NOOKSACK CHINOOK SPAWNING & INCUBATION ASSESSMENT

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Timothy L. Hyatt

and

Angel D. Rabang

Nooksack Natural Resources Department

Nooksack Indian Tribe

5016 Deming Road

Deming, WA 98244

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In memory of Virgil Bailey.

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EXECUTIVE SUMMARY

The purpose of this study is to quantify factors limiting the spawning and incubation success of North and South Fork Nooksack native spring chinook, with an assessment of spawning gravel size, fine sediment levels, and channel instability. Streambed instability is thought to be widespread and is generally considered the most important factor affecting chinook productivity in the Nooksack (Neff et al. 1996). Most channel instability occurs during high water events coincident with the chinook incubation period. Both vertical (scour and deposition of sediment) and lateral (channel shifting and dewatering) instability have been suspected for many years to cause extensive mortality in many spring chinook spawning areas (Schuett-Hames and Schuett-Hames 1987; Neff et al. 1996). Likewise, fine sediment intrusion has long been suspected of limiting survival to emergence by suffocating developing embryos before they emerge.

The spawning gravel portion of this study looked at gravel samples collected from chinook spawning areas throughout the North and South forks and their tributaries. During the 2001 field season 60 McNeil samples were collected from 20 sites in the North and South Forks. During the 2002 field season 41 barrel samples were collected at as many scour transects. The sampling design was changed for the 2002 field season to better capture the characteristics of the larger gravels used by chinook. Spawning gravel data collected throughout the watershed by Lummi Natural Resources (LNR) in the mid-1980s (Schuett-Hames et al. 1988a) was obtained, aggregated with data from 2001-02, and analyzed for spatial and temporal trends in fine sediment accumulation. Within-site variability and minor modifications in sampling protocol often obscured trends in gravel composition between sites and over time. However, many sites with consistently high spawning density also had consistently high-quality spawning gravels. Often the best spawning sites were in the upper watershed where land use impacts were the least apparent.

The channel stability portion of the study used scour chains and channel cross-sectional surveys to measure the extent to which redd damage was occurring in chinook spawning areas. Eighty scour chains were placed along 14 transects at 7 sites for the first (2001-02) flood year, and extensive flooding that year resulted in high redd failure rates. In the second flood season (2002-03), 160 scour chains were placed along 39 transects at 15 sites, but light flooding that year resulted in less scour, reduced channel shifting, and less dramatic redd damage. Field data collection for scour chains was completed in April 2003. In each of the two sampling years clear differences in redd survival were evident depending on habitat type. Redds-- or at least the scour chains that represented redds-- in mainstem and braided reaches had consistently high failure rates, while redds in sloughs and tributaries had relatively low failure rates. Redds in back channels that were separated from mainstems by woody vegetation had more ambiguous failure rates, depending on the location and year. Channel shifting and dewatering were often less of a concern than bedload transport in most of the basin, particularly in the lighter 2002-03 flood year, but shifting was a significant problem in certain reaches.

Both the North Fork and South Fork carry seasonally high suspended sediment loads, due at least in part to active glaciation on the North Fork, quaternary lacustrine deposits on the South Fork, and extensive networks of logging roads throughout the basin (Kirtland 1995, Zander 1996, Zander 1997). Thus fine sediment intrusion in mainstem redds is, and will continue to be, a chronic problem. Redds in many tributaries and off-channel habitats are by contrast somewhat immune from mainstem effects, but subject to other sources of fine sediment. Within-site variability in fine sediment concentration was often as high as between-site variability, or variability over time. Good, fair, and poor spawning gravels were obtained in a variety of sites, and often in close proximity. Given the inherent variability in spawning gravel composition, a basin-wide strategy to combat fine sediment accumulation in redds was not apparent.

If scour chains installed in mainstem and braided reaches had a disproportionate tendency toward “redd failure” (defined as >20 cm scour, complete dewatering, or 50 cm overburden at emergence) and scour chains in tributaries, sloughs, and back channels a

disproportionate tendency towards redd survival, then a basin-wide strategy to improve incubation survival does emerge: protect the tributaries and off-channel spawning areas, and improve or enhance the braids and mainstems. Although not specifically a part of this study, other research provides guidance on how this can be accomplished. Historically the lower Nooksack River mainstem was dominated by anastomosing reaches where we now have braided reaches (Collins and Sheikh 2003). River reaches with stable channel islands of mature woody vegetation— the so-called "island braided" habitat type— would, according to this study, provide more stable spawning areas. Further, stable channel islands would also increase LWD contributions, increase channel shading, increase channel edges, and would significantly enhance juvenile survival (Sedell et al. 1982; Sedell and Froggatt 1984; Collins and Montgomery 2002). The key to creating or encouraging the island braided channels, and the formation of floodplain habitats around those channels, is the addition of large stable wood accumulations in the appropriate reaches (Fetherston et al. 1995; Abbe and Montgomery 2003). Thus replacing the large wood accumulations that were historically present in the Nooksack mainstems may lead to returning endangered fish populations to their historical levels as well.

REVIEW OF RELEVANT LITERATURE

Redd locations and characteristics

The size, structure, and functioning of salmon and trout redds have been extensively studied for several decades, despite the difficulties of measuring redd conditions without destroying embryos. Several studies have noted that as the female digs she often does not or cannot lift the largest particles in the substrate. The largest cobbles remain in the bottom of the egg pocket (the centrum) and provide a stable anchor around which the eggs adhere and coalesce (Burner 1951; Vronskiy 1972; Chapman 1988; Kondolf 2000). Kondolf and Wolman (1993) showed that the upper limit of particles that can be lifted by a spawning female is approximately 10% of her body length. The finer sediments are winnowed into the streamflow, the gravels and small cobbles are forced downstream into a tailspill or over the previous egg deposit, and the largest particles remain to form the centrum of the new egg pocket (Chapman 1988; Kondolf et al. 1993). The concavity in the redd shape creates a pocket of low-velocity current where eggs are less likely to be swept away, and in downwelling reaches the eggs are instead forced into the substrate (Vronskiy 1972). Burner (1951) noted that in some instances the eggs are actually swept slightly upstream by reverse currents in the bottom of the egg pocket.

