC). The equation was developed by fitting to data from Beacham and Murray (1990).

Daily emergence monitoring began immediately following installation of the trap covers during the week of February 3, 2002 and continued through March 15. Thereafter, emergence was monitored every third day because of decreasing numbers of emerging fry, continuing through April 15 until essentially all fry stopped emerging.

Emergence traps were checked in the morning and any emerged fry found in the collection bottle were placed into a bucket. Fry collected from each trap were processed on the bank before moving on to the next trap. The fork length, total length, and sac width of the first 50 fry collected was recorded on standardized data sheets. Additional fry were counted but not measured, and mortalities were noted. After processing, fry were released into the river along the margin of the bank. Trap covers were checked frequently to ensure that skirts were still properly anchored and were cleaned often to remove any accumulated algae or debris. Additionally, if a large number of fry were observed in the morning, the trap was checked again in the afternoon.

Gravel permeability, hydraulic gradient, DO, and temperature were measured during both the incubation and emergence period at each redd from December 21, 2001 through April 12, 2002. Gravel permeability was measured during five sampling trips and reported as a site average of three standpipes at each redd using a backpack monitoring device according to established methods (Bernard and McBain 1994). Hydraulic gradient was measured on three dates using the methods described above. Dissolved oxygen was measured on eight occasions at each artificial redd using a dissolved oxygen meter (YSI 600XL, Yellow Springs Instruments, Yellow Springs, OH) inserted into the egg pocket standpipe. Upon completion of the study, the trap covers, frames, standpipes, rebar, and recording thermographs were removed from each redd. All temperature data were downloaded from the thermographs for use in subsequent analyses.

3.8 Redd Excavation

On April 14, 2002 after emergence and trap removal was complete, two redds, one with a 20:1 gravel mixture and another with a 1:1 mixture, were excavated to investigate possible causes of *in-situ* egg mortality. As substrate removal neared the egg pocket (the location of which was recorded during redd construction), observations were made of the channel bottom to detect unhatched eggs and alevin mortalities. All mortalities were noted and described according to developmental stage. After excavation, the substrate was returned to the channel bed.

4 RESULTS

The results showed a strong positive relationship between permeability and egg survival-to-emergence, with fry emergence ranging from near zero in the lowest permeability treatments to approximately 40% in redds with the highest permeability. The hatching success of the control group was high, with 97% of the eggs reaching the alevin stage.

4.1 Permeability

The observed permeability for the gravel mixtures used in the artificial redds was similar to predicted permeability (**Figure 9**) using the Fair-Hatch formula (**Equation 2**). Permeability in the redds remained relatively constant over the study period, and the least variation was seen in artificial redds that had the greatest proportions of fine sediment (**Figure 10**).

4.2 Emergence

The degree day model (**Equation 1**) predicted that emergence would occur after 714 ATUs. Chinook fry began to emerge about 66 days after fertilization (712 ATUs), with median emergence occurring 93 days after fertilization (990 ATUs), or 77 days after placement (**Figure 11**, Appendix A).

4.3 Survival to Emergence

The relationship between permeability and observed survival-to-emergence was highly significant ($p = 4*10^{-6}$, $r^2 = 0.89$) (**Figure 12**); however, the observed survival-to-emergence was lower than the predicted survival-to-emergence at all redds. Two redds, with 1:1 and 2:1 gravel mixtures, had no fry emerge from the gravel. The redd with a 1:3 gravel mixture and the second redd with a 2:1 mixture had just two and one fish emerge, respectively.

4.4 Dissolved Oxygen

Although oxygen requirements of developing embryos increase during incubation, DO measured in the egg pockets of all artificial redds remained well above the critical concentration threshold (1.6 mg/l) required for embryo hatching (Silver et al. 1963, Eddy 1972) (**Figure 13**). The lowest concentration of dissolved oxygen of 5.6 mg/L occurred within the 1:3 gravel mixture, which is still above the critical concentration threshold. Dissolved oxygen in all other gravel mixtures ranged from 7 to 12 mg/l over the entire study period.

4.5 Temperature

Intragravel temperatures fluctuated in response to flow and air temperature, but remained cool and within the optimal range for salmonid egg incubation and alevin development (4° to 12°C [39.2° to 53.6°F]) (Myrick and Cech 2001) (**Figures 14 and 15**). The root mean squares of daily intragravel temperatures exhibited variability over time, although redds with high amounts of fine sediment exhibited little temperature variability (**Figure 16**).

4.6 Apparent Velocity

The relationship between apparent velocity and observed survival-to-emergence was highly significant ($p = 7*10^{-5}$, $r^2 = 0.81$) (**Figure 17**). The artificial redds with the 20:1 and 1:0 mixtures had the greatest apparent velocities and survival-to-emergence, while mixtures with a greater percentage of fines (2:1, 1:1, and 1:3) had much lower values. Of the two 6:1 mixtures, one showed high apparent velocities and survival to emergence, while the other had much lower values.

4.7 Post-emergence Redd Excavation

Post-emergence excavation of two artificial redds with different gravel mixtures (20:1 and 1:1 mixtures) revealed the cause of mortality was *in-situ* egg death. Upon excavation, we observed numerous white eggs, indicating death before hatching. Entombment of alevins, which is thought to cause mortality for sac fry where fine sediment deposition in the bed surface layer is substantial (Phillips et al. 1975), was not observed in the two excavated redds.

5 DISCUSSION

Although the relationship between survival-to-emergence of Chinook salmon eggs and *in-situ* gravel permeability and intragravel flow are highly significant and similar to previous studies of survival-to-emergence and gravel quality, the study results indicate lower survival-to-emergence than predicted. Numerous other studies have shown that survival to emergence of salmonid eggs in gravel that has low amounts of fine sediments is between 80 to 90% (Cooper 1965, Koski 1966, Mason 1969, Cederholm and Salo 1979, Koski 1981, Shirazi et al. 1981, Tappell and Bjornn 1983, Irving and Bjornn 1984, Tagart 1984, Shepard et al. 1984, Sowden and Power 1985). There are at least two possible reasons for the lower than predicted survival-to-emergence:

1) Redd hydraulics and interstitial velocities are insufficient to support predicted survival-to-emergence
2) Mechanical or temperature shock during egg placement

5.1 Effect of redd hydraulics on egg survival

This experiment controlled for the permeability of the artificial redds with the gravel mixtures and the redd profile (**Figures 2 and 6**), but may not have effectively controlled for larger channel bed features that can affect the direction and magnitude of the water velocity vector at the redd location. Although artificial redd locations were selected based on water depth, velocity, and substrate criteria for Chinook salmon spawning areas (see **Section 3.1**), the locations were also those remaining after most wild salmon had already spawned. The locations chosen for our artificial redds might therefore have been those with substandard hydraulic conditions, with less lower apparent velocity, downwelling, and intragravel flow through the spawning substrate (Cooper 1965, Milhouse 1982). Chinook salmon may prefer sites with greater downwelling due to channel morphology and local hydraulics, which may explain why spawning fish are sometimes observed in dense aggregations where individual redd excavations overlap, but adjacent, seemingly similar locations remain unused throughout the spawning period (Vronskiy 1972). Greater downwelling promotes higher apparent velocity thought the egg pocket, increasing DO delivery to the egg surface and raising the probability of successful emergence from the redd.

Apparent velocity estimates were determined using differences in the differences in temperature variability between thermographs located within the egg pocket and in the overlying water column (**Appendix B**). **Figure 17** shows a strong relationship between apparent velocity and survival-to-emergence, and the effect that differences in hydraulic gradient and intragravel flow may have on observed survival-to-emergence. Within the two 6:1 gravel mixtures, despite similar gravel: fine composition and dissolved oxygen concentration, the survival-to-emergence rate at the one site with higher apparent velocity was 35%, whereas survival was 5% at the other site with the lower apparent velocity suggesting differences in redd hydraulics may explain differences in survival-to-emergence. On examination of **Figure 17**, higher survival results occur within a higher range of apparent velocity whereas all low survival results were associated with low apparent velocity. This suggests the possibility of a threshold level for intragravel flow below which high mortality occurs. The data collected during this study show that levels of dissolved oxygen within artificial redds were above the critical concentration threshold (1.6 mg/l) required for embryo hatching (Silver et al. 1963; Eddy 1972) (**Figure 13**). But, even with these high concentrations, the delivery of dissolved oxygen at the egg surface due to the velocity dependence on interfacial mass transfer (Nazaroff and Alvarez Cohen 2001) at the egg surface may have been inadequate to support high survival rates.

5.2 Mechanical and Thermal Shock

Chinook salmon eggs are quite sensitive to mechanical shock from shortly after fertilization until they reach approximately 190–200 ATUs (e.g., 16 days at 11°C) (Jensen 1997). To ensure that the eggs used in the study were not susceptible to mechanical shock a sample of eggs from the egg lot used in the experiment were shocked in the hatchery. No mortality occurred indicating that the eggs were past the period of high sensitivity to shock. Although it is possible that the shock resulting from redd construction was greater than that conducted for the hatchery test group, no mortality occurred due to mechanical shocking of the control group sample. Reduced humidity, high temperatures, or abrupt changes in temperature may also have occurred during the transport of the eggs from the hatchery. However, the high rate of 97% of successful hatching in our control group rules out this potential source of egg mortality in our artificial redds.

6 SUMMARY AND RECOMMENDATIONS

We demonstrated a highly significant relationship between survival-to-emergence of Chinook salmon eggs and *in-situ* gravel permeability as well as a highly significant relationship between survival and intragravel flow. The results of this study demonstrate the applicability of *in-situ* permeability measurements as a cost effective means to assess spawning gravel quality. However, several important questions remain regarding the effects of gravel quality upon survival-to-emergence.

As a means of improving the relations developed in this study, we recommend that a follow-up study be conducted in the future to further quantify the relation between permeability and survival-to-emergence of Chinook salmon eggs in the Tuolumne River. Future studies will be initiated earlier in the spawning season to ensure the health of the egg lot used in the study. Uniform redd hydraulics will be verified by measurements of the velocity field on the leading and trailing faces of the constructed redds. Because of the difficulties in direct measurements of intragravel flow using piezometers and dye tracers (Grost et al 1988), intragravel flow will continue to be estimated using comparisons between temperature variability of embedded thermographs and water column temperatures (**Appendix B**). The thermograph will be affixed to a single permeability standpipe within the constructed egg pocket for use in both *in-situ* permeability measurements and water quality sampling.

Because salmon alter the substrate composition during redd construction, we recommend that future gravel quality assessments be conducted using permeability measurements in natural redd locations. As our study showed that permeability did not change significantly during the incubation period, monitoring could take place after emergence. If this is not feasible, then the relationship between the permeability in undisturbed gravels and in nearby redds needs to be established and we would recommend future gravel quality assessments include comparisons of permeability at redd locations with those taken within the surrounding riffle areas. Redd monitoring would be conducted within relatively undisturbed riffle areas with natural mixtures of gravel and fine sediment as well as at gravel augmentation sites with lower amounts of fine sediment. The size of the defending female for each redd will be estimated or measured directly to provide an estimate of the number of deposited eggs. Emergence trapping of natural redds will be used to provide an estimate of survival-to-emergence and related to both riffle gravel quality estimates from spatially averaged permeability as well as direct post-emergence permeability sampling of the redds after the fry have emerged.

It is our hope that additional studies will improve our understanding of the relationship permeability to salmonid egg survival-to-emergence and refine our methods for targeting restoration efforts and evaluating restoration success.

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FIGURES

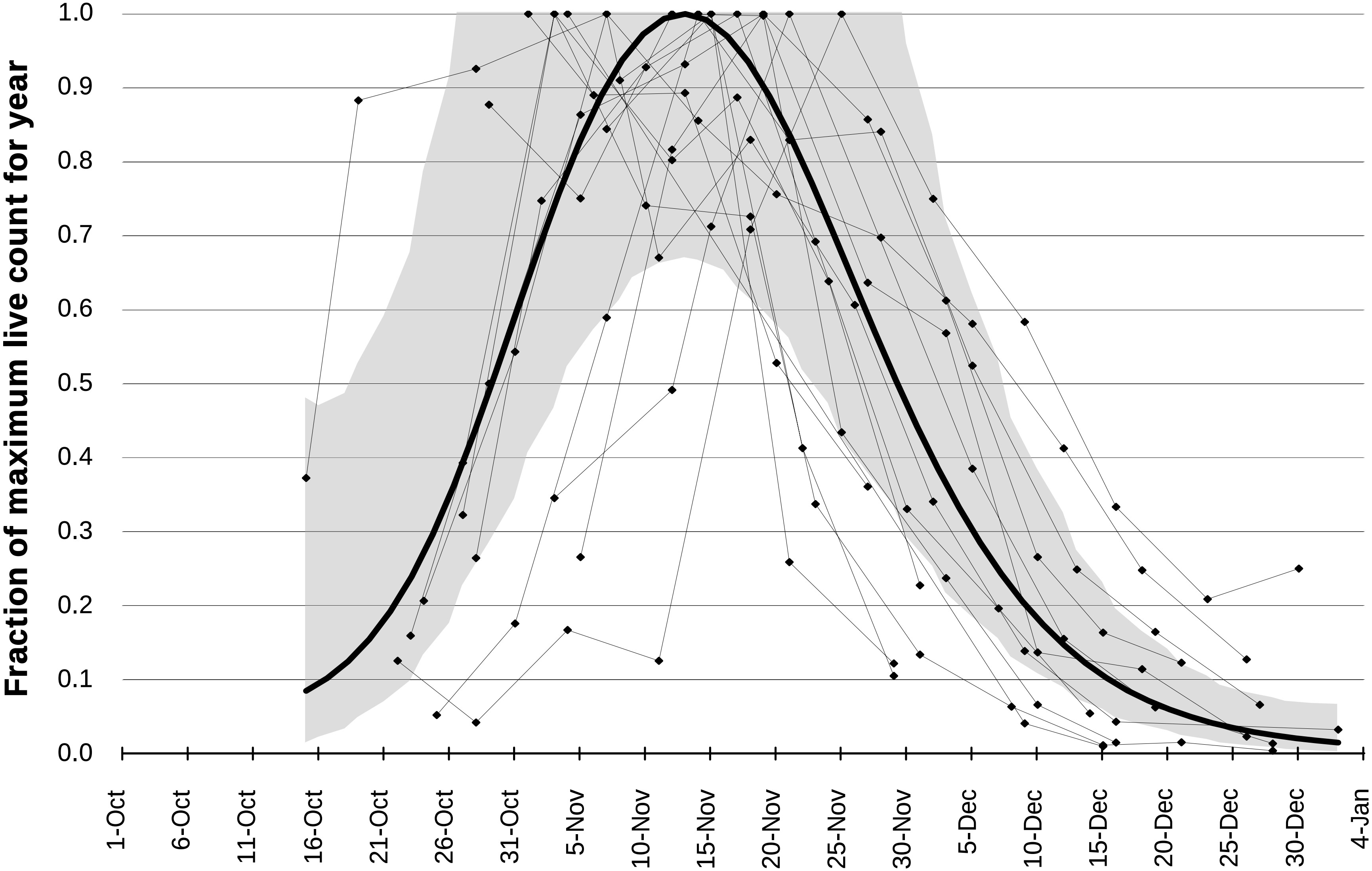

Figure 1. Peak spawning activity from Tuolumne River spawning surveys, 1981–1995. Plot shows patterns in live fish found in weekly spawning surveys for individual years (markers and light lines) and as a long-term average (heavy line and shaded 95% confidence band)

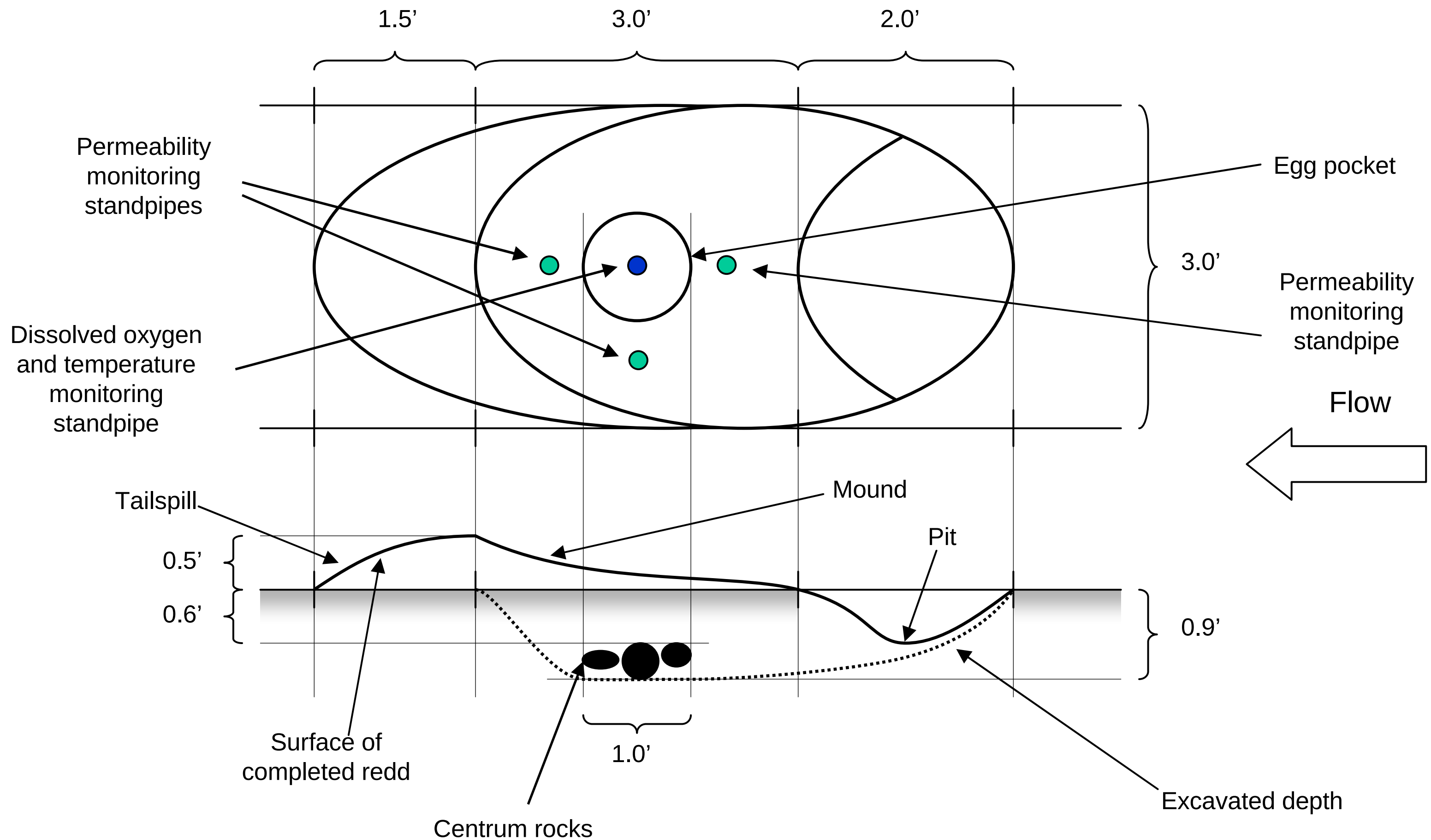

Figure 2. Artificial redd schematic diagram.