All salmon, by winnowing fines during redd construction, coarsen the gravel in spawning beds (McNeil and Ahnell 1964; Kondolf et al. 1993; Montgomery et al. 1996). Spawning gravel studies should therefore adjust gravel sizes to reflect the probable cleaning effect during spawning (Kondolf 2000). For chinook salmon the range of gravels used varies widely, depending in large part on availability. Although large chinook females may be capable of spawning in steep, coarse-bedded channels, they may choose to spawn in smaller gravels if those are available. In several tributaries to the Columbia River, Burner (1951) observed that chinook redds are usually larger where the gravels are small and loosely packed, since redd excavation is easier there. Chinook redds have been documented in gravels with median diameters between 16 and 69 mm, with a typical median of around 35-40 mm. However, in one study on the Vernita Bar of the Columbia

River, chinook redds typically had 100 mm cobble in the centrum and were placed in areas where flow velocities were often greater than 2 m/s (Chapman et al. 1986).

Chinook spawning areas, by virtue of their low stream gradients, also function as deposition areas for fine sediment (Platts et al. 1989). In a study of chinook spawning in Kamchatka, Vronskiy (1972) noted that approximately 95% of redd locations were in the tailouts of pools, where downwelling currents tended to force eggs into the gravel and where the adjacent pools provided holding and cover for skittish fish. Side channels were favored locations for many chinook redds, as were patches of gravel downstream from LWD obstructions (Vronskiy 1972). Vronskiy (1972) expressed concern at the paucity of eggs in many chinook redds, and surmised that the population was limited by the high proportion of eggs that were swept away in the swift currents which chinook seem to prefer.

Although chinook (and other salmonid) redds exhibit wide variation in structure, an extensive review of redd characteristics suggests that the top of the chinook egg pocket is on average at a depth of about 15 cm, and thus damage to chinook redds begins when scour depths reach 15 cm, but few redds are deeper than about 50 cm (DeVries 1997).

Chinook spawning areas are generally characterized by stream gradients of less than 2%, velocities between 30 and 110 cm/s, depths >24 cm, and gravel-cobble substrates up to about 100 mm (Burner 1951; Vronskiy 1972; Platts et al. 1989; Bjornn and Reiser 1991). A study of South Fork spring chinook spawning conditions (Schuett-Hames et al. 1988b) revealed that depths were typically between 25 and 45 cm, velocities between 0.4 and 1.1 m/s, and substrates were less than 150 mm. Extremes of chinook redd characteristics were found on the Vernita Bar of the Columbia River (Chapman et al. 1986) where spawning depths exceeded 7 m, redd areas averaged 17m^2, water velocities typically exceeded 67 cm/s, mean depth to the bottom of the egg pocket was 29 cm, and about 1/3 of each spawning gravel sample was larger than 77 mm.

Embryo survival in fine sediment

For salmon egg incubation to be successful the spawning gravel must be coarse enough to resist bedload scour, fine enough for female fish to excavate a redd, and free from the fine sediments that block alevin emergence and suffocate developing embryos (Tripp and Poulin 1986). Although there is no single measure that describes spawning gravel suitability, the most sensitive measure of egg survival is often the proportion of gravel finer than 0.85 mm (McNeil and Ahnell 1964; Tripp and Poulin 1986; Reiser and White 1988; Young et al. 1991a; Kondolf 2000). Early efforts at evaluating egg survival suggested that geometric mean diameter (d_g) is an appropriate measure of gravel quality (Shirazi and Seim 1981). Although fine sediment is responsible for suffocating eggs, the sediment sizes most responsible for blocking emergence are typically between 1 and 10 mm (Kondolf 2000).

Working in pink salmon spawning beds in Southeast Alaska, McNeil and Ahnell (1964) were among the first to demonstrate that high proportions of bed particles finer that 0.833 mm reduced gravel permeability and threatened incubation survival. Stream reaches with low volumes of fine sediments had higher spawner returns over several years, whereas reaches with higher proportions of fine sediments had repeatedly lower relative returns.

Cordone and Kelly (1961) demonstrated that the timing of fine sediment intrusion is highly important for survival—that eyed eggs and alevins are less susceptible to fine sediments than eggs undergoing the first 10-20% of the incubation period. For example, Hobbs (1937), as summarized by Cordone and Kelly (1961), found that chinook eggs were less susceptible to fine sediments than trout eggs, due to their deeper burial, and hence the eggs were at the eyed stage by the time fine sediments settled lower into the gravel. In laboratory tests the newly fertilized ova attracted and held a coating of fine sediment, and subsequently perished, while eyed ova survived the same short exposures to fine sediments, and developed alevins were able to repel suspended particles by flexing their fins and tails (Stuart 1953, cited in Cordone and Kelly 1961). The amount of

interstitial fine sediment will naturally increase over the term of the incubation period (Kondolf 2000).

Tappel and Bjornn (1983) related salmonid embryo survival to various gravel mixtures in laboratory tests and found that 93% of the variation in chinook egg to fry survival could be explained by changes in substrate composition. The most suitable size classes for predicting embryo survival were gravels less than 9.5 mm and 0.85 mm. Reiser and White (1988) showed in laboratory results that sediment less than 0.84 mm was the most detrimental to developing chinook and steelhead embryos. Kondolf (2000) reviewed several survival to emergence studies and generalized that the percentage of sediment finer than 0.833 mm was about 14% for a 50% emergence.

Tripp and Poulin (1986) reported a decrease in coho emergence with increasing sand content in laboratory incubation boxes. Survival from the eyed stage to emergence fell from 41% in a 9% sand mixture, to 16, 7, and 5% survival in mixtures containing 14, 28, and 39% sand, respectively. Scrivener and Brownlee (1989) measured coho and chum incubation success in basins with various logging treatments, and were able to show that the survival of coho was positively correlated with the d_g and the Fredle Index (*Fi*) of the lower layer of the gravel cores, but was not correlated with gravel composition in the top layer. (The d_g and Fredle index are described later in this document.) Peak flood flows also played a role. Peak flows and d_g of the lower layer of streambed cores explained 73% of the variability in coho incubation survival (Scrivener and Brownlee 1989).