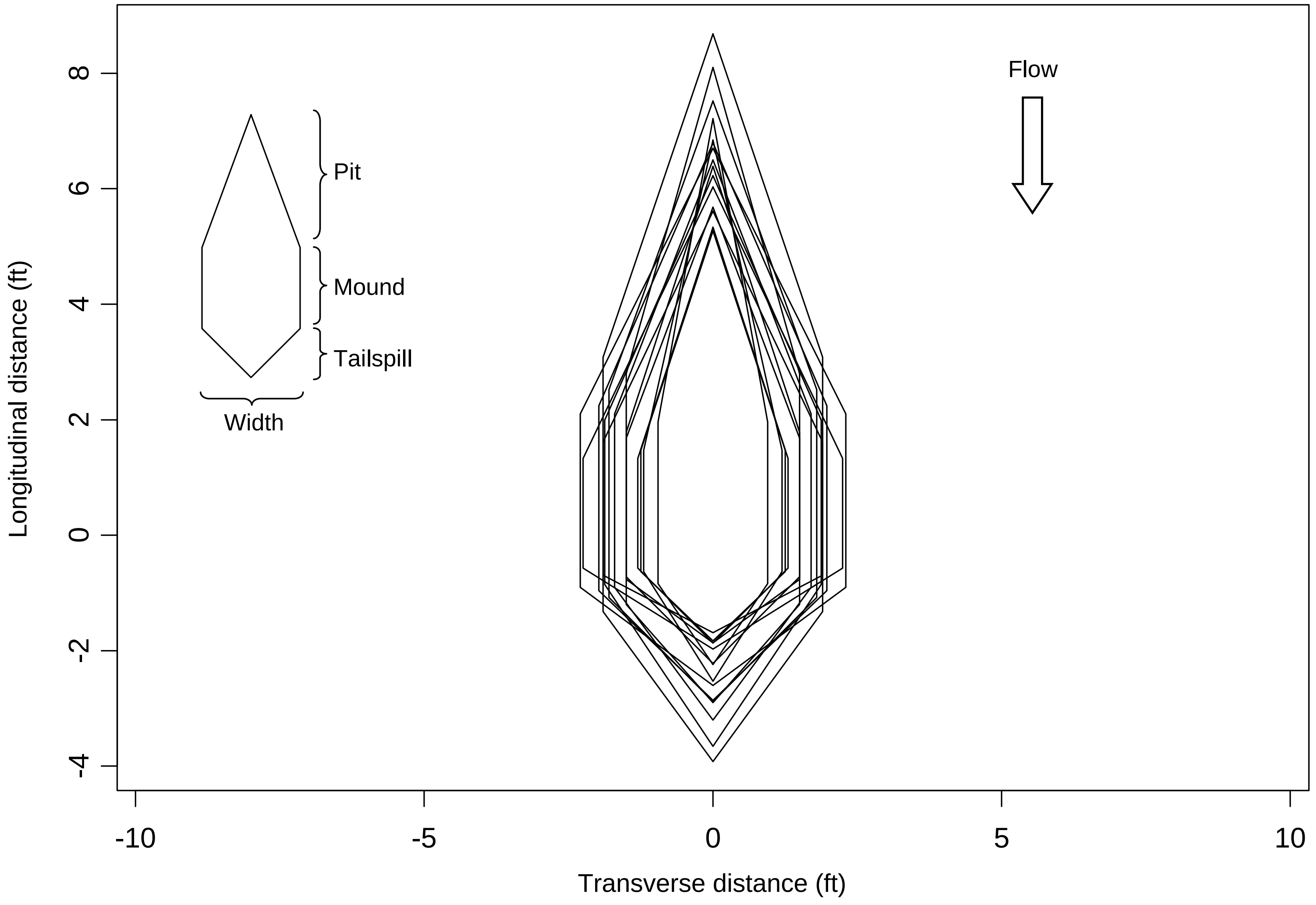

Figure 3. Redd dimensions of smaller natural Chinook salmon redds at spawning riffles in the lower Tuolumne River (from TID/MID 1992c).

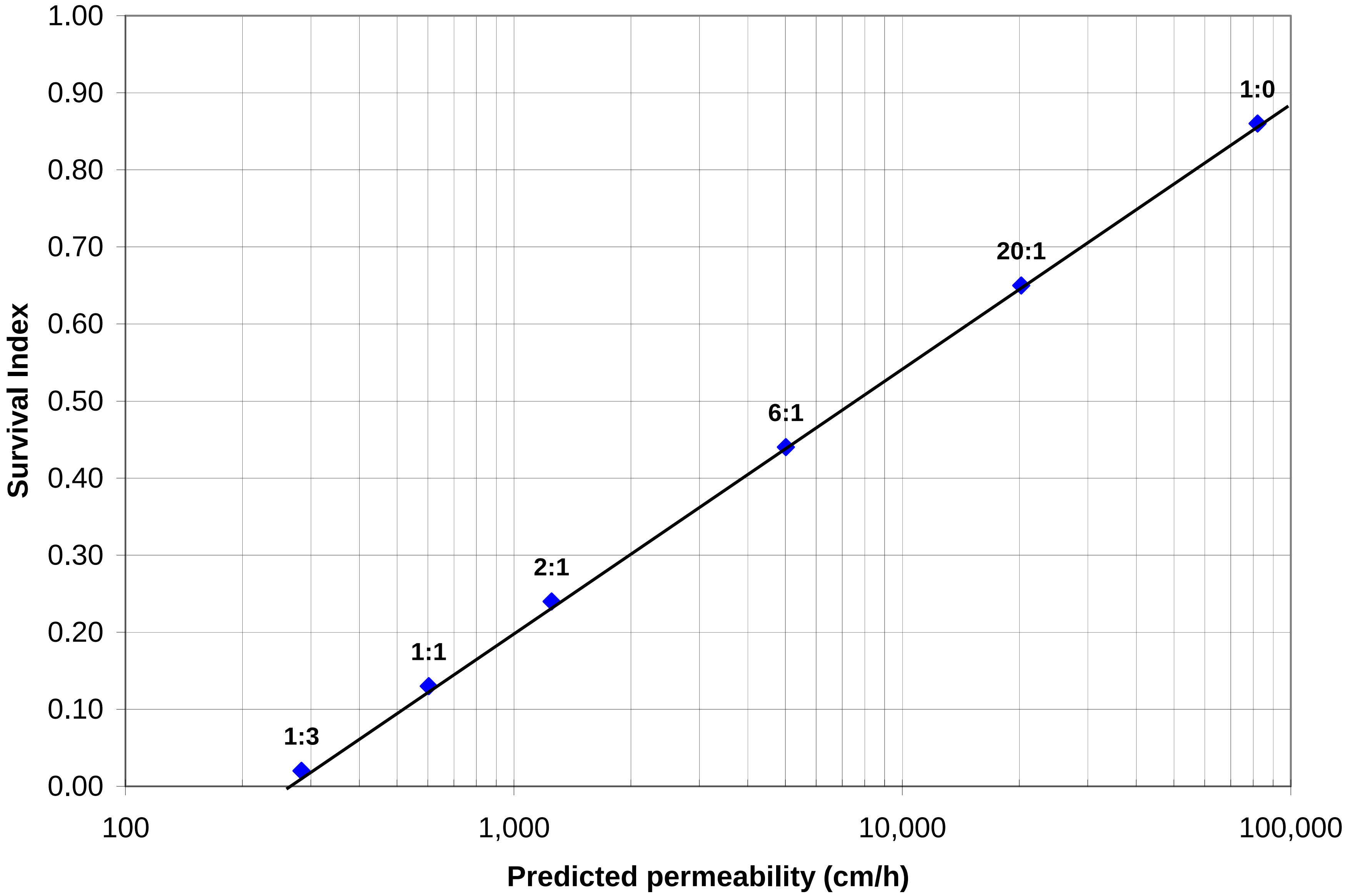

Figure 4. Predicted permeability and survival for gravel mixtures used in artifical redds. Mixture ratios are weight of gravel to fine sediment.

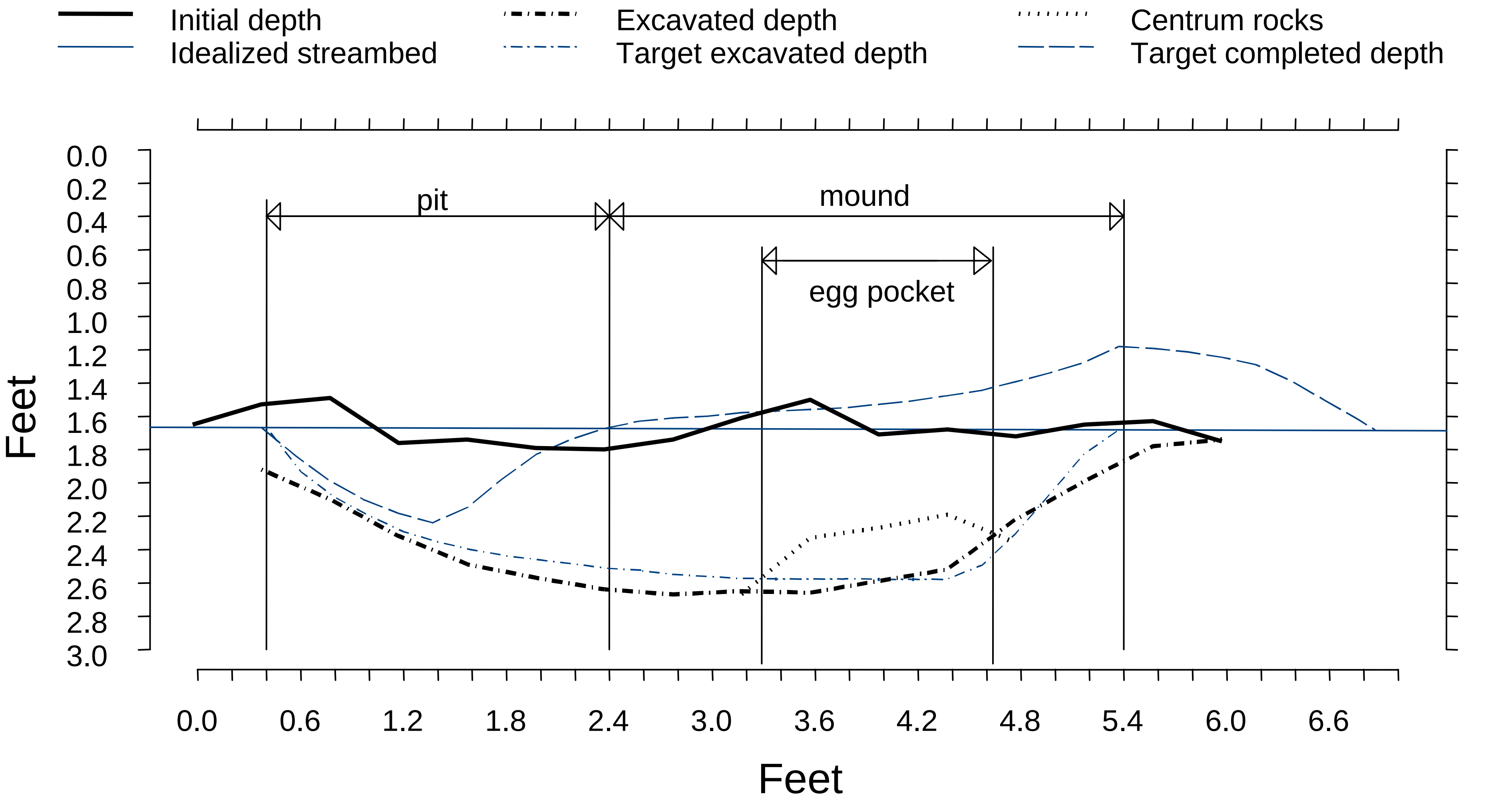

Figure 5. Excavated and constructed profiles for typical artificial redd.

Figure 6. Installed emergence trap with four monitoring standpipes at the far end.

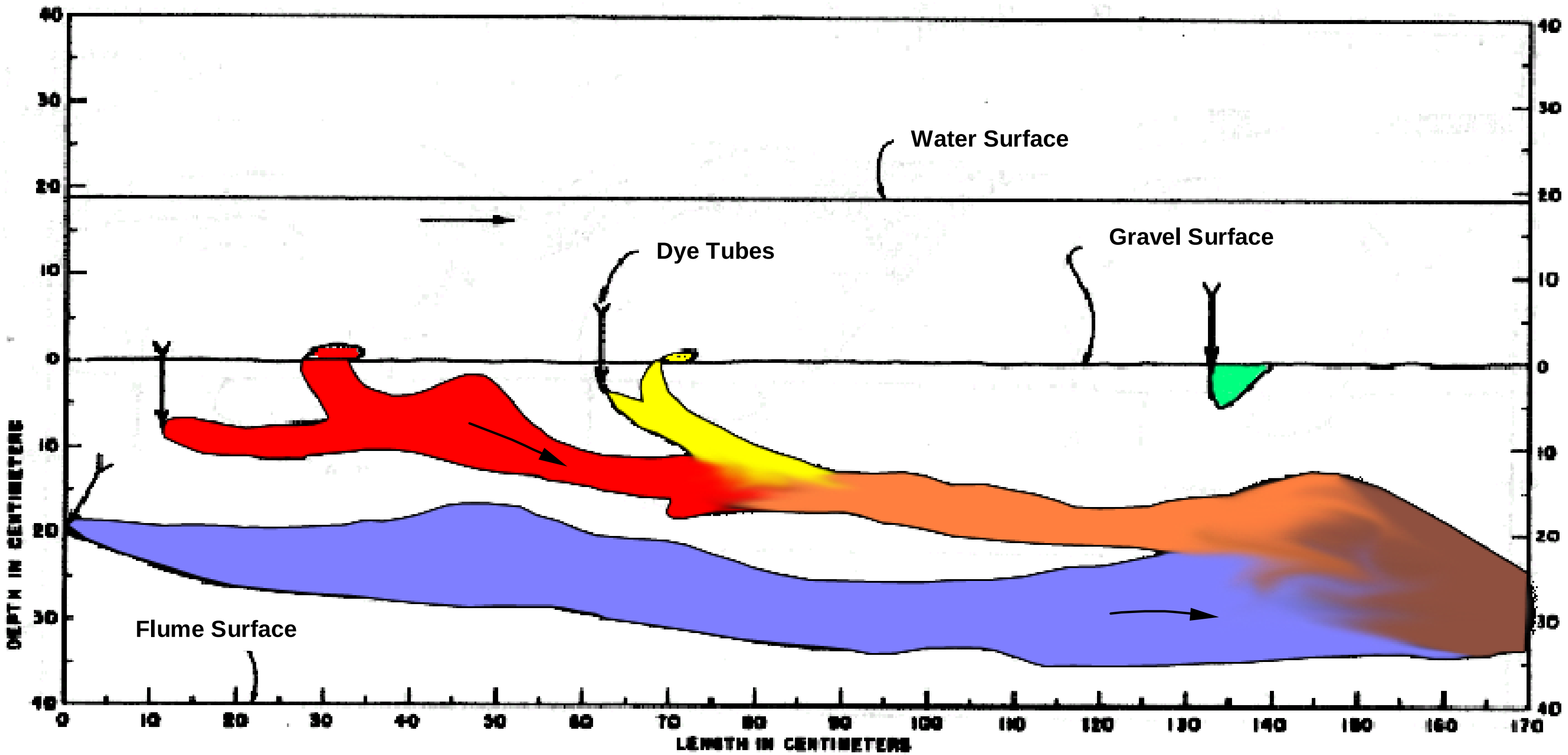

Figure 7. Flow paths of dye tracer through homogeneous gravel with level gravel surface. Modified from Cooper (1965).