Not only do fish embryos show higher survival in gravels with low concentration of fine sediments, river cobble is also one of the most productive substrates for aquatic invertebrates and macro- and microscopic organisms that form the base of the aquatic food chain (Cordone and Kelly 1961; Hawkins et al. 1983). Although sediment and embeddedness play a role, light and shade also determine the preferred habitat structure of aquatic invertebrates and macroinvertebrates alike (Hawkins et al. 1982, Hawkins et al. 1983, Murphy et al. 1981).

Effects of logging and mass wasting

The effects of mining, clearcut logging, road building, and mass wasting on downstream salmon redds has been frequently investigated, particularly in regards to the intrusion of fine sediments and the suffocation and entombment of alevins (see reviews by Cordone and Kelly 1961; Everest et al. 1987; Hicks et al. 1991). In addition to direct effects of sediment on salmon redds, Cordone and Kelly (1961) reviewed several studies that demonstrated fine sediment impacts on juvenile refuge habitat (in interstitial gravel spaces), and food supplies for salmon and trout. Coho, steelhead, and river-type chinook production are often highly dependent on the quantity and quality of overwintering habitat (Bustard and Narver 1975; Tschaplinski and Hartman 1983, Cunjak 1996). Juvenile chinook and steelhead frequently find winter refuge in the interstitial spaces between large cobbles (Edmundson et al. 1968; Hillman et al. 1987), so fine sediment intrusion can affect populations during more than the incubation life stage. Cordone and Kelly (1961) surmise that indirect damage to the fish population through destruction of the food supply, eggs or alevins, or changes in the habitat probably occur long before fish are directly harmed by high concentrations of suspended fine sediments.

Platts et al. 1989 analyzed chinook spawning gravels from Idaho's South Fork Salmon River over a twenty year period and documented extraordinary decreases in fine sediment (<4.75 mm) after a 1965 logging moratorium. Sediment delivery in the highly erodible Idaho Batholith soils increased 350% over pre-logging levels. After the moratorium fine sediments peaked at 48% of the sample volume in 1966, and then fell to 25.4% of the volume by 1985. A 25% fine sediment equilibrium appeared to have been reached by 1975.

Tripp and Poulin (1986) found that sites directly affected by mass wasting had the highest variability in gravel quality, and often had the cleanest spawning gravels (i.e. lack of fine sediments) if enough time had elapsed for the fines to be washed from the recent deposits. However, gravel samples taken further downstream of mass wasting sites

reacted differently. The streams with the highest concentrations of fine sediment were those in logged basins downstream of mass wasting sites (Tripp and Poulin 1986).

Scrivener and Brownlee (1989) examined fine sediment intrusion and incubation success under various logging treatments and concluded that suspended sediment did not increase after road construction or logging, but that pea gravel and fine sediment increased according to the proximity of various logging treatments, time span since logging, and frequency and magnitude of peak flows since logging. Forest practices that had the greatest destabilizing influence were streamside felling and yarding.

Murphy et al. (1981) examined the effects of streamside logging on primary productivity and concluded that any productivity decrease from increased sedimentation was offset by canopy opening along the streambanks. Relatively higher biomass of trout, epithelium, benthos, and drifting macroinvertebrates were observed in the logged reaches vs. the old-growth reaches.

Sampling techniques and procedures

Many habitat evaluation techniques include a visual assessment of spawning gravel, requiring the observer to estimate percentages of cobble, gravel, and fine sediment in each habitat unit (e.g. Bovee 1982). There is strong evidence that these subjective estimates are not reproducible between observers (Platts et al. 1983; Wang et al. 1996; Kondolf 2000).

McNeil and Ahnell (1964) showed a clear inverse relationship between fine sediments and permeability of spawning gravels. They developed the McNeil sampler for use in shallow water that removes a standard cylinder of potential spawning gravel and retains the silt going into suspension during collection.

In a test between freeze cores, McNeil samples, and shovels, Young et al. (1991b) found that McNeil samples most frequently approximated the true substrate composition. A

similar study by the Northwest Indian Fisheries Commission found that compared to McNeil samplers, shovels under-sampled fine sediments (Schuett-Hames et al. 1996). As substrate size increases the difference between shovel and McNeil samplers increases. Freeze cores and McNeil samplers tend to under-collect large particles in the substrate (Young et al. 1991b; Milhous 1995; Schuett-Hames et al. 1996). Milhous et al. (1995) compared freeze cores to a 46 cm diameter barrel sampler and found the freeze core samples were approximately an order of magnitude finer than the gradations determined using the barrel sampler.

Scrivener and Brownlee (1980) processed over 1000 spawning gravel samples (freeze cores) and reported that fine sediments increase with sample depth. Lotspeich and Everest (1981) suggest that spawning gravel samples should be only as deep as the average depth of egg deposition for the species in question.

Beschta and Jackson (1979) found in a laboratory flume that flushing of fine sediments from the interstitial spaces of spawning gravels will not occur unless the armor layer moves, as in large flood events.

Church et al. (1987) examined particle size distributions from the Fraser River (British Columbia) and noted that large particles were underrepresented in all but the largest bulk samples. The largest particles should therefore determine sample size, since these will be fewest in number and the least well represented. Thus the largest particle should not constitute more than 1% of the sample by weight. Such a rule poses an upper limit to practical sampling—an adequate sample of spawning gravel with the largest particles in the 130 mm range would amount to almost 300 kg. The 35 kg samples typically collected for spawning gravel studies are not considered accurate for particles greater than about 64 mm. Larger particles probably do not affect the viability of egg survival, except to place an upper limit on clasts that can be moved by a spawning female. True representative samples should be truncated before the size at which non-representative proportions appear. Truncating larger size classes necessarily raises the percentage of fine sediment in a sample, so it is imperative that the truncation level and sizes of larger particles be

reported to allow comparisons between studies (Kondolf 2000). Church et al. (1987) also noted that a lower-limit truncation of bulk samples to exclude particles finer than 8 mm resulted in median sizes that matched surface counts.

Statistical analyses on spawning gravels are more accurate and informative when data from the entire particle distribution are used, but this holds true only if the accuracy of data is high over the entire range (Young et al. 1991b; Bunte and Abt 2000). Distribution tails are prone to errors in gravel bedded rivers. Small (hand extracted) samples with a few large particles cause error at the coarse end, and error bias against fine sands (as in pebble counts) or disregard for spatial variability in fines within the sampling area (in spawning gravels) can cause uncertainty in the fine end (Bunte and Abt 2001).

Particle size distributions in gravel bedded rivers tend to resemble normal distributions when measured in logarithmic units, but resemble lognormal distributions when measured in arithmetic units. Sedimentologists and geomorphologists typically express particle size in $\log_2$ units, or the Wentworth scale. The Wentworth *psi* (ψ) units are the $\log_2$ of arithmetic measures in mm, and are the negative of *phi* (φ) units. *Phi* unit transformations produce positive values for particles smaller than 1 mm and are convenient for studies focusing on sands and silts. By contrast, the *psi* (ψ) scale produces increasingly larger values as particle sizes increase from sands to boulders, and is thus more intuitive than the *phi* scale for studies involving spawning gravels (Bunte and Abt 2001).

Particle size distributions are commonly characterized by four distribution parameters: mean, sorting, skewness, and kurtosis. The mean characterizes the central tendency of the distribution. The sorting, or standard deviation, is a measure of the dispersion, or width of the distribution. The skewness measures the degree to which the distribution is biased either to the left or right of what would be expected in a normal, or Gaussian, (bell) curve. The kurtosis is a measure of the flatness or peakedness of the distribution, which affects the proportions of gravel in the extremities, and hence the validity of many

statistical tests. A normal distribution is both assumed and required for many common statistical tests.

Many research papers have attempted to define a single statistic that serves as an index of gravel quality. Kondolf (2000) reviewed several such papers and concluded that no single statistic adequately described gravel quality, since the gravel requirements of salmonids varies with life stage. Shirazi et al. (1979) suggested using the geometric mean diameter (d_g) calculated from the d_{16} and d_{84} as an appropriate statistic since 1) similar measures are used in hydrology and engineering, 2) d_g is a more complete description of sediment sizes than percent fines, and 3) d_g relates to the permeability and porosity of gravels. In a subsequent paper Shirazi and Seim (1981) used coho and steelhead spawning gravel samples <25 mm to show clear relationships between d_g and survival to emergence. The principal drawbacks to d_g is that only two points on the distribution curve (d_{16} and d_{84}) are used to calculate d_g, such a calculation does not encompass the full spectrum of particles in a sample, and two very different samples can have the same d_g (Lotspeich and Everest 1981; Tappel and Bjornn 1983). Lotspeich and Everest (1981) suggest using all available size classes in calculating the d_g, and emphasized that use of either d_g or percent fines as the sole indicator of gravel quality could lead to erroneous prediction of egg survival. Cumulative distribution curves provide complete information on the range of sizes in a given gravel, but are unwieldy for comparing more than a few samples at a time (Kondolf 2000). Young et al. (1991a) compared several different measures of gravel quality in the laboratory and concluded that geometric mean diameter and the Fredle index accounted for the greatest proportion of variance in egg survival, but that the percentage of substrate less than 0.85 mm was the most sensitive measure of sediment change (due to land use) in the field. Several other studies have concluded that fine sediment <0.85 mm is the most sensitive statistic in predicting incubation survival (McNeil and Ahnell 1964; Tripp and Poulin 1986; Reiser and White 1988; Young et al. 1990).

Lotspeich and Everest (1981) combined a measure of central tendency (d_g) divided by a sorting coefficient to generate an index of spawning gravel quality they called the Fredle

Index (*Fi*). The sorting coefficient (S_o) is calculated as the $(d_{75}/d_{25})^{½}$ -- where d_x is the diameter of the *x* percentile of the sample-- and indicates a measure of pore space between particles in the sample. A perfectly sorted gravel with only one particle size will have a sorting coefficient of 1 and an *Fi* equal to the d_g. A sorting coefficient greater than 1 implies that pores between large grains are filled with smaller grains, hence S_o is inversely proportional to permeability. Thus the Fredle index is a measure of both pore size and relative permeability, both of which increase as the index becomes larger. Lotspeich and Everest (1981), using the data of Phillips et al. (1975), related the Fredle index to the survival to emergence of coho and steelhead based on the particle size distributions in spawning gravels from California rivers.

Intrusion processes

In a flume study of the intrusion of fine sediments, Beschta and Jackson (1979) noted that the streamflow velocity and depth (Froude number) strongly influenced the depth and rate of formation of a sand "seal" near the surface of the streambed surface. Higher water velocities (and hence higher Froude numbers) disturbed the bed slightly and the sand seal formed deeper and more quickly than at lower Froude numbers. Finer sands penetrated the bed deeper and more thoroughly than coarser sands (Beschta and Jackson 1979). After the sand seal had formed the fine sediment supply was curtailed to assess flushing from the gravels. Sands were flushed from the top 1 cm of gravel but no further, suggesting that bedload movements are necessary to cleanse spawning gravels of fine sediments (Beschta and Jackson 1979).

Scrivener and Brownlee (1980) used freeze cores to analyze spawning gravels and found that fine sediments (< 9.5 mm) increased with depth, although other studies have noted that the insertion of freeze cores can drive fine sediments to the bottom of the sample (Beschta and Jackson 1979). Nevertheless, post-logging accumulations of fines less than 9.5 mm increased in the top gravel later after the first major freshet (Scrivener and Brownlee 1980).

METHODS

Due to the nature of this study, the methods section has been split into separate discussions of techniques used to collect the spawning gravel data and those used to collect the scour data. These are preceded by a discussion of the general study area and by specific study site descriptions. Description of data reduction and analysis methods complete the section.