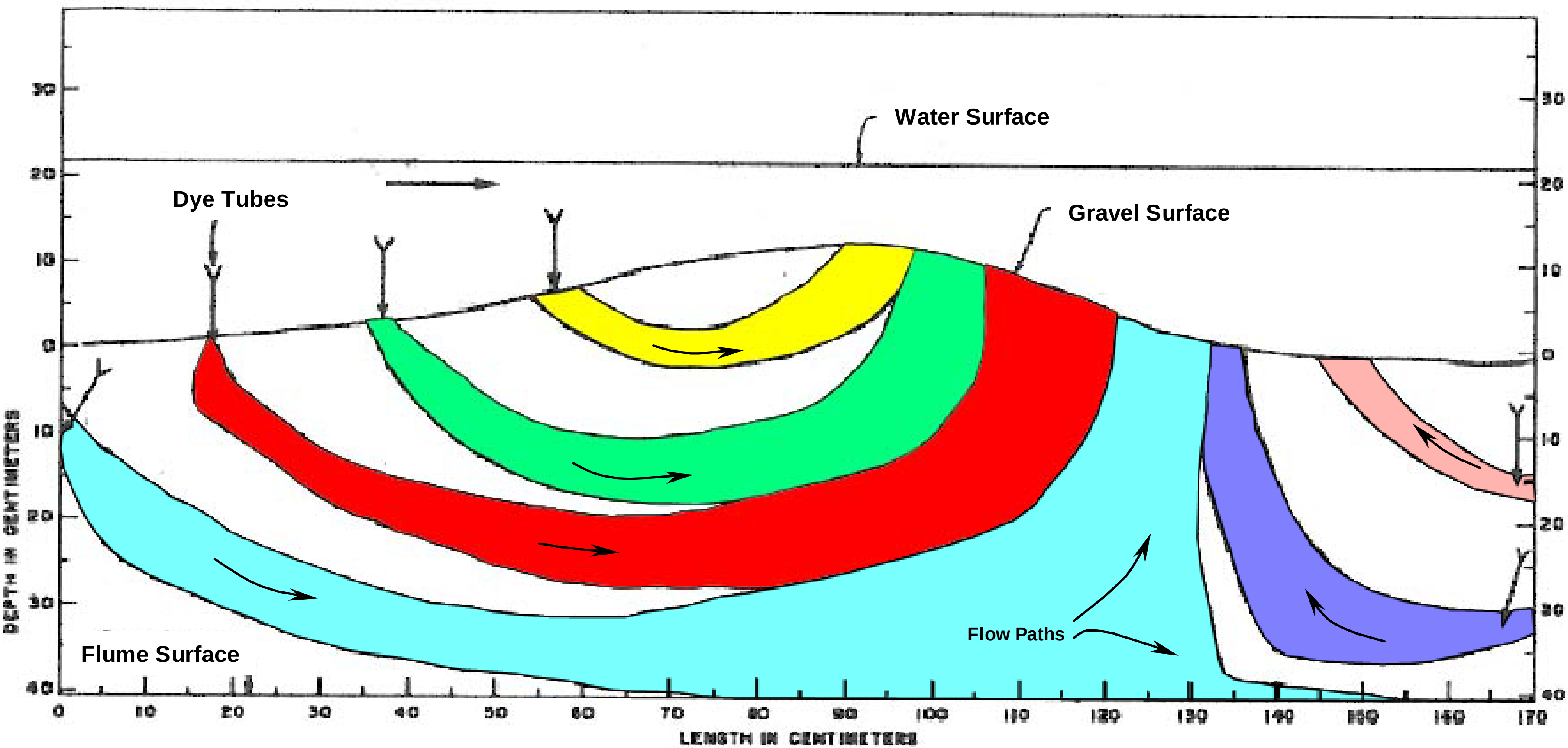

Figure 8. Flow paths of dye tracer through homogeneous gravel with a surface similar to a new salmon redd. Modified from Cooper (1965).

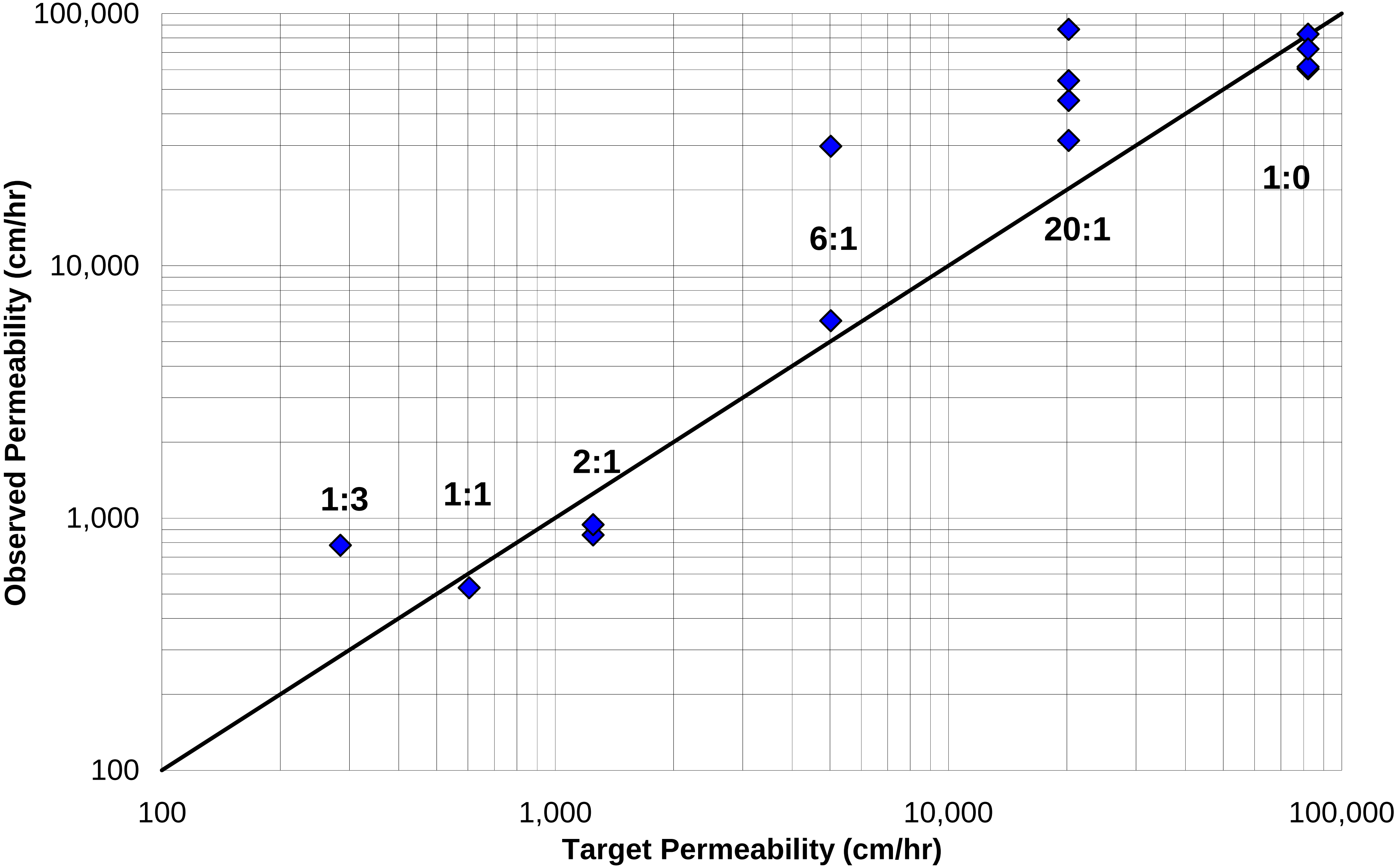

Figure 9. Predicted vs. observed permeability for gravel mixtures used in artificial redds. Mixture ratios are weight of gravel to fine sediment.

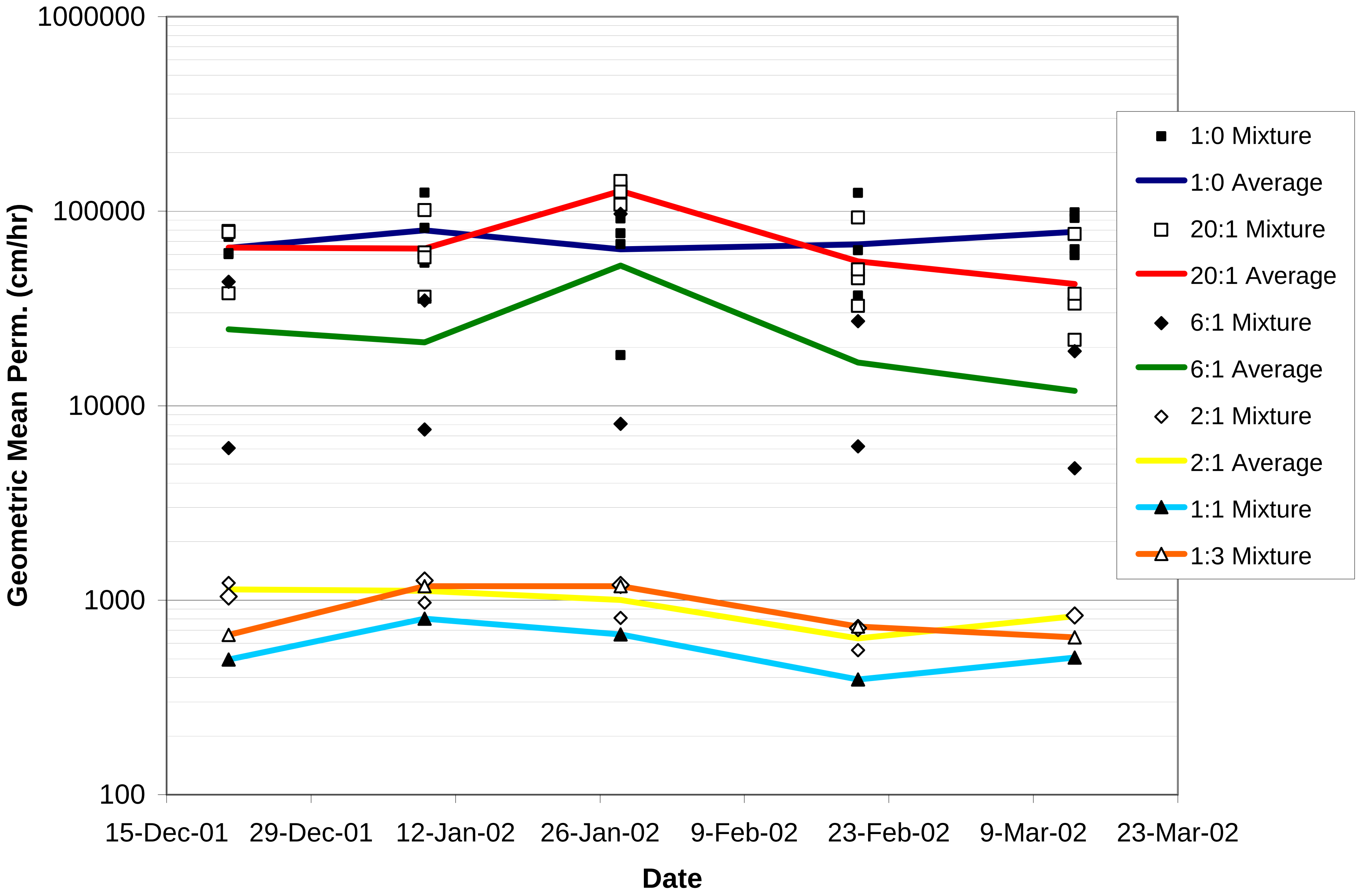

Figure 10. Observed permeability measured over time for each substrate mixture. Mixture ratios are weight of gravel to fine sediment.

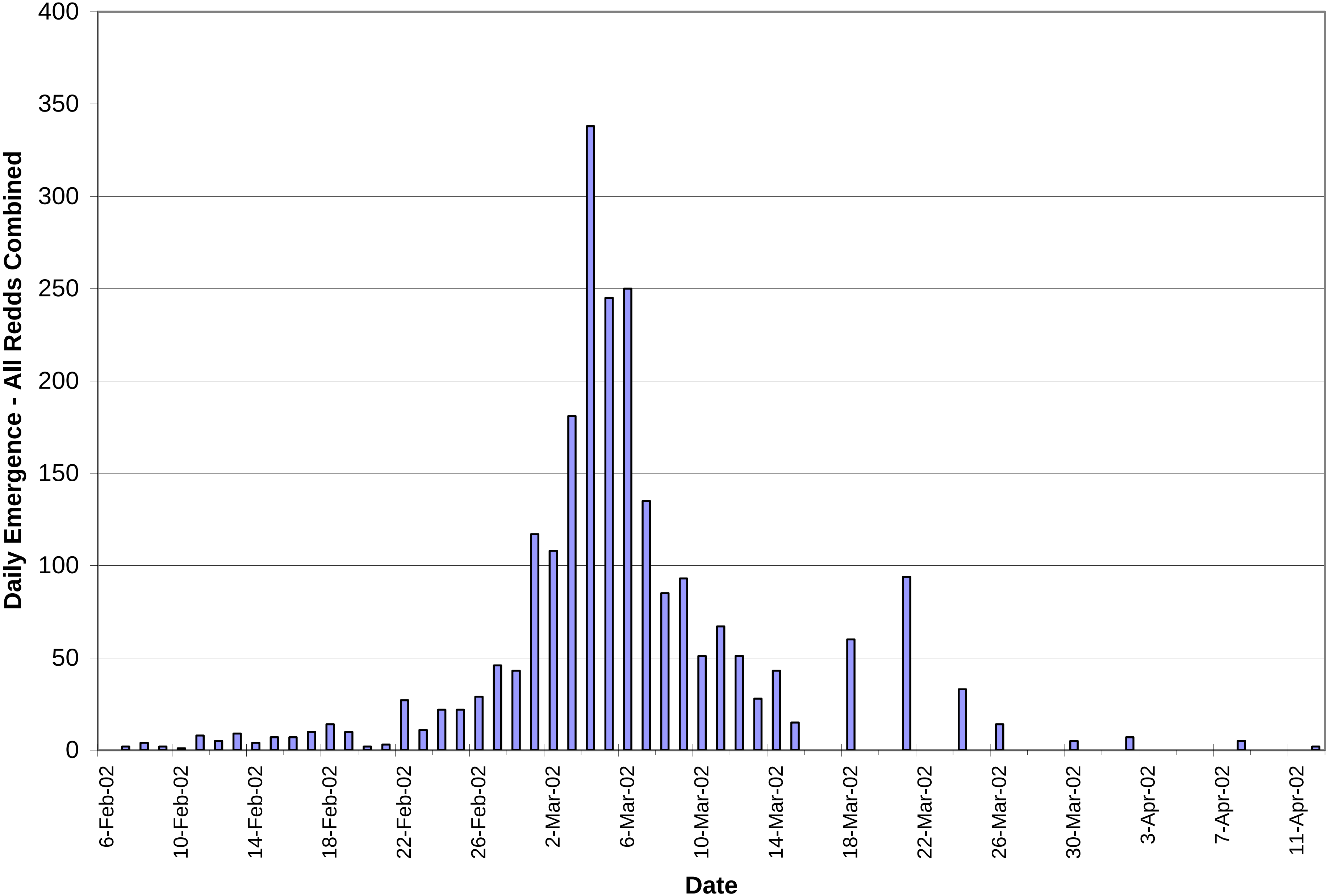

Figure 11. Combined daily emergence for all artificial redds, spring 2002.

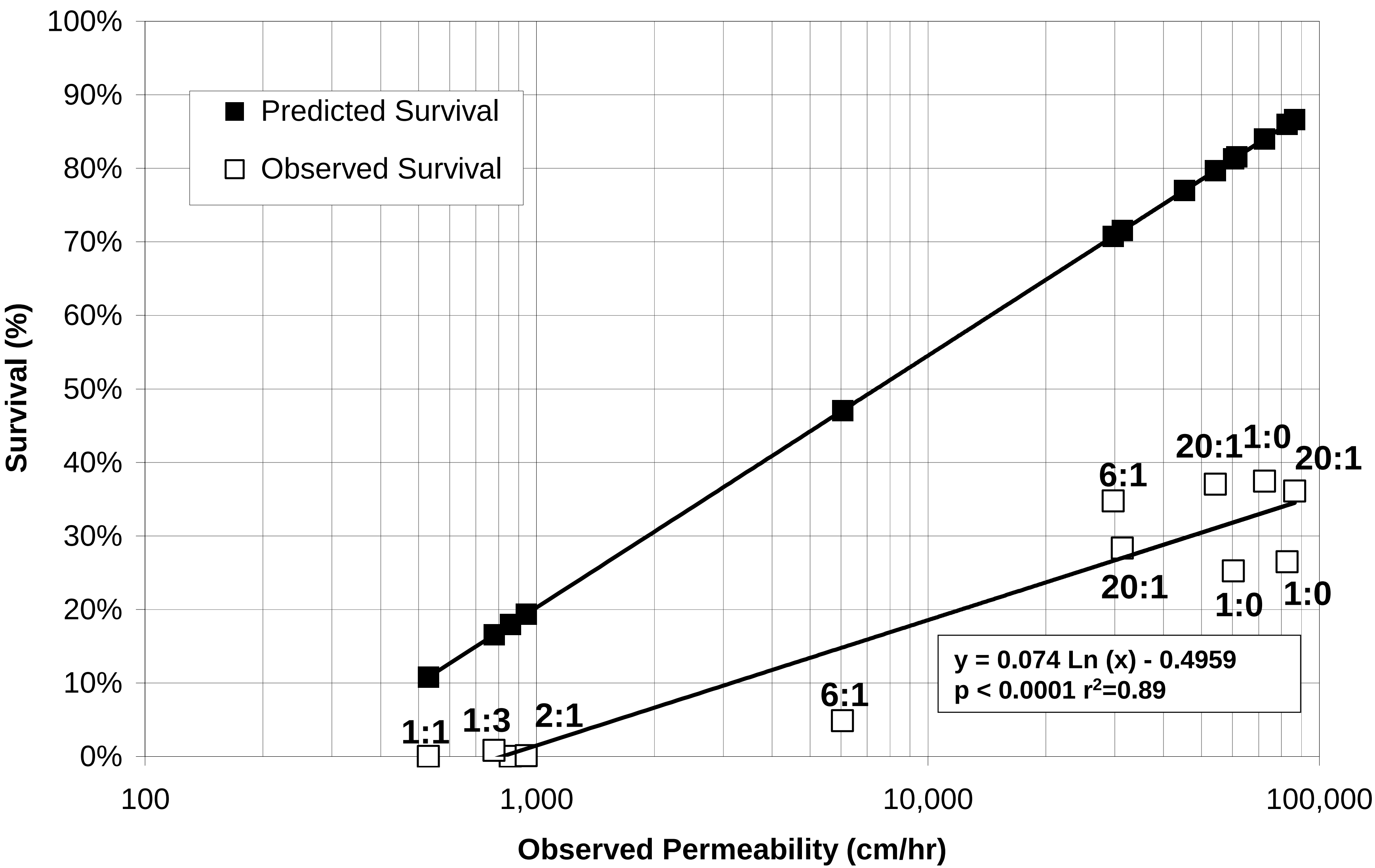

Figure 12. Predicted and observed survival to emergence vs. observed permeability for gravel mixtures used in artificial redds. Mixture ratios are weight of gravel to fine sediment.