Study Area

The Nooksack River originates on the glaciated flanks of Mount Baker and the Sisters Peaks near the Canadian border in Whatcom County, and ultimately flows into Puget Sound near the city of Bellingham, Washington. At 786 square miles the Nooksack is the fourth largest watershed in Puget Sound and shares many characteristics typical of west-Cascade river systems. It is home to all of the anadromous salmon and trout species native to the Pacific Northwest, specifically: spring/summer and fall chinook *(Oncorhynchus tshawytscha)*, summer and winter run steelhead (*O. mykiss*), coho (*O kisutch*), chum *(O. keta)*, pink *(O. gorbuscha)*, sockeye (*O. nerka*), cutthroat (*O. clarki*), bull trout (*Salvelinus confluentus*) and Dolly Varden (*S. malma*). All stocks in the Nooksack basin have substantially declined from historical abundances, and habitat loss and degradation have been cited as primary factors in the decline (Nehlsen et al. 1991). Fish hatcheries in place since 1899 on the North Fork and 1969 on the South Fork have not fulfilled the promise of sustainable harvest, due in part to the complications of managing a mixed-stock fishery.

Habitat problems affecting anadromous salmonids in the basin are extensive. Over the past 140 years, the floodplain reaches of the Nooksack River have been cleared of timber, ditched, and drained, while both mainstem and tributary channels have been dredged and cleared of debris (Sedell and Luchessa 1982; Collins and Sheikh 2003). Dikes and levees have both confined and simplified the mainstem channel, resulting in decreased floodplain connectivity, reduced habitat complexity, and elimination of many sloughs and

side channels which provided important flood refuge and juvenile rearing habitat (Crown Pacific Ltd. 1999, Collins and Sheikh 2003). Levees and riprap have also resulted in a straighter, shorter mainstem channel with diminished flood storage capacity and increased velocities and sediment transport capacity, compromising the stability of suitable spawning gravels. Present mainstem habitat functions primarily as a conduit for outmigrating smolts and inmigrant adults, especially in the lower reaches.

Scour Site Selection

The strategy for selecting scour sites in 2001 and 2002 was to install scour chains in a manner that would reflect the location and density of chinook salmon redds. Spawner survey databases, GIS coverages, and interviews with spawner survey personnel were used to select appropriate reaches for study sites. First, spawner databases were queried for highest densities of chinook redds between August 1st and September 31st over the most recent ten years (1990-2000). The sites were then ranked by density and examined in the field. Spawner survey personnel from WDFW, the Lummi Tribe (LNR), and Nooksack Tribe (NNR) were questioned about these and other high-density sites. Sites where heavy spawning densities had dropped off in recent years due to habitat changes (such as debris flows or channel avulsions) were eliminated from consideration, as were sites with no practical or legal access (e.g. Middle Fork Nooksack mainstem). Field suitability determined final selection. Site locations are depicted in Figure 1.

Scour study site criteria focused on substrate composition, water depth and velocity, and access. Once a site had been selected, scour chains were arranged in transects orthogonal to flow, so spawning conditions had to be met for all or most of the wetted channel width. Many sites with known chinook spawning were examined and bypassed due to substrate sizes and water velocities where installing and accurately monitoring scour chains would be impossible. Substrates greater than 150 mm, depths greater than 0.6 m, and velocities greater than 0.6 m/s were avoided for safety and practicality, even though those conditions have been observed in chinook spawning areas (Chapman et al 1986, Kondolf

and Wolman 1993). In 2001 spawning gravel and scour sites were chosen according to different selection protocols. In 2002 the study sites were combined.

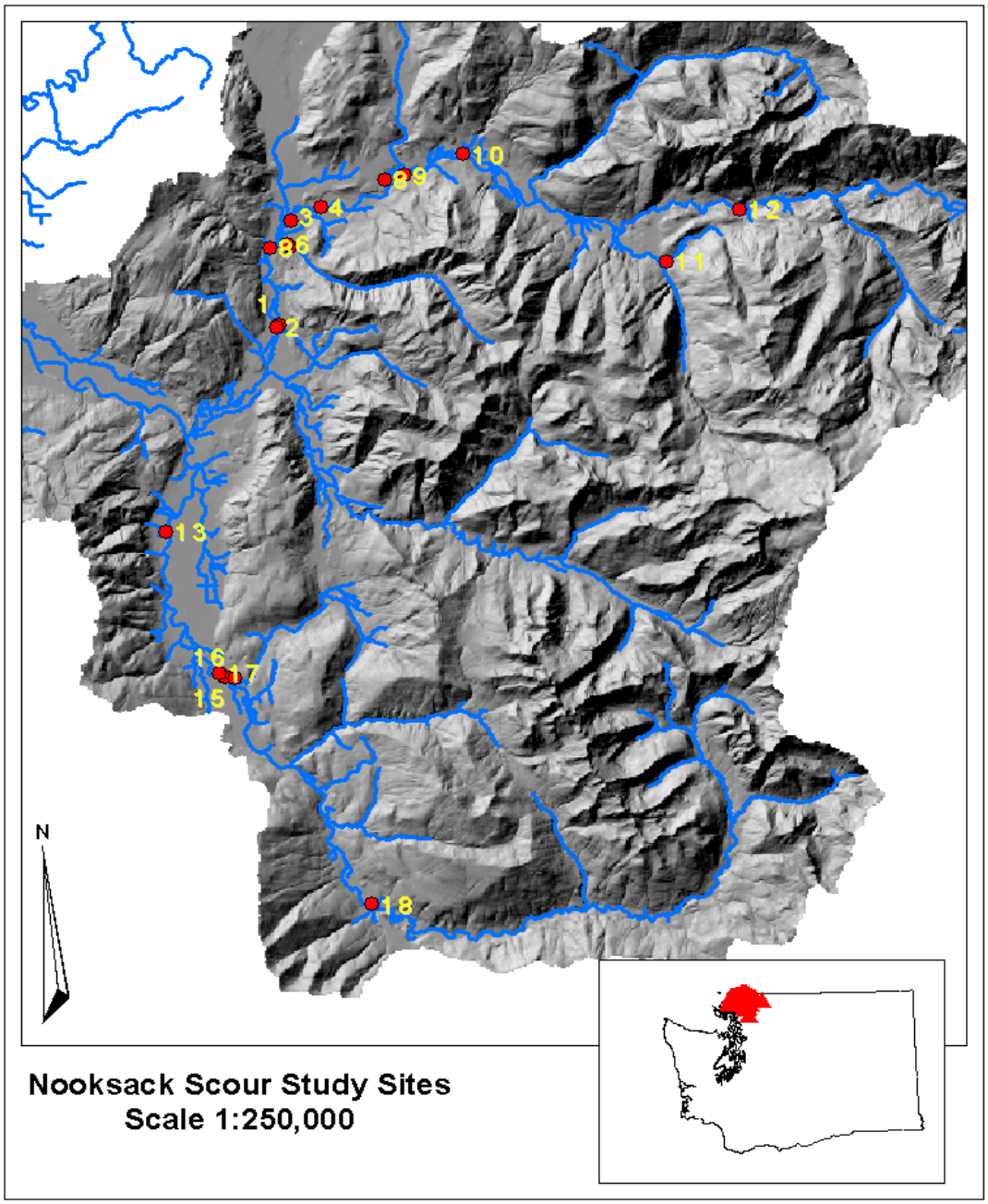

Figure 1. Scour study sites. Numbered sites are keyed to text descriptions below.

In 2001-02 it was noticed midway through the flood year that scour was occurring differently in certain sites according to habitat type. In 2002 sites were chosen specifically to elucidate these differences. Habitats were classified into mainstems, braids, back channels, sloughs, and tributaries. Mainstem sites were those on the North and South forks of the Nooksack, in channels that carried >40% of the discharge through that reach. Braids were adjacent to the mainstems and carried <40% of the reach flow, and were separated from the mainstem by low, vacant, cobble bars. Back channels were often similar to braids in flow depth, width, and volume, but were separated from the mainstem by bars with persistent woody vegetation >7-10 years old. Sloughs were similar to back channels except they were blocked at the upstream end except during flood events, (i.e. a high flow channel connected the slough at the upstream end but the slough was directly connected to the mainstem at the downstream end). Tributary sites were those not on the mainstems, but in all cases were within one kilometer from a tributary-mainstem confluence.

Descriptions of individual study sites follow. Headings include the site number referenced in Figure 1, the site name, the water-years the study sites were actively monitored (water years begin on October 1 and end on September 30), and the habitat types that were represented there. Cross-section plots of each site are in Appendix A.

1) North Fork Nooksack Slough (2002-03; slough). The North Fork slough is a former mainstem reach that has been blocked off at the upstream end by an avulsion of river cobble, and continues to receive ample flow from sub-surface (hyporheic) sources and backwatering during flood events. It is located adjacent to the North Fork Nooksack near river mile (RM) 42.2, on the left bank, above the Kenny Creek confluence and immediately upstream of the North Fork Road lookout. Chinook spawning is known to occur in the slough, but chum often supersede the chinook due to redd superimposition. Four transects were established at the site in early May 2002, and spawning gravel samples were collected at each transect in early July. TR1 is at the very bottom of the slough with 4 scour chains and an average d_{50} of 43 mm. TR2 is also towards the downstream end of the slough with 3 scour chains and a d_{50} of 41 mm. TR3 is in a pool

near the top of the slough and has three chains and a d_{50} of 28 mm. TR4 is on the riffle flowing into the pool and has a d_{50} of 52 mm. Substrate in the slough was formerly mainstem river cobble, although fine sediments are deposited in the slough during flood events. Mainstem river flow through the old channel upstream from the slough occurs rarely, during high-flow events. Apparently no flood event in 2002-03 was high enough to inundate the upper channel.

2) North Fork Braid (2002-03; braid). The North Fork Braid site was established in October 2002 after spring chinook had vacated the area. The site is adjacent to the North Fork at about RM 42.2, and is between the North Fork mainstem and the North Fork slough. Each of the two transects at the site has three scour chains. TR1 has a d_{50} of 48 mm and a gradient of 0.004. TR2 has a d_{50} of 42 mm and a gradient of 0.0004. The North Fork braid was observed to fluctuate in the proportion of flow that it carried during the winter of 2001-02. It started the season as a high-flow (dry) channel, but during the middle of the season it carried almost 30 percent of the North Fork discharge. Later in the spring a minor gravel avulsion caused the channel to revert to high-flow only transport. In the fall of 2002 the channel functioned as a braid, carrying a shallow flow when the North Fork was at moderate discharge. The channel was shallowly inundated during spawning season, and redd building could have occurred there, but only chum were observed to spawn and no redds were located in the vicinity of the scour chains. Early in the spring of 2003 the left bank at TR1 was eroded approximately 4 meters, the left bank hub was lost, the channel bed aggraded by more than 40 cm, and the channel reverted to carrying high flows only. Redds at the North Fork braid were considered destroyed.

3) Kendall Hatchery (2001-02; mainstem and braid). The Hatchery site consists of a nine-chain mainstem transect (TR1) and two braid transects (three chains on TR2 and five chains on TR4; TR3 was not installed). All transects were established in early October 2001. Bankfull width in the reach varies both spatially and temporally, but widened from 90 to 107 meters at TR1 due to cutting on the left bank (the right bank is reinforced with rip-rap to protect the hatchery). Median surface particles sizes are 55 mm on TR1 and 34 mm on both of the side channel transects. Mainstem (TR1) scour chain

installation was difficult due to large substrates and swift water. Channel depths at TR1 were only on the order of 10-20 cm at time of channel installation but increased to 0.9 m during moderate mid-winter flows. Extensive chinook spawning occurs in the reach due to hatchery straying. Channel shifting in both the side channel and mainstem is frequent and severe. Scour chains at TR2 were buried by nearly 0.5 m of fill in January 2002 and were considered destroyed.