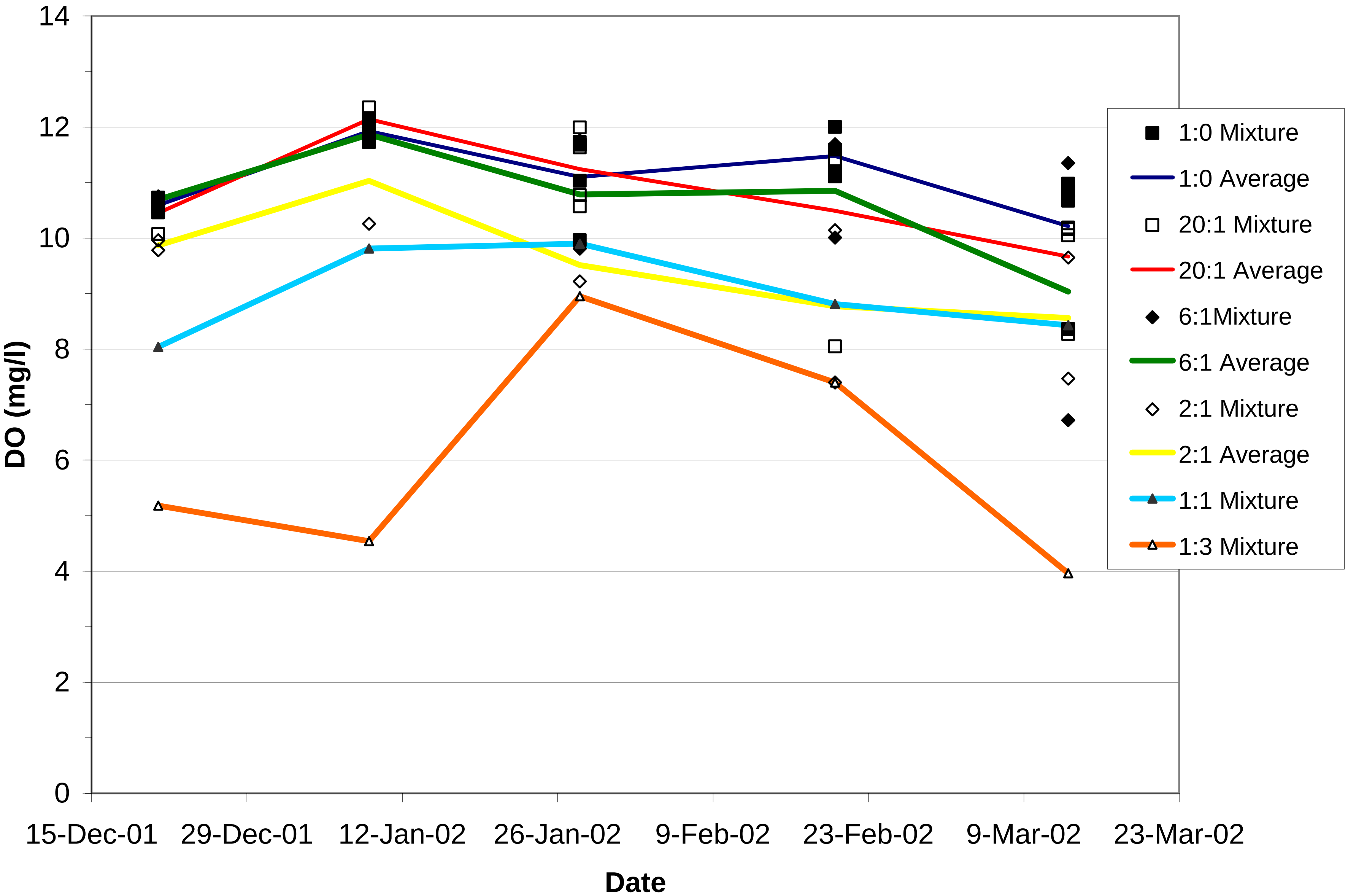

Figure 13. Observed egg pocket dissolved oxygen (DO) measured over time in each substrate mixture. Mixture ratios are weight of gravel to fine sediment.

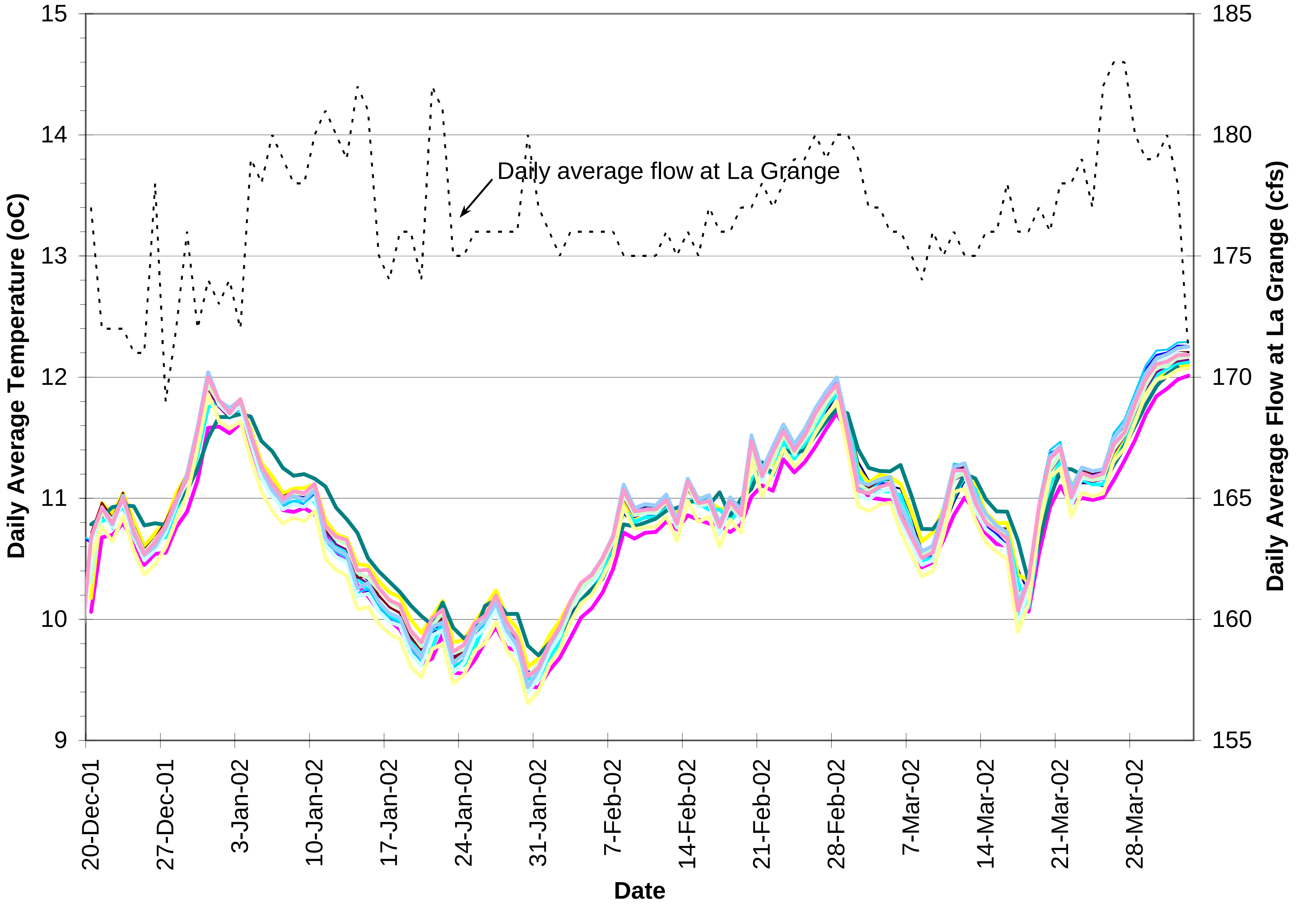

Figure 14. Daily average intragravel temperatures in artificial redds for the period from December 20, 2001 to April 14, 2002..

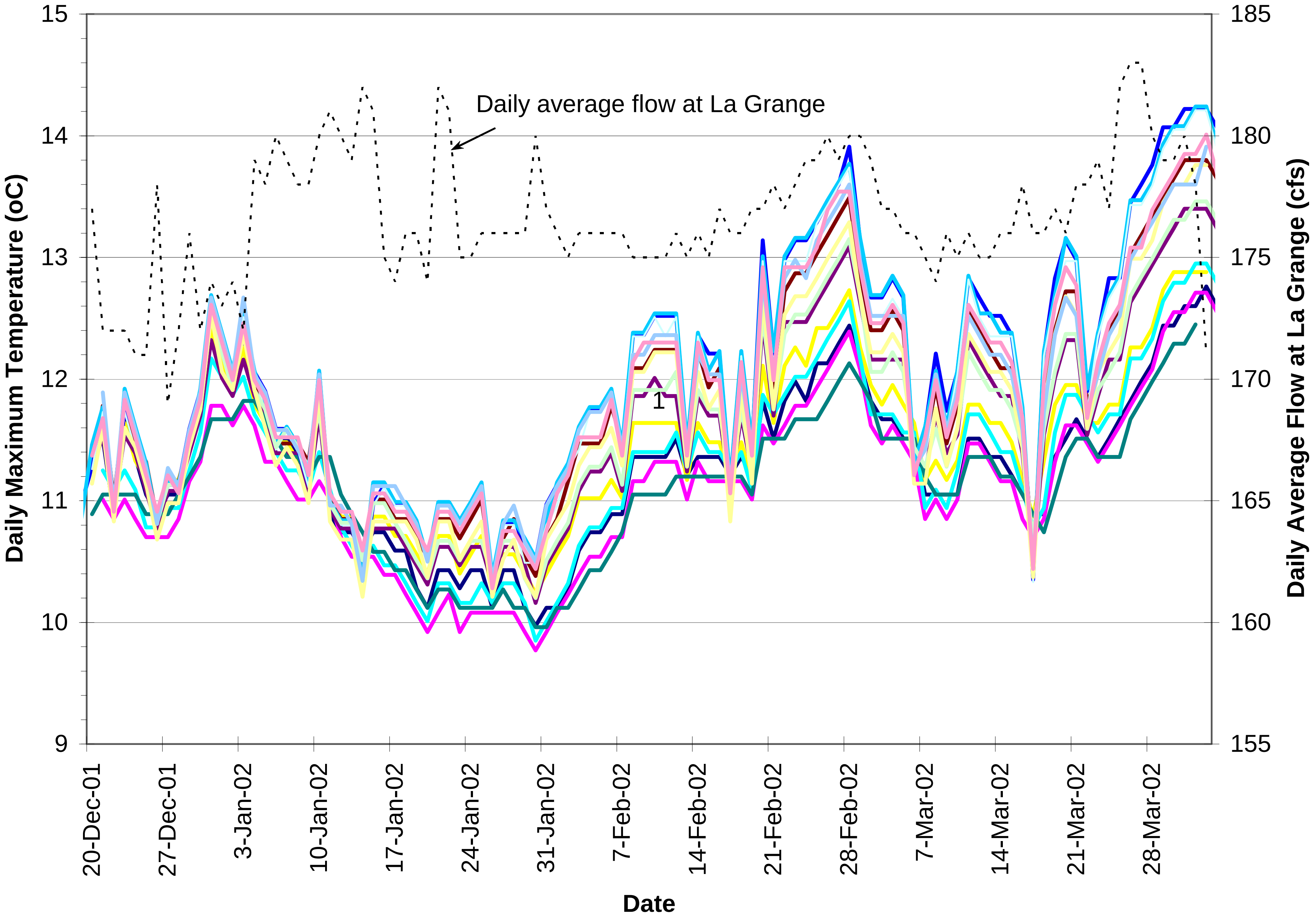

Figure 15. Daily maximum intragravel temperatures in artificial redds for the period from December 20, 2001 to April 14, 2002.

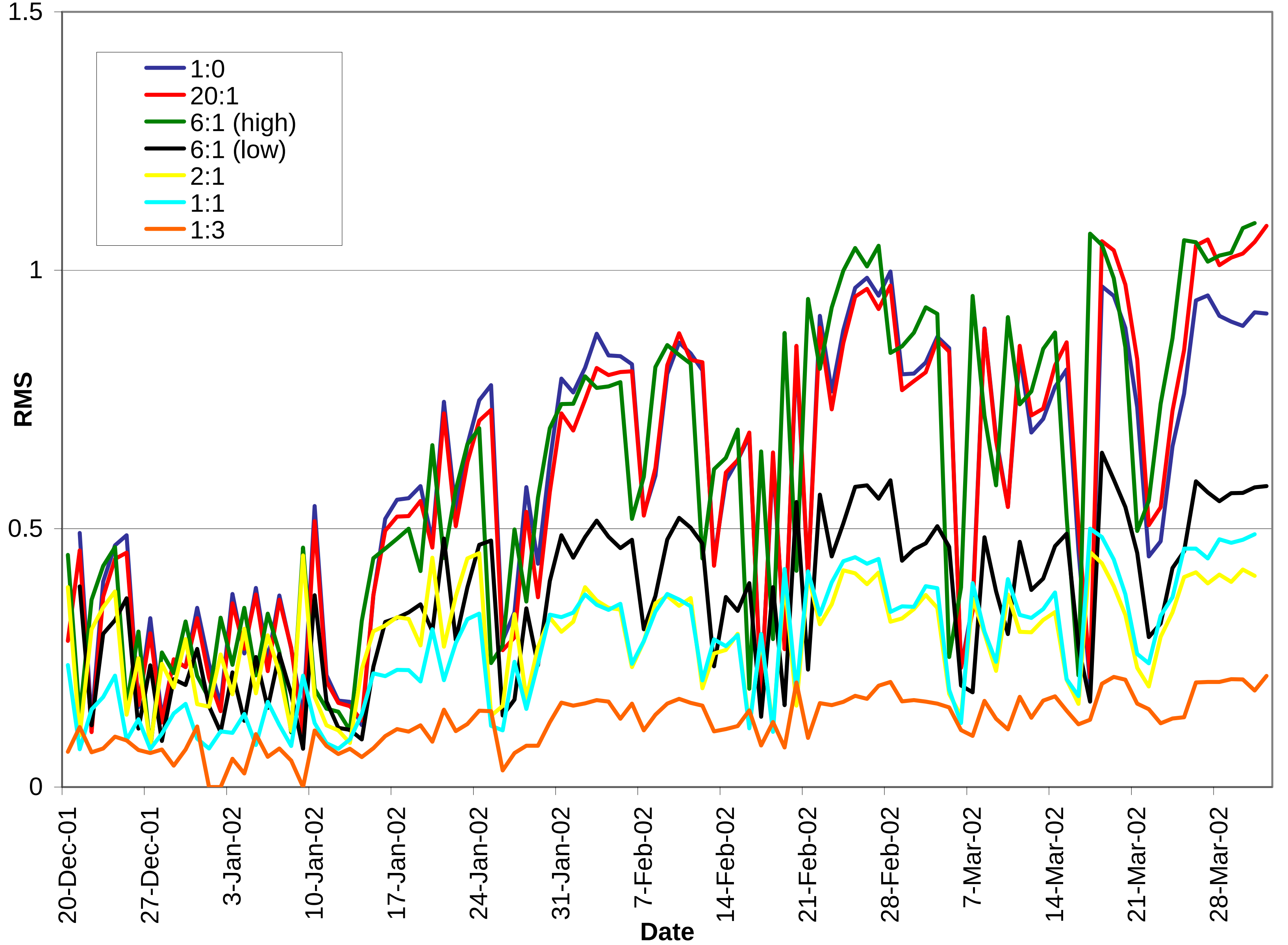

Figure 16. Variability of daily intragravel temperatures within artificial redds. Variability plotted as root mean square (RMS) of daily temperature range (daily minimum minus maximum). Mixture ratios are weight of gravel to fine sediment.

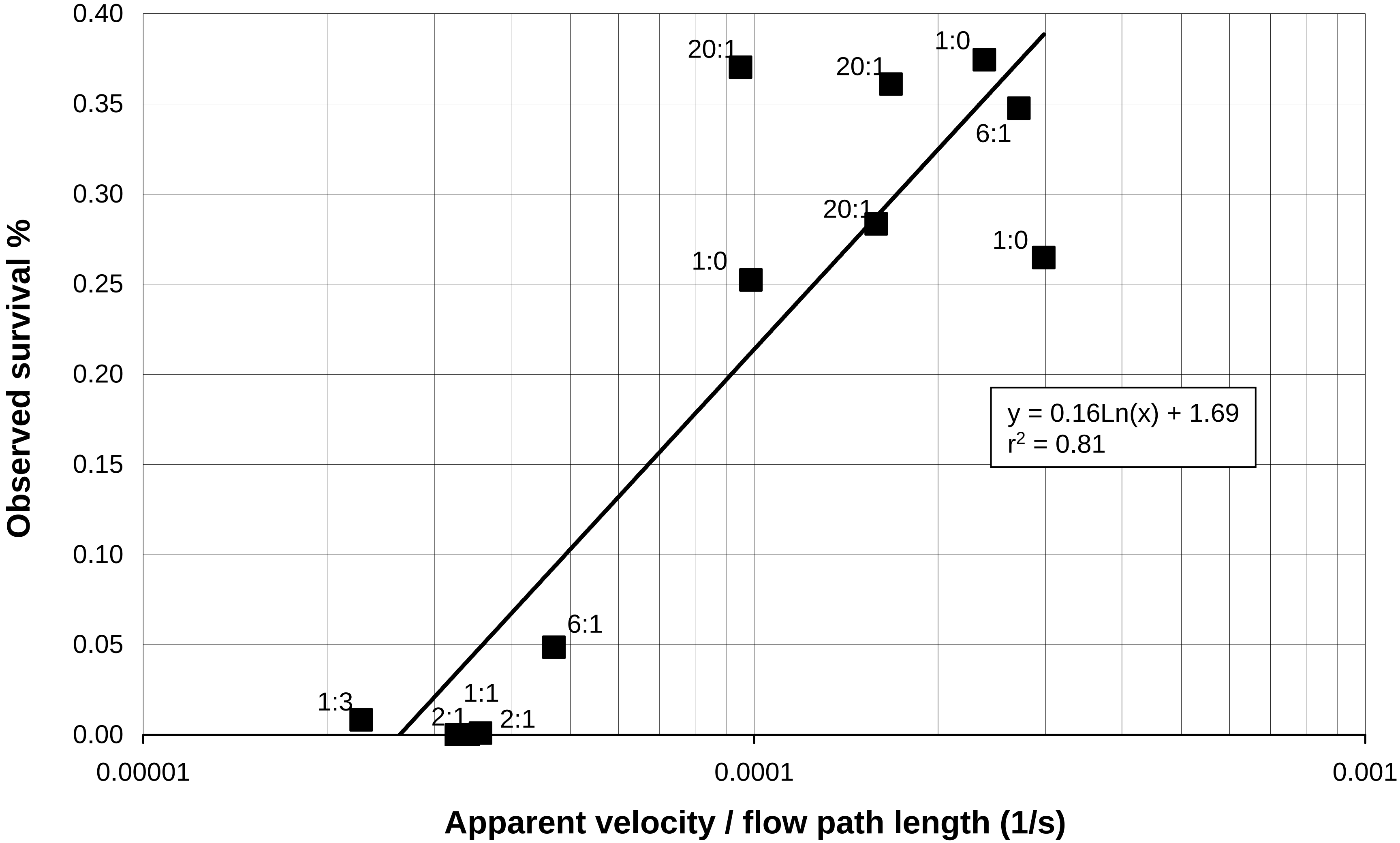

Figure 17. Egg survival vs apparent velocity based upon March 1, 2001 temperature variability. The ratio of apparent velocity to flow path length is estimated by fitting diurnal patterns in surface and subsurface water temperatures over a 15 day period to an intragravel heat conduction model (Appendix B). Mixture ratios are weight of gravel to fine sediment.

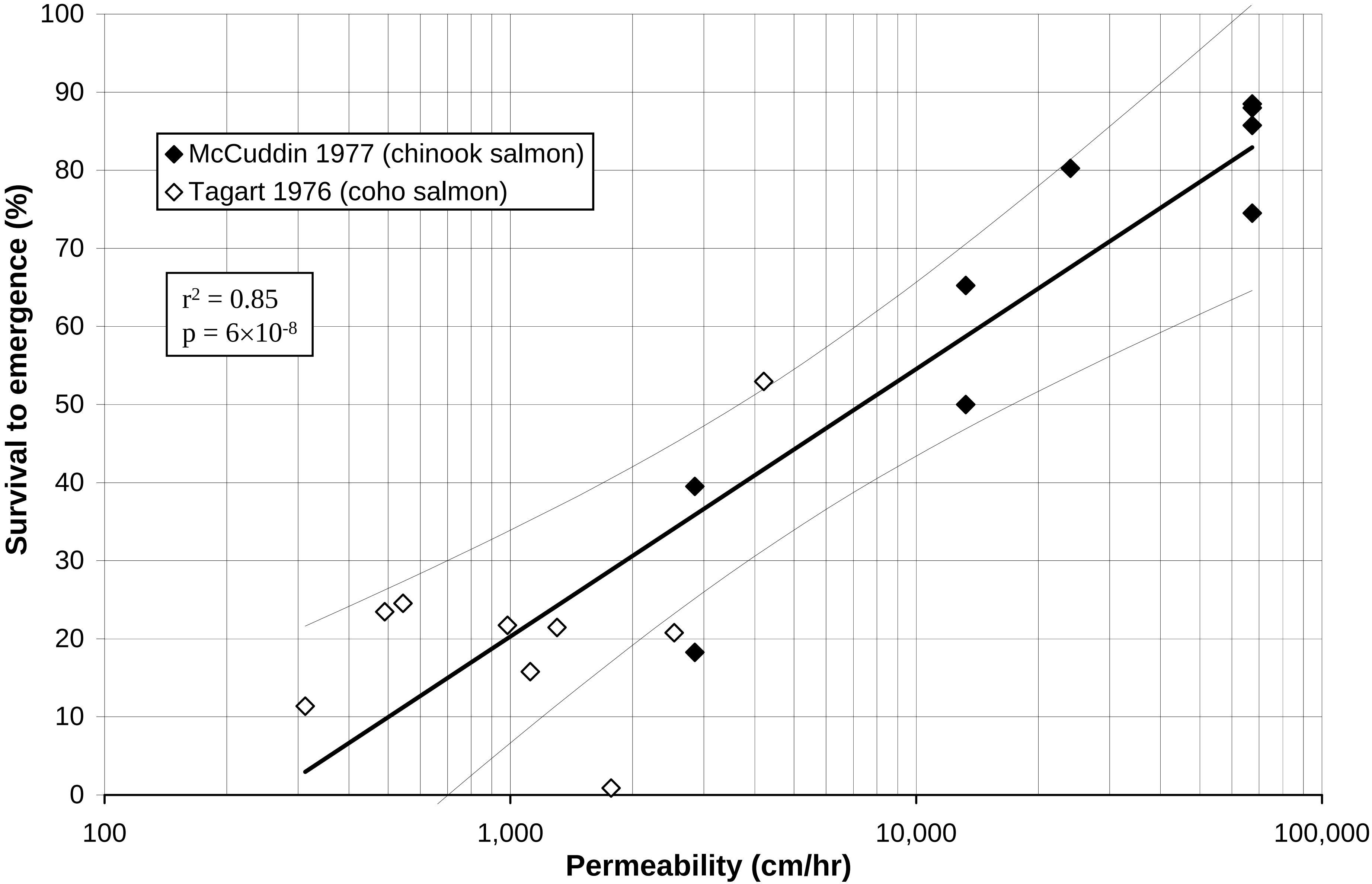

Figure 18. Salmonid survival-to-emergence vs. permeability, with 95% model confidence band (Tagart 1976, McCuddin 1977).

Appendix A

Daily Emergence Data from Artificial Redds

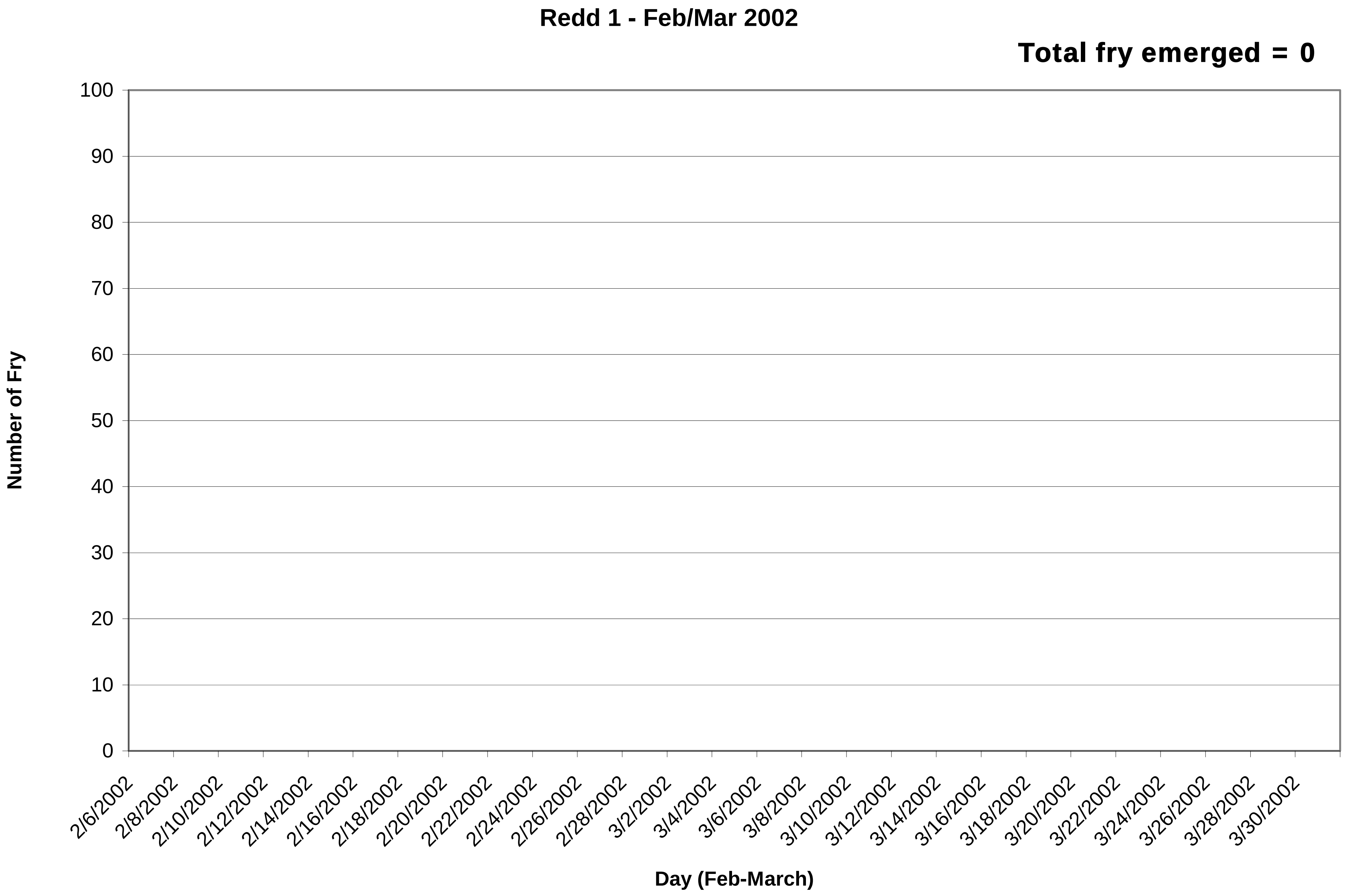

Figure A-1. Daily emergence for Redd 1 corresponding to a 2:1 mixture ratio as weight of gravel to fine sediment.

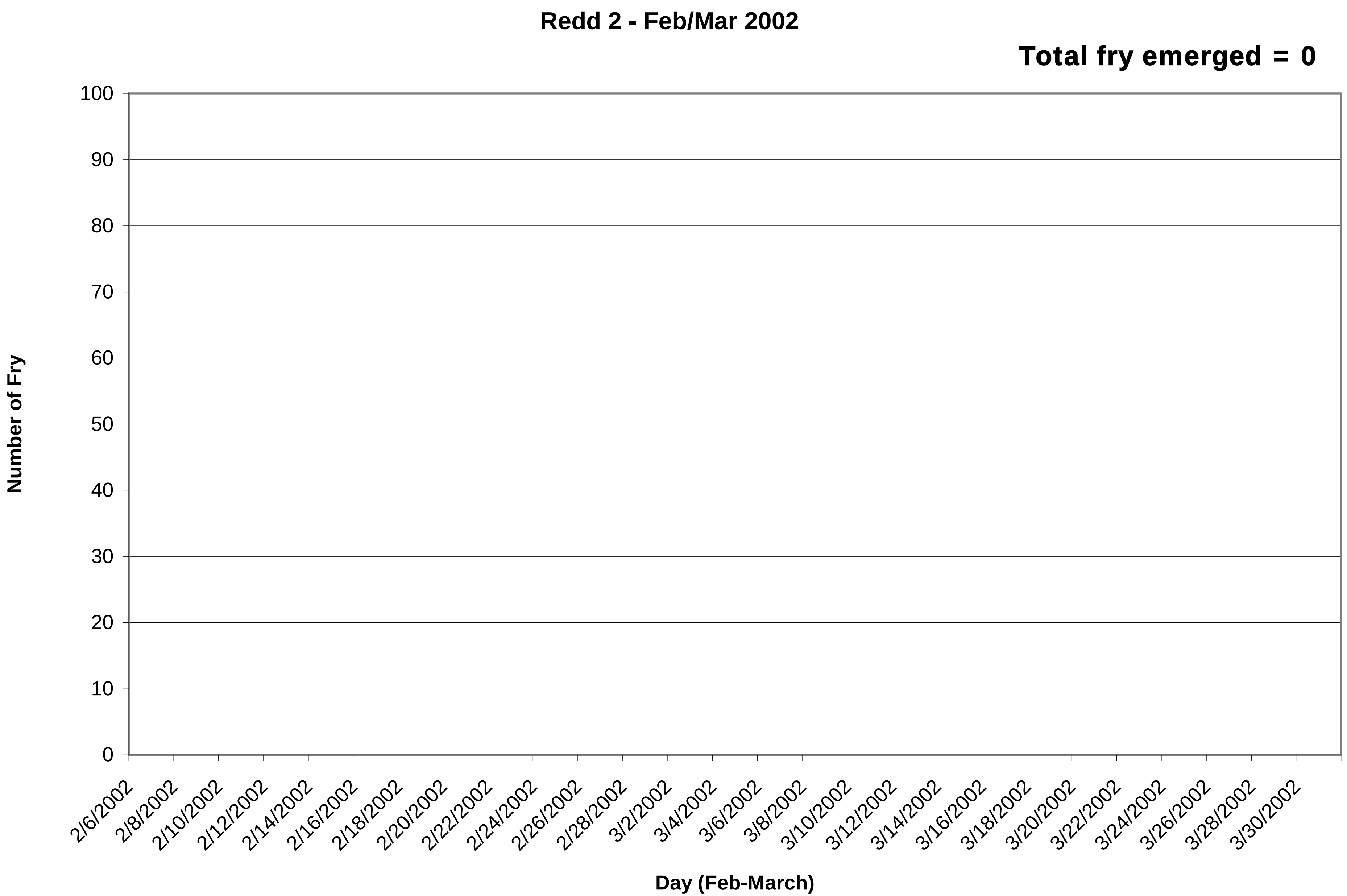

Figure A-2. Daily emergence for Redd 2 corresponding to a 1:1 mixture ratio as weight of gravel to fine sediment.

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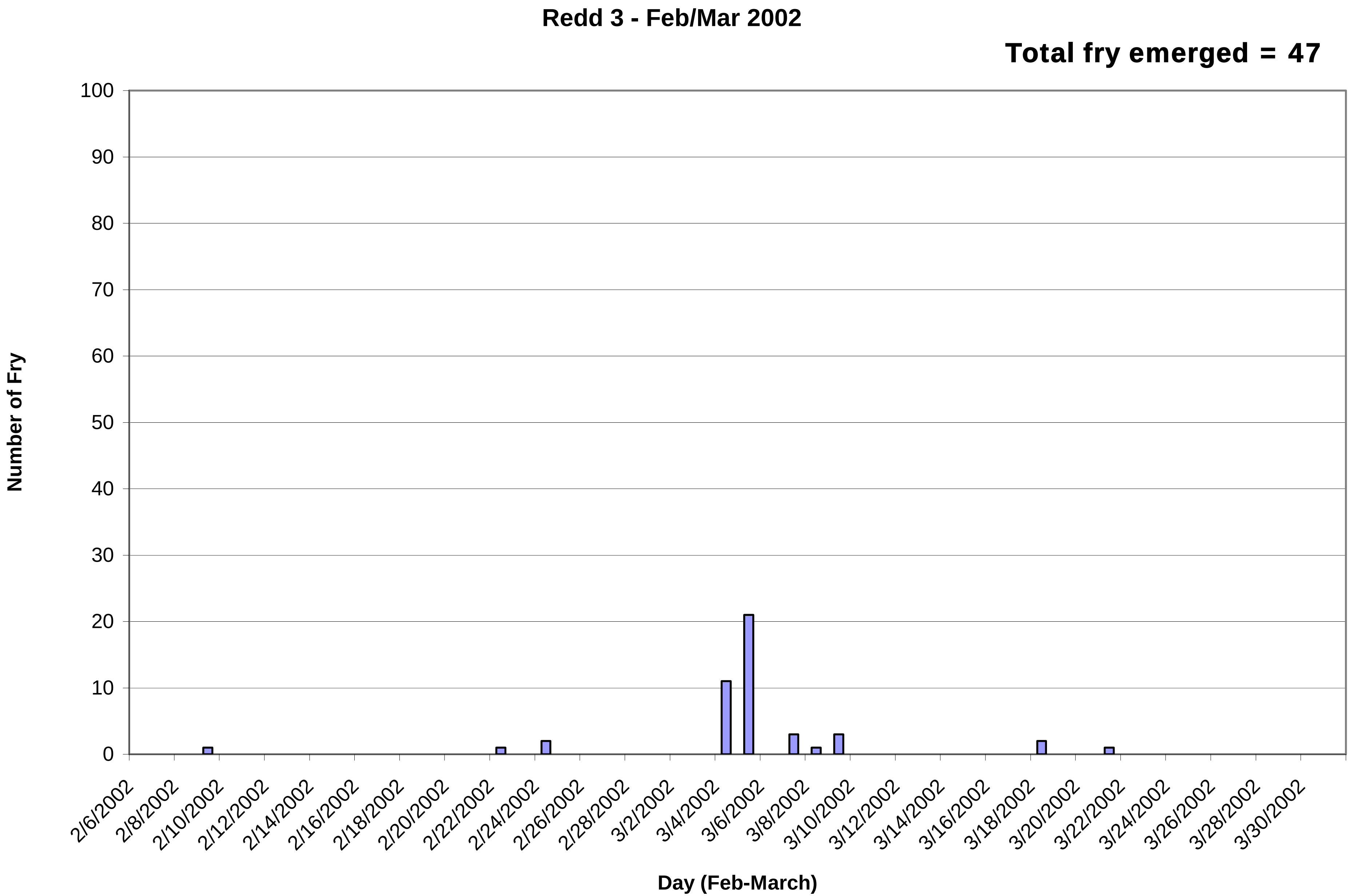

Figure A-3. Daily emergence for Redd 3 corresponding to a 6:1 mixture ratio as weight of gravel to fine sediment. .