4) Farmhouse Reach (2002-03; mainstem, back channel, braid). The Farmhouse Reach is located on the North Fork Nooksack above the Kendall fish hatchery, about 2300 m upstream of the 2001 Hatchery site and 900 m upstream of a USU instream flow intensive study site. The site was first established in April 2002 with one mainstem transect, two transects on a right bank braid/back channel, and two transects on a left bank back channel. A minor flood in late May 2002 destroyed the mainstem site and blocked water from entering the left bank back channel. Two new transects were established on the Bear Creek side channel in September 2002 to replace the dried up back channel site. Local gradients at study transects vary between 0.003 and 0.008, and d_{50} varies between 48 and 76 mm. The reach is noted for both heavy chinook spawning, due in part to its proximity to the Kendall hatchery, and high-frequency channel shifting. Channels in the Farmhouse Reach have been observed to shift multiple times during the same flood season. For example, a minor avulsion in February 2002 shifted approximately 40% of the Nooksack discharge into the adjacent Bear Creek side channel. By May 2002 the discharge had been shifted back to the mainstem, but a half-meter of cobble was deposited in the upper Bear Creek side channel in the interim. The right-bank braid/back channel was subjected to similar fluctuations. Although the mainstem scour chains (TR1) were destroyed early in the summer and were not re-established, the channel was observed to fluctuate around the TR1 vicinity over several minor floods that exceeded the 8000 cfs flood that destroyed the transect. With such volatile shifting it was clear that if the transect had been re-established and monitored that it would have been destroyed again during the incubation season, and therefore the redds represented by the chains would have been destroyed. The June 2002 destruction was therefore identified as

a “redd failure” for 8 mainstem chains, even though the actual event took place prior to spawning.

5) Racehorse Creek Upstream (2001-03; tributary). The upstream Racehorse Creek site was established in September 2001 with six chains in a single transect across a short glide. This tributary site is located at about RM 5.1 in a forested area frequented by fishermen and biologists. McNeil samples were collected in the same reach by LNR in the mid-1980s. Racehorse Creek is known as an important chinook spawning stream, although no chinook spawning was observed there in fall 2002 due to low flows. The USGS operates a continuous stream gauge at the North Fork Road bridge, approximately 0.5 miles upstream from the scour transect. A peak flow monitor was installed in November 2001 at the transect. Mean surface particle diameter at the site was 39 mm on both the 2001 and 2002 pebble counts. Low-flow channel depths vary from 0.1 to 0.6 m. The channel is not wadable at high flows. Bankfull channel width increased from 14 to 16 m during the 2001-02 flood season as the channel shifted and deepened into the right bank. The transect was re-established in June 2002 and expanded to eight scour chains—the two additional chains occupying new wetted area near the shifted right bank. A new peak monitor was installed on the left bank for the 2002-03 flood season.

6) Racehorse Creek Downstream (2001-03; tributary). The downstream Racehorse site shares many features with the upstream site, and both sites were established and monitored during the same site visits. The downstream Racehorse transect is contiguous with a USU instream flow rapid assessment site. The transect was initially established in September 2001 with five scour chains at a 2-meter interval. Bankfull width at the transect is 17 m and average low-flow depth is approximately 0.2 m. Surface particle size averages 40-44 mm. A peak flow monitor was installed in November 2001, but was repeatedly disturbed in the first flood season by high flows and accumulating debris. During the first fall storms in 2001 the channel accumulated significant small woody debris and sand on the left bank and scoured slightly on the right bank. The transects was re-established in June 2002 with an additional (sixth) scour chain near the right bank.

7) Coal Creek Slough (2002-03; slough). The Coal Creek site was established in late September 2002 to assure adequate sample size and variability in slough habitats. The channel was thoroughly examined prior to chain installation to locate existing redds (several were observed) and transects were placed to avoid any conflict with spawning fish. Two transects have 3 scour chains each. TR1 was located approximately 50 m upstream of the confluence with the North Fork, and TR2 was installed 50 m upstream of TR1. Surface d_{50} in TR1 and TR2 is 44 mm and 21 mm respectively, although both transects had particles >100 mm in surface and subsurface samples. Spawning gravel samples were collected at each transect in early October. The Coal Creek site, like Boyd Creek and other sites, has characteristics that could be interpreted as either slough, back channel, or tributary habitat, depending on the exact location. The channel bed was formerly a mainstem bed, but currently the mainstem has shifted away and an extensive vegetated bar separates it from lower Coal Creek. A high flow channel upstream of the slough is inundated during floods, and isolated pools in the high flow channel had juvenile salmonids emerging in spring 2002. Although flood flows from the mainstem inundate the lower Coal Creek reach, both from upstream via the high flow channel and downstream from a backwater effect off the mainstem, the medium and low flows in the slough are from Coal Creek tributary. Due to the high-flow inundation and a substrate from the former mainstem, Coal Creek was classified as slough habitat and analyzed accordingly.

8) Maple Creek (2002-03; tributary). The Maple Creek site encompasses three transects between 250 and 450 m upstream of the confluence with the North Fork Nooksack, and coincides with a USU instream flow study site. The study area is generally open pasture, but both banks have had the riparian zone planted. The right bank is privately owned and the left bank was recently purchased by WSDOT for restoration and enhancement. In 2002 the reach was heavily used for both chinook and chum spawning. Three scour transects were established and surveyed in early June 2002. TR1 was initially established with four scour chains and had a d_{50} of 19 mm. TR2 had 3 chains and a d_{50} of 23 mm. TR3 had 3 chains and a d_{50} of 19 mm. Local water surface slopes range between 0.003 and 0.005. Bankfull widths average about 5 m. Spawning gravel

samples were collected at each transect in mid-July 2002. All chains on TR1 were tampered in late November 2002 and the transect was re-established in mid-December, after which little scour was recorded.

9) Teepee/Cromwells (2001-02; mainstem and back channel). The Teepee site is located on the North Fork mainstem at RM 50.4, approximately 500 m above Maple Creek. The site name was due to a temporary shelter erected there in winter 2001. The site consists of one mainstem transect and four back channel transects. The back channel flows along the left bank and is accessed from the North Fork Road, while the mainstem flows along the right bank and is accessed from the Mount Baker Highway (State Route 542). The mainstem is wadable only at low flows (less than 400 cfs). The mainstem transect (TR1) has 12 scour chains and was established in early October 2001. Bankfull width at TR1, not including the mid-channel island, is 45 m, and depths at low flow exceed 0.6 m. Median surface particle size along TR1 is 55 mm. The mainstem channel was laterally stable over the 2001-02 flood season but vertical mobility (bed movement) was high and all scour chains were eventually lost. The first two back channel transects TR2 (3 chains) and TR3 (4 chains) were established the same week as the mainstem transect. The second two back channel transects were established later when changes at the site and opportunity dictated. The site was discontinued for the 2002-03 season due to access uncertainty.