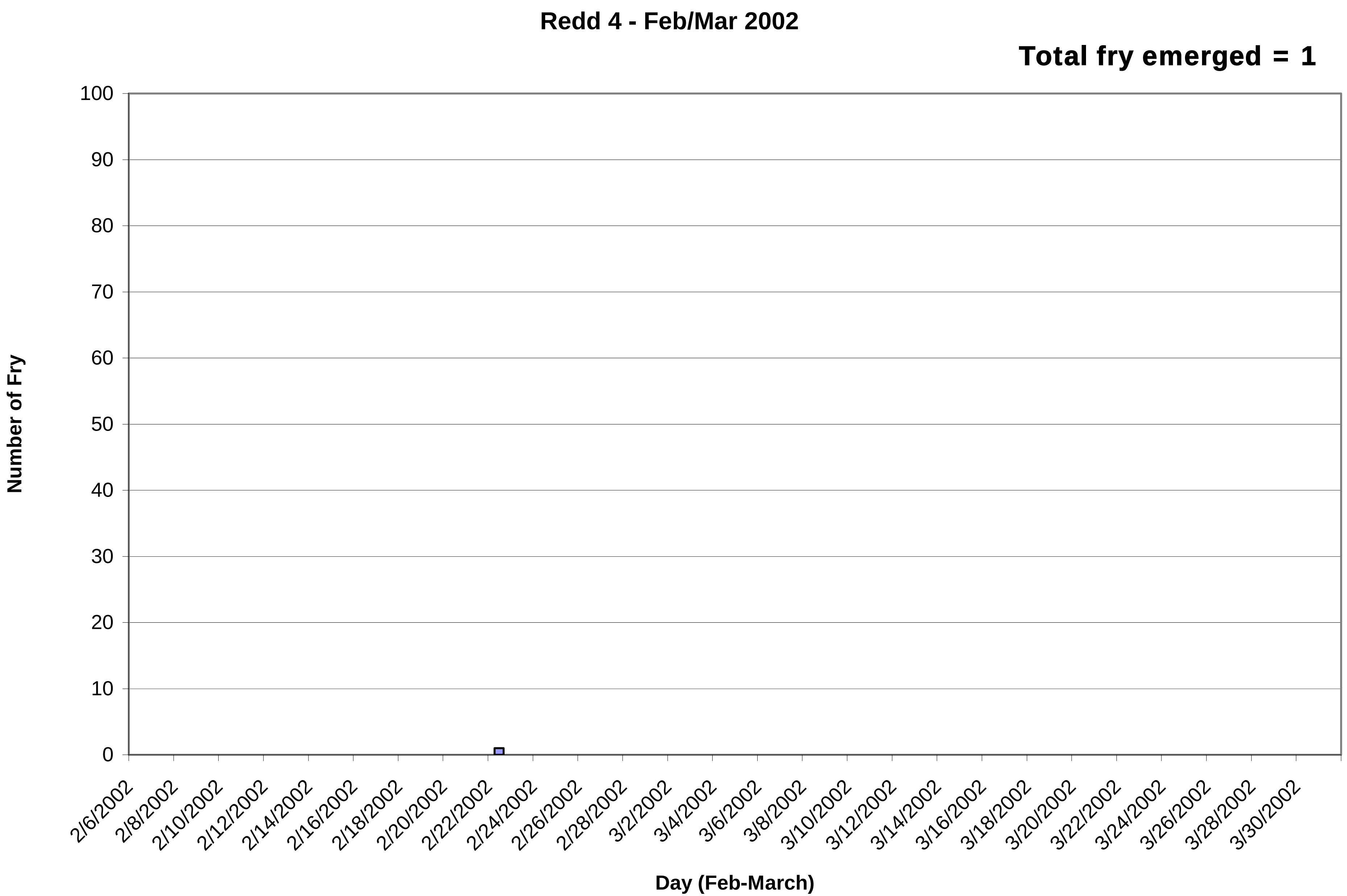

Figure A-4. Daily emergence for Redd 4 corresponding to a 2:1 mixture ratio as weight of gravel to fine sediment.

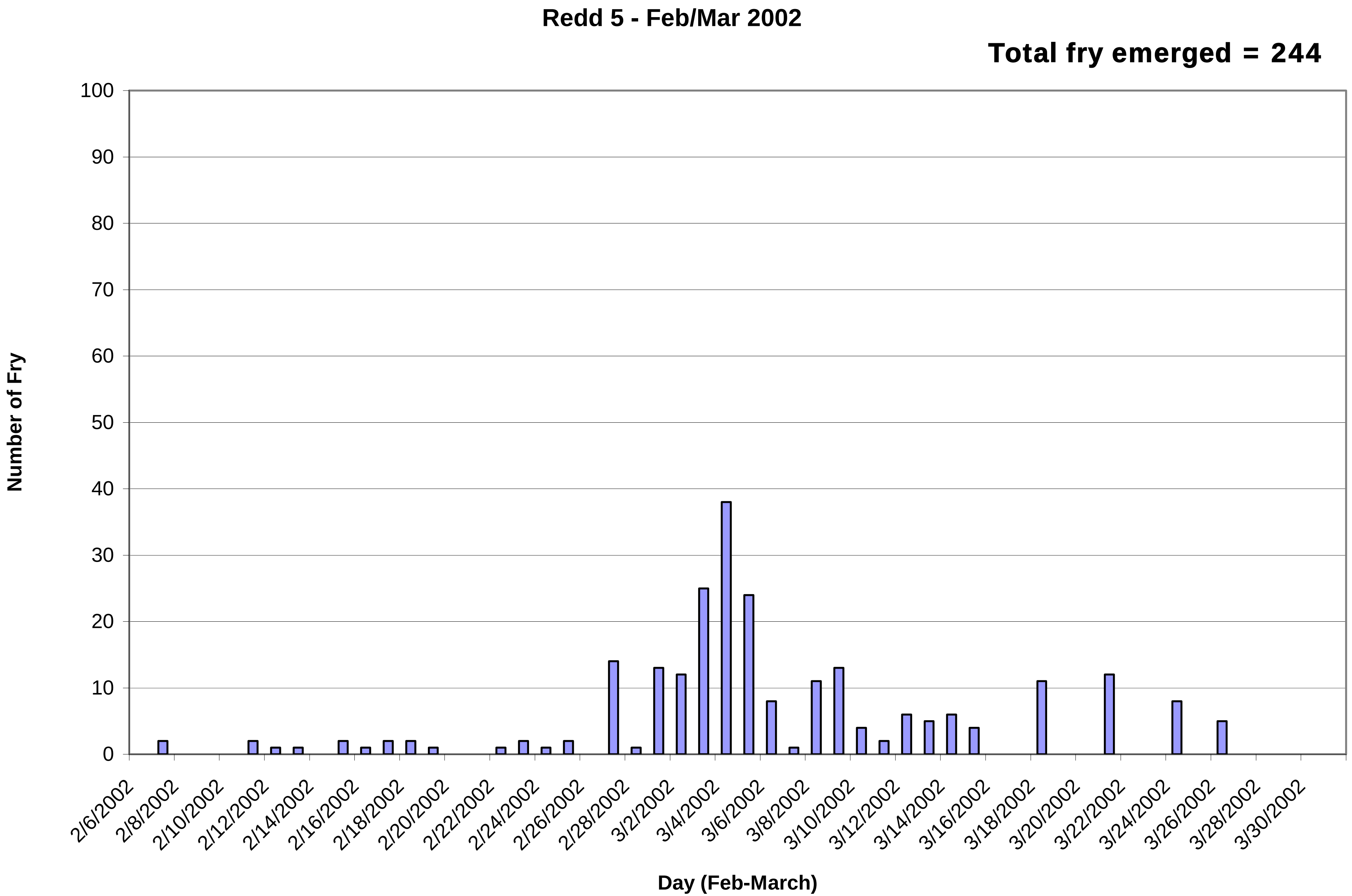

Figure A-5. Daily emergence for Redd 5 corresponding to a 1:1 mixture ratio as weight of gravel to fine sediment..

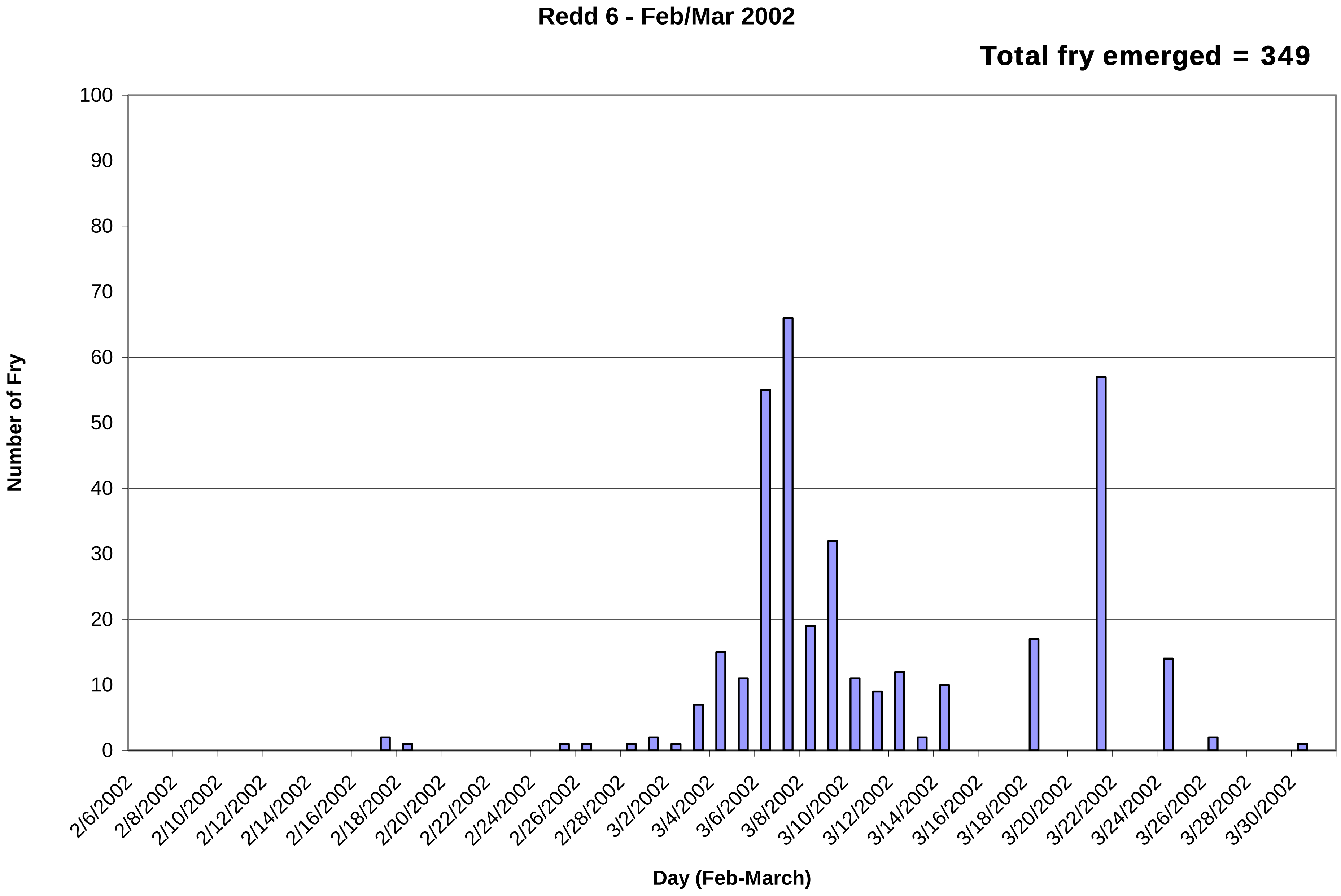

Figure A-6. Daily emergence for Redd 6 corresponding to a 20:1 mixture ratio as weight of gravel to fine sediment.

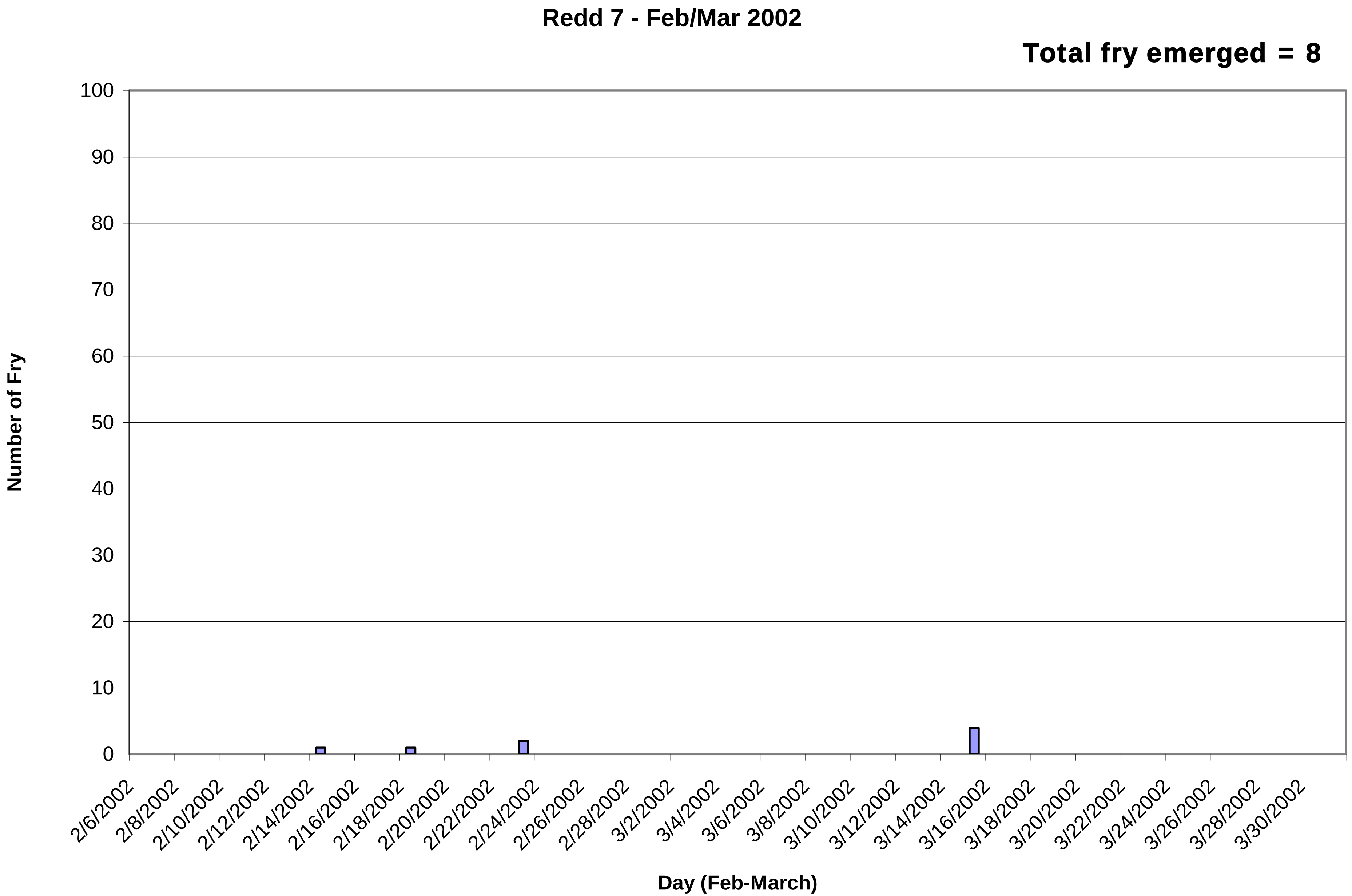

Figure A-7. Daily emergence for Redd 7 corresponding to a 1:3 mixture ratio as weight of gravel to fine sediment.

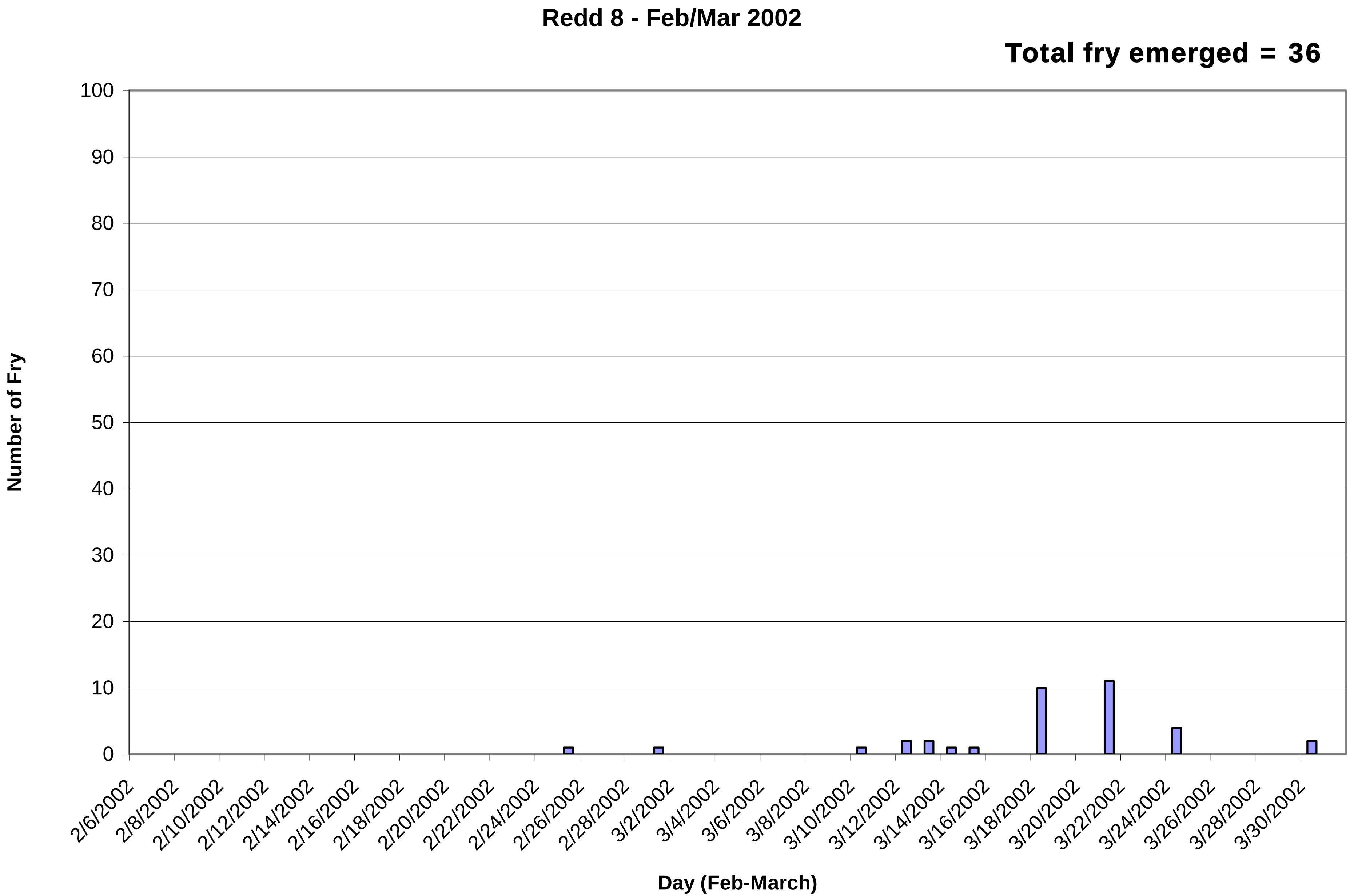

Figure A-8. Daily emergence for Redd 8 corresponding to a 20:1 mixture ratio as weight of gravel to fine sediment.

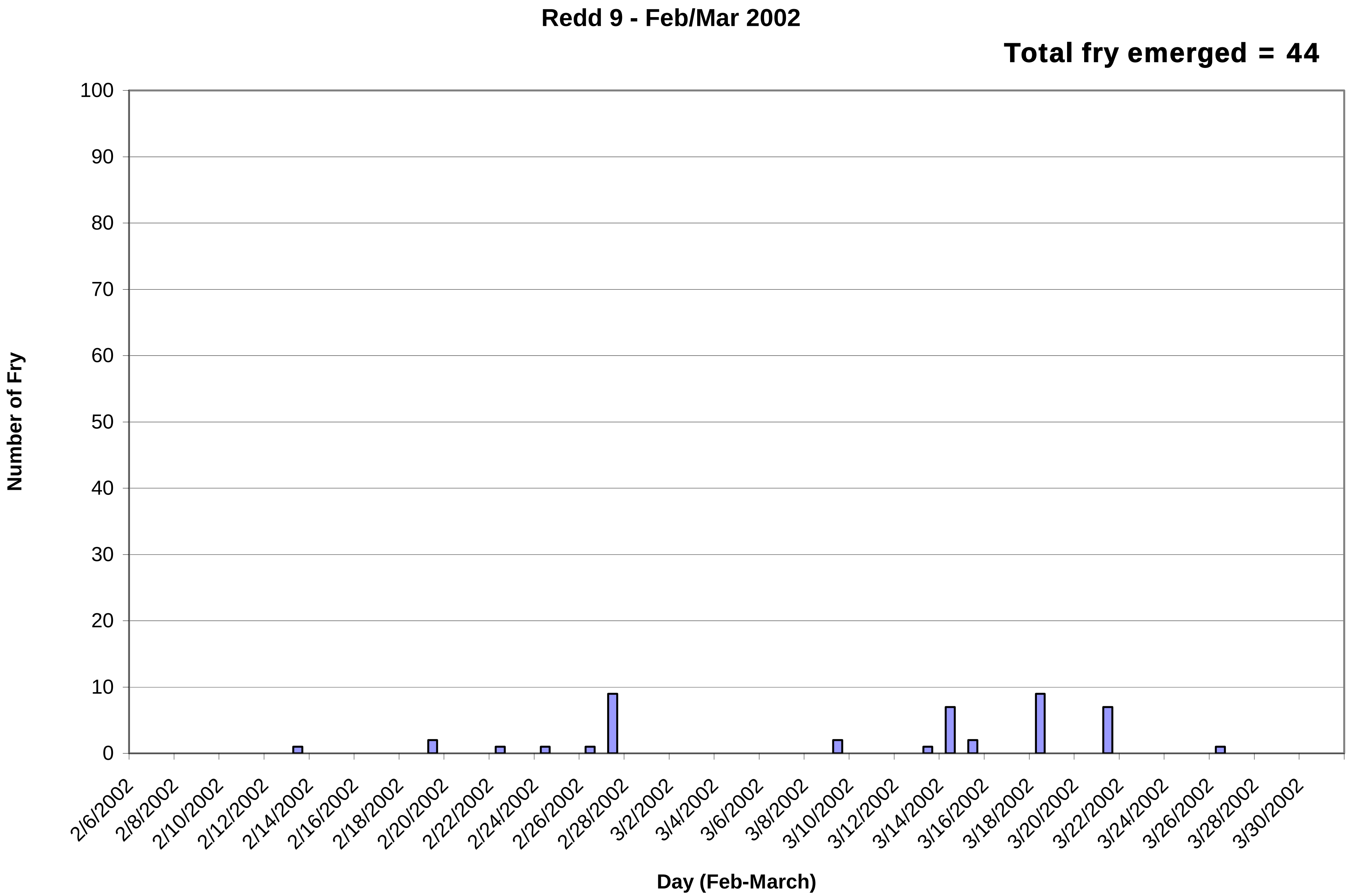

Figure A-9. Daily emergence for Redd 9 corresponding to a 1:1 mixture ratio as weight of gravel to fine sediment.

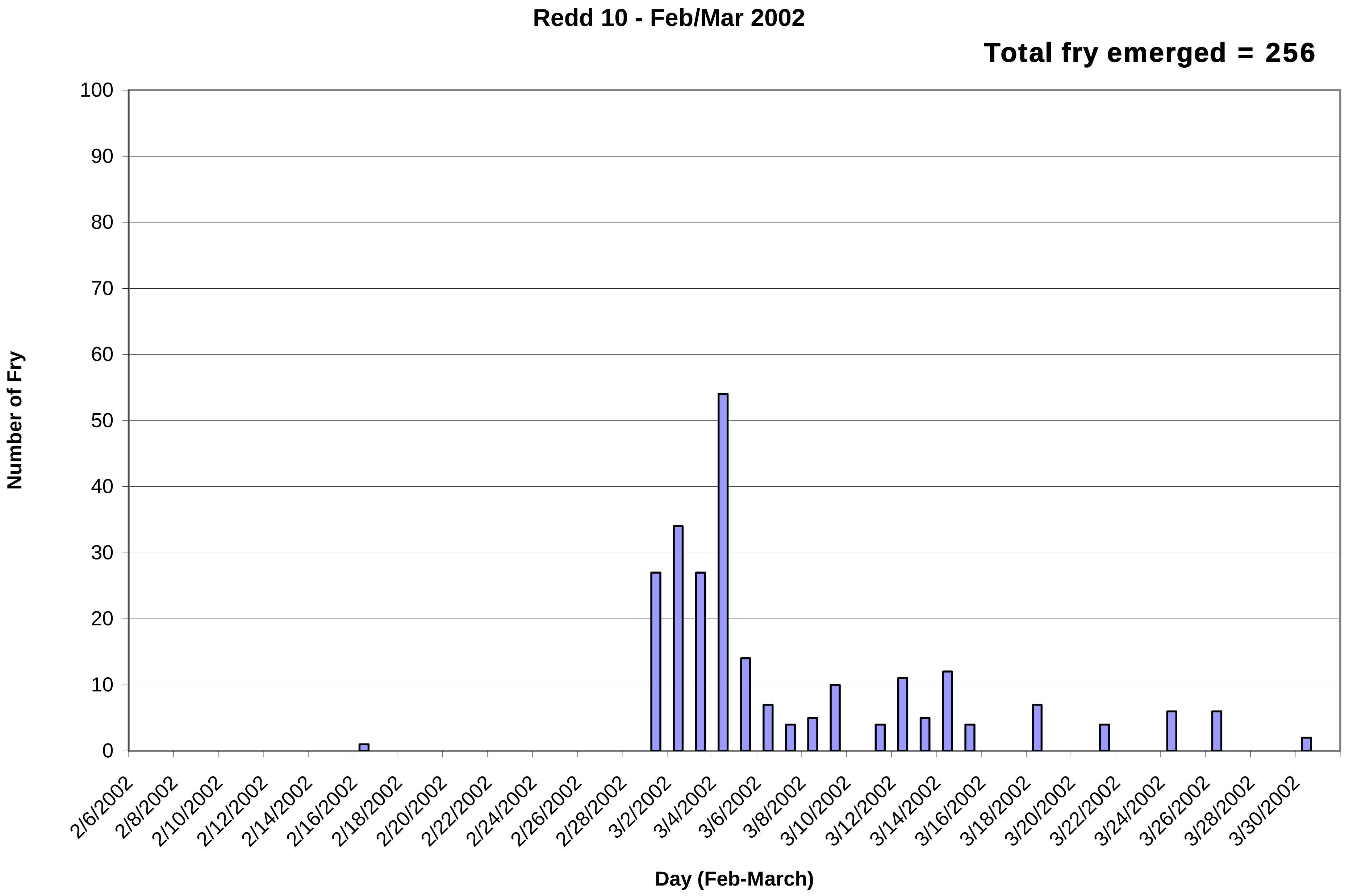

Figure A-10. Daily emergence for Redd 10 corresponding to a 1:1 mixture ratio as weight of gravel to fine sediment.

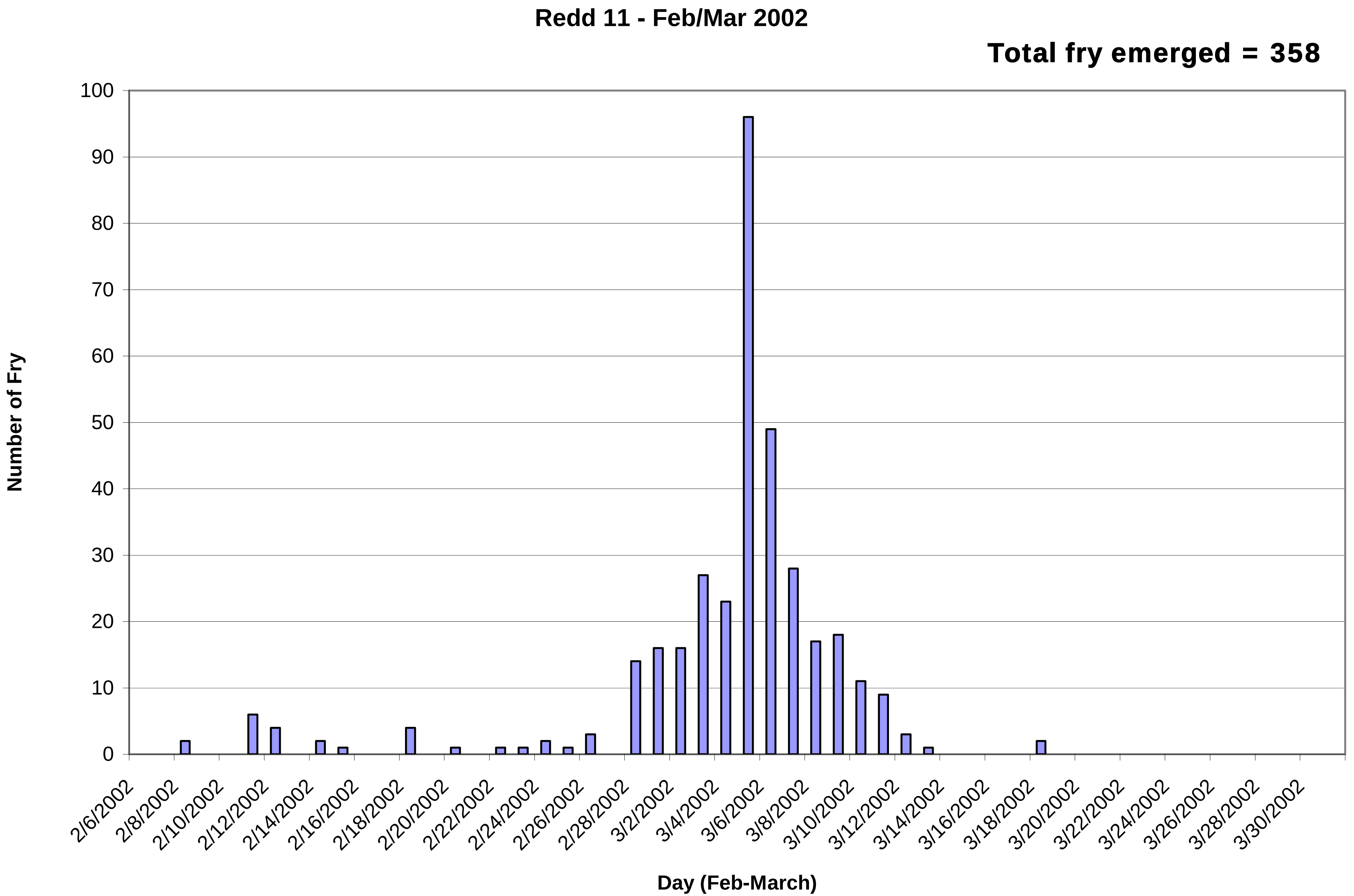

Figure A-11. Daily emergence for Redd 11 corresponding to a 20:1 mixture ratio as weight of gravel to fine sediment.

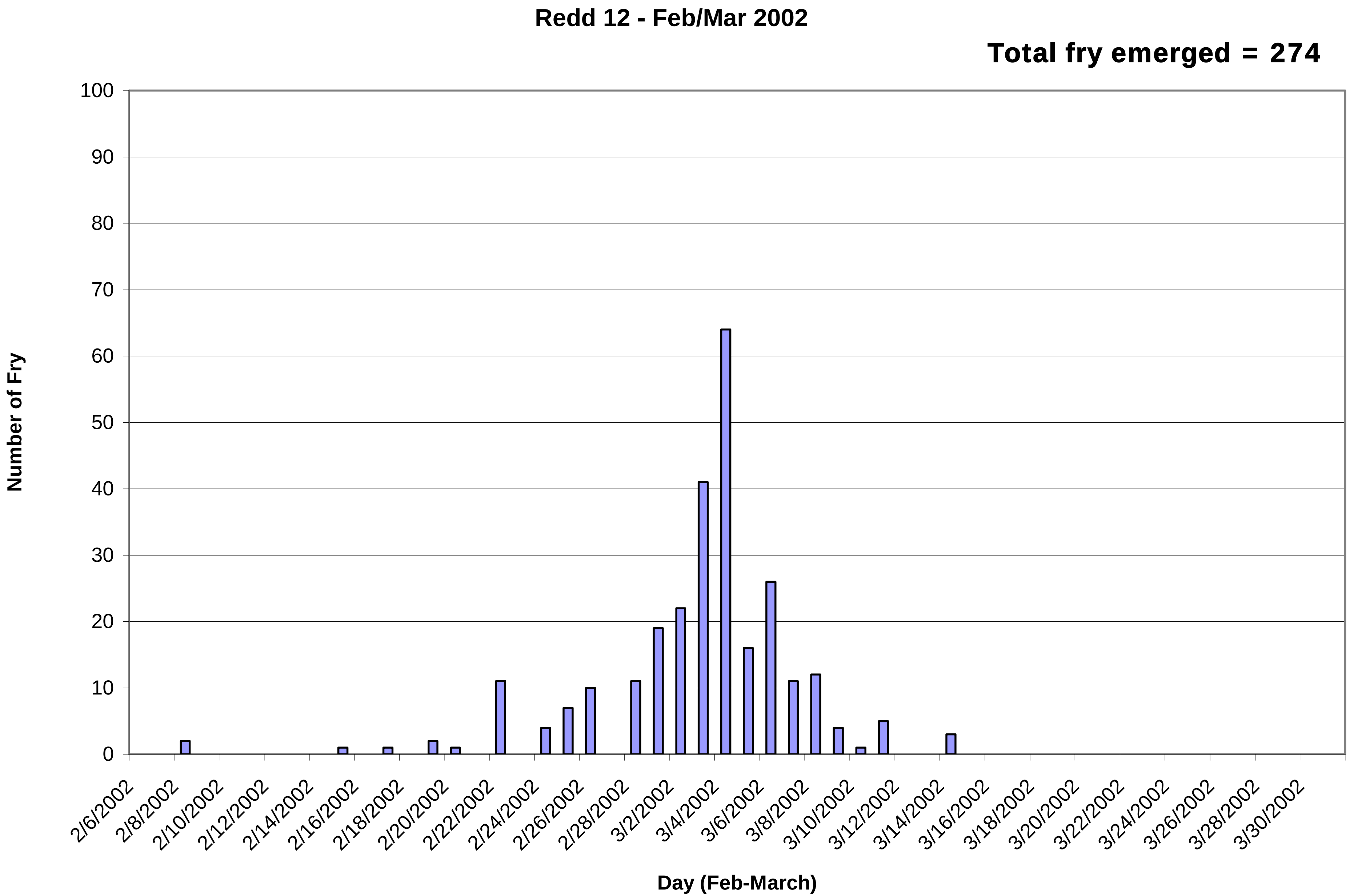

Figure A-12. Daily emergence for Redd 12 corresponding to a 20:1 mixture ratio as weight of gravel to fine sediment.

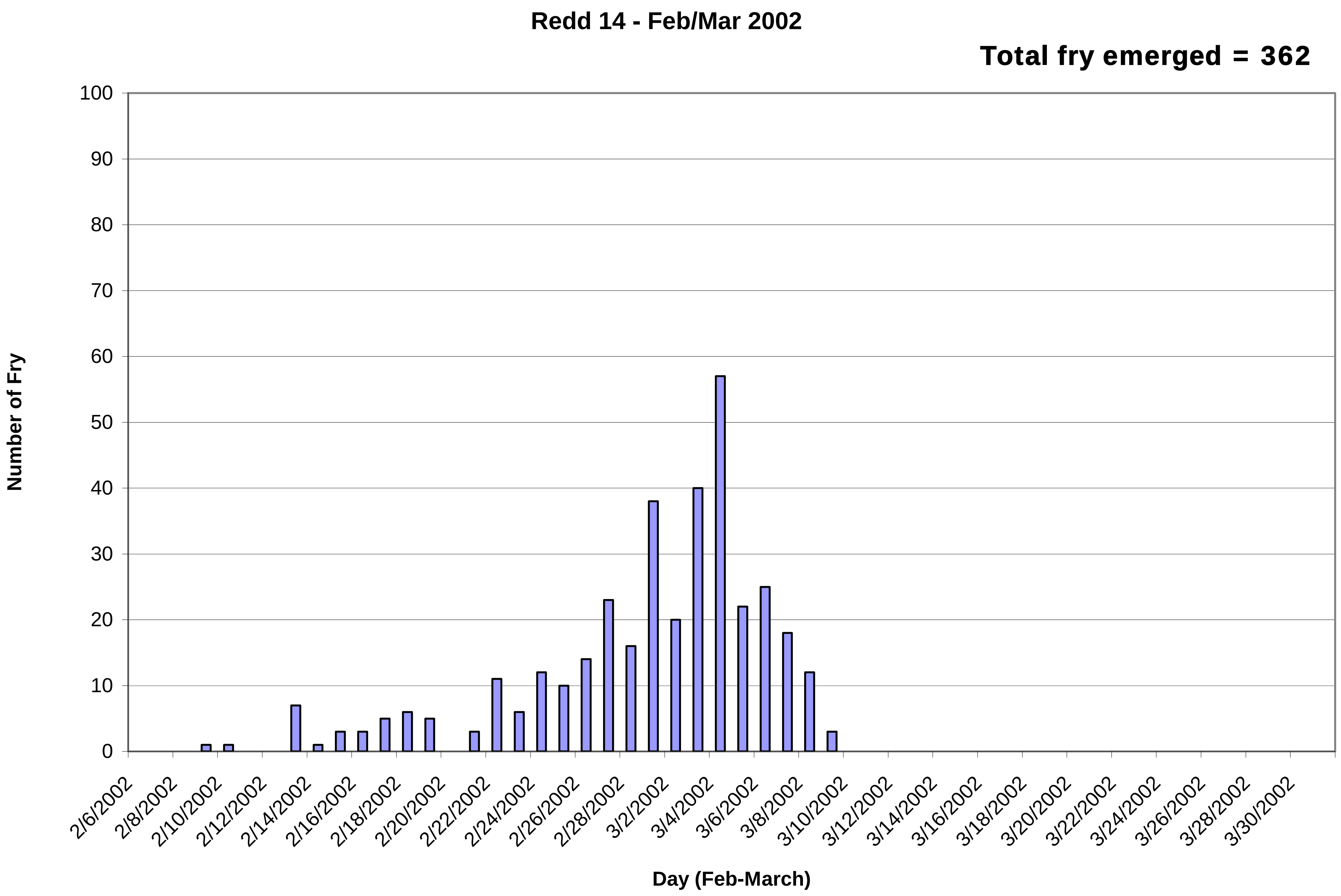

Figure A-13. Daily emergence for Redd 14 corresponding to a 1:1 mixture ratio as weight of gravel to fine sediment.

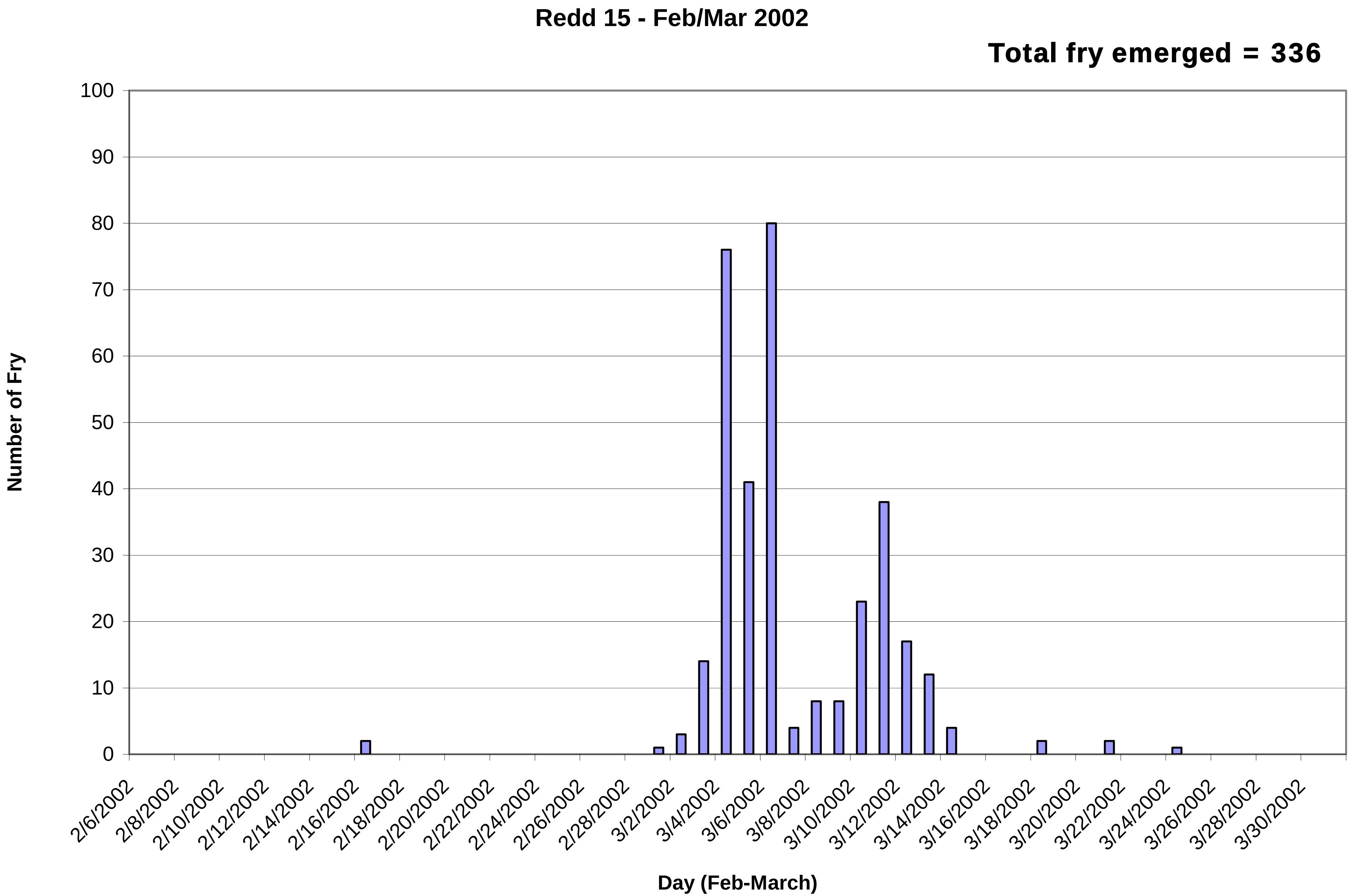

Figure A-14. Daily emergence for Redd 15 corresponding to a 6:1 mixture ratio as weight of gravel to fine sediment.

Appendix B

Apparent Velocity-Heat Conduction Model

INTRODUCTION

In gravel-bedded river systems and in spawning redds, water exchanges between the water column and subsurface (hyporheic) region influence both temperatures of the stream and their underlying sediments. Of particular interest is the effect of hyporheic flows on intragravel water temperatures in spawning redds. Based on general observations of the proportionality of hyporheic water temperature variability with gravel quality, we sought to develop a relation between temperature variability and intragravel water flow. The use of heat as a tracer has been used to quantify surface water-groundwater exchanges in a range of environments, from perennial streams in humid regions (Lapham 1989, Silliman and Booth 1993) to ephemeral channels in arid locations (Stonestrom and Constanz 2003).

Stream temperatures have a characteristic diurnal pattern superimposed on seasonal patterns, and are influenced by changes in solar radiation, air and ground temperature, rainfall, and stream inflows that include groundwater sources (Sinokrat and Stefan 1993). These diurnal variations often exhibit a distinct signal that is easy to determine from thermograph data recorded within the subsurface and overlying water column. In contrast, the temperature of regional groundwater tends to be relatively constant at the daily scale. Within the spatial scale of an individual spawning redd, the influences of groundwater upwelling upon intragravel flow may be neglected, and we develop a simple model below to predict intragravel flow as a function of stream and intragravel temperature variability.

CONDUCTION MODEL

The movement of heat between surface water and the subsurface is both advective (i.e., associated with fluid movement) and conductive (i.e., heat transfer across a static solid/liquid interface). Channel bed forms such as riffles and individual redd structures are often associated with standing wave patterns that increase hyporheic exchanges and advective transport (Packman et al. 2004). Ignoring the effect of *in-situ* sources of thermal energy such as from the biological activity of the developing eggs, the temperature pattern in the shallow stream sediment profile can be used to evaluate intragravel flow as described below.

Definitions

Consider a hypothetical control volume V within an individual spawning redd with an intragravel flow path from the upstream to downstream faces of the gravel mound. Let η be the porosity, so that the control volume V contains a volume ηV of water and $(1-\eta) V$ of substrate. Let $v(t)$ be the velocity of water along the flow path across the upstream boundary of the control volume. The apparent velocity across the control volume is then $v_a = \eta v$.

Because the substrate consists of relatively small particles, we expect that the surface area of substrate in the control volume that is in contact with water should be proportional to that volume. Let M be the constant of proportionality, or "specific surface area", so that the contact area within the control volume is MV. From a practical standpoint, however, it can be difficult to estimate specific surface area accurately.

The rate of heat exchange across a water-substrate interface should be proportional to the temperature difference across this surface and the area of the surface. Let λ be the constant of proportionality, or "heat transfer coefficient." Heat transfer coefficients (units: $cal/cm^2/s/°C$) are often determined empirically and vary by greater than an order of magnitude (White 1988).

Let γ and γ_S be the heat capacity (units: $cal/cm^3/°C$) for water and the substrate material, respectively.

Finally, define the intragravel water temperature $T(x,t)$ as the temperature in the (moving) water and $T_s(x,t)$ as the temperature of the substrate at a particular distance x along the flow path at time t.

Governing Equation

Let $H(x,t)$ and $Hs(x,t)$ represent the heat contents (i.e., enthalpy) per unit volume of water and substrate around the location x at time t. Then $H = \gamma \eta T$ and $H_S = \gamma_S (1-\eta) T_S$, and

$$H(x+v\,dt, t+dt) - H(x,t) = -\lambda M (T - T_s)\,dt$$
$$H_s(x, t+dt) - H_s(x,t) = \lambda M (T - T_s)\,dt$$

This give rise to the governing equations:

$$v\frac{\partial T}{\partial x}+\frac{\partial T}{\partial t}=-\alpha(T-T_s)$$
$$\frac{\partial T_s}{\partial t}=\alpha_s(T-T_s)$$

where

$$\alpha=\frac{\lambda M}{\gamma\eta}$$
$$\alpha_s=\frac{\lambda M}{\gamma_s(1-\eta)}$$

A second-order equation for T alone can be obtained from

$$\frac{\partial^2 T}{\partial t^2}+v\frac{\partial^2 T}{\partial t\partial x}+(\alpha+\alpha_s)\frac{\partial T}{\partial t}+(\frac{dv}{dt}+\alpha_s v)\frac{\partial T}{\partial x}=0$$

Constant Velocity Assumption

For the case of constant intragravel velocity and sinusoidal input $T(0,t)=b+a\sin\omega t$, it is straightforward to obtain the explicit solution

$$T(x,t)=b+a\exp\left(-A_\omega\frac{x}{v}\right)\sin\omega\left(t-B_\omega\frac{x}{v}\right)$$

where

$$A_\omega=\frac{\omega^2\alpha}{\omega^2+\alpha_s^2},\ B_\omega=1+\frac{\alpha\alpha_s}{\omega^2+\alpha_s^2}$$

That is, the temperature remains sinusoidal, with amplitude dampened by the factor $f=e^{-A_\omega\tau}$ and phase-shifted by $\phi=B_\omega\tau$, where $\tau=x/v$ is the time water at x has been in the substrate. In particular, the phase shift is always greater than the residence time.

More generally, for constant velocity and not-necessarily-sinusoidal $T(0,t)$ input, writing $\hat{T}_x$ for the Fourier transform with respect to t,

$$\hat{T}_x(\omega) = \int_{-\infty}^{+\infty} e^{-i\omega t} T(x,t)\,dt$$

the solution becomes

$$\hat{T}_x(\omega) = e^{-i\omega A_\omega x/v}\hat{T}_0(\omega),\ A_\omega = \frac{\alpha + \alpha_s + i\omega}{\alpha_s + i\omega}$$

In particular, this relates the velocity to the transforms of the temperature at the bed surface T_0 and the temperature at the buried thermograph T_L. Using $\hat{T}_0 \pm \hat{T}_L = (1 \pm e^{-i\omega A_\omega x/v})\hat{T}_0$ and substituting $z = i\omega A_\omega$ into the formula, we obtain

$$z = 2\left(\frac{1-e^{-z}}{1+e^{-z}} + \frac{1}{3}\left(\frac{1-e^{-z}}{1+e^{-z}}\right)^3 + \frac{1}{5}\left(\frac{1-e^{-z}}{1+e^{-z}}\right)^5 + \dots\right)$$

(valid for $\operatorname{Re} z \geq 0$, $z \neq 0$), and this relation can be written as

$$\frac{v}{L} = iA_\omega \frac{\omega}{2}\left(\frac{\hat{T}_0 - \hat{T}_L}{\hat{T}_0 + \hat{T}_L} + \frac{1}{3}\left(\frac{\hat{T}_0 - \hat{T}_L}{\hat{T}_0 + \hat{T}_L}\right)^3 + \frac{1}{5}\left(\frac{\hat{T}_0 - \hat{T}_L}{\hat{T}_0 + \hat{T}_L}\right)^5 + \dots\right)^{-1}$$

It is useful here to introduce the weighted mean heat capacity of the substrate and water within the control volumes $\gamma_m = \eta\gamma + (1-\eta)\gamma_s$. If $|\omega|$ is sufficiently small, then

$$A_\omega \approx \frac{\alpha + \alpha_s}{\alpha_s} = \frac{1}{\eta}\frac{\gamma_m}{\gamma}$$

and

$$\left|\frac{\hat{T}_0 - \hat{T}_L}{\hat{T}_0 + \hat{T}_L}\right| << 1$$

lead to the following approximation for apparent velocity normalized to path length L:

$$\frac{v_a}{L} \approx \frac{\gamma_m}{\gamma} \frac{\omega}{2} \frac{|\hat{T}_0 + \hat{T}_L|}{|\hat{T}_0 - \hat{T}_L|}$$

Notice that the most difficult parameters to estimate, λ and M, have dropped out in the approximations above, and that the porosity factor η has been moved to the left hand side of the equation to produce an expression for *apparent* velocity as a function of the amplitudes of the diurnal temperature variations within the subsurface and overlying water column.

Parameter Estimates

Heat capacity of water (γ, cal/cm³/°C): In principle, this depends on water temperature, water purity, and so on, but the variation is extremely small and the heat capacity of water is given by $\gamma \approx 1$ cal./cm³/°C. In particular, the value for air-free pure water at atmospheric pressure is between 1.004 and 0.995 for temperatures from 3 to 26 °C

Heat capacity of dry rock (γ_S, cal/cm³/°C): This depends on the type of rock (also on temperature, but this is too minor a correction to warrant consideration). The heat capacity by weight is typically fairly close to 0.20 cal./g/°C (Bear 1972), but the volumetric heat capacities are more varied since the densities are more variable. Overall, we expect $\gamma_S \approx 0.5$ Cal./cm³/°C

Gravel porosity (η, dimensionless): Typical values for porosity in river substrates range from η=0.3 (for coarse gravel or uniform sand) to η=0.5 (for fine silt).

Angular frequency (ω, 1/s): Typically, the most obvious scale of temperature variation is diurnal, $\omega = 2\pi/(24 \times 60 \times 60)$ 1/s.

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