10) Boulder Creek Side Channel (2001-02; braid). The Boulder Creek study site is located on the North Fork Nooksack mainstem at approximately river mile 52.3, in a right bank side channel where all flow is from Boulder Creek (except during floods). Water depths in the side channel during low-flow are approximately 30 cm. Water surface slope at the transects is 0.005. Side channel widths vary between 10 m and 14 m. Bankfull channel width of the mainstem has increased from 130 m to 160 m over the recent past due to the mainstem capturing the side channel and eroding the right bank. Average surface particle diameter is 20 mm at TR1 and 27 mm at TR2. The Boulder Creek side channel is heavily used by returning chinook, chum, and pink salmon, as is the lower half-mile of Boulder Creek itself. Two scour chain transects were installed in the side

channel in October 2001. The downstream transect (TR2) had five chains at one and two meter intervals, the upstream transect (TR1) had four chains at irregular spacing that followed bedform variations. The entire site was resurveyed twice following floods but was entirely destroyed by channel shifting during a flood on January 7, 2002.

11) Thompson Creek (2002-03; tributary). Thompson Creek is widely recognized as one of the most prolific pink salmon streams in all of Puget Sound. Chinook salmon spawning was observed there in September 2001. The lowest 1 kilometer of Thompson Creek has been modified by placement of artificial instream log structures, most of which are high flow deflectors at the bankfull level. Two scour transects were established in June 2002 with 5 scour chains each on a 1 m interval. Bankfull stream width at the transects is about 7.5 m, and steep valley sidewalls are about 25 m apart. Dimensionless water surface slope through the study reach is 0.02. Spawning gravel samples were collected at each transect in July 2002. Surface d_{50} was 42 mm and 41 mm at TR1 and TR2, respectively.

12) Boyd Creek (2001-03; back channel, mainstem, and tributary). The Boyd Creek site was sampled for gravel composition in 2001, in the vicinity of what was later established as scour transect TR2. Scour chains were installed on four transects in the Boyd Creek vicinity in early June 2002. TR1 was installed on the mainstem approximately 200 m downstream of the confluence with the Boyd Creek side channel. It was destroyed in late summer 2002 by construction of instream logjams, and was re-established in late September. TR2 was composed of three back channel scour chains approximately 75 m upstream of the confluence with the mainstem. TR4 was also on the back channel, also had three scour chains, and was placed approximately 30 m upstream of the confluence with Boyd Creek (tributary). TR4 was on the Boyd Creek tributary about 20 m upstream of the confluence with the side channel, and had three chains. Chinook spawning was noted in both the mainstem and back channel in early September 2002. Releases of scour chain wiffle balls at TR2 and TR3 were attributed to redd building. Coho spawning was noted in the tributary in late fall. An avulsion on the upstream end of the back channel, as a result of LWD placement the previous summer,

essentially dried up the upper half of the back channel after a flood in mid-December 2002. Flow into TR3 was henceforth due to hyporheic (i.e. shallow subsurface) seepage into the surface channel, except at flood stage. Flow at TR4 was unaffected, and TR2 continued to benefit from the Boyd Creek tributary. Bulk spawning gravel samples, surface counts, and pebble counts were collected at each transect in mid-July 2002, except for the mainstem TR1, which was sampled in late September.

13) Sygitowicz Creek (2002-03; tributary). The Sygitowicz site encompasses three transects, starting at 60 m and ending approximately 300 m upstream from the confluence with the South Fork Nooksack. The area is privately owned and the riparian zone has been recently planted to widen its extent. Gradient through the study reach averages 0.02. Bankfull width averages 5-7 meters, although a history of debris flows has created natural levees approximately 10-15 m apart. Substrate is dominated by angular sandstone, which contributes ample fine sediment to the spawning gravels. All three transects were installed in early June and spawning gravel samples were collected at each transect in mid-July 2002. TR1 has 3 scour chains and a d_{50} of 65 mm. TR2 has three scour chains and a d_{50} of 70 mm. TR3 has four scour chains and a d_{50} of 52 mm. The creek is documented as supporting chinook salmon, although supporting evidence is scanty. Due to the coarse substrate, relatively steep gradient, and low watershed area, Sygitowicz Creek often runs sub-surface in the low-flow summer months.

14) South Fork Nooksack at Hutchinson confluence (2001-03; mainstem). The South Fork mainstem site is at RM 10.1, at the confluence with Hutchinson Creek. Two other scour sites are in the vicinity. The South Fork braid site is downstream approximately 300 m along the left bank of the mainstem, and the lower Hutchinson Creek site is 75 m upstream on Hutchinson Creek. The South Fork mainstem site consists of 12 chains on one transect, and was first established in late October 2001. Bankfull width at the transect has been stable at 68 m. Low-flow depths average 20 cm but max low-flow depth is 60 cm, and the transect is not wadable at moderate flows (>500 cfs). Monitoring of the South Fork scour chains was difficult due to the turbidity of flow for much of each year. Many of the South Fork chains were not recoverable after the winter of 2001-02, due to

scour, burial, and tampering. A second South Fork(b) transect was established in July 2003, but was heavily tampered by recreational river users, and had to be re-established in late September in preparation for the winter 2002-03 flood season. The South Fork b transect was located 5 m downstream from the first (a) transect, and scour chains were positioned at approximately the same stations (5 m interval) as the first transect. Widths and depths of the two transects were similar, but median particle size diameter increased from 27 mm at TR1a to 38 mm at TR1b.

15) Lower Hutchinson Creek (2001-03; tributary). The lower Hutchinson site is comprised of a single transect located approximately 75 m upstream of the confluence with the South Fork Nooksack. The site is contiguous with an instream flow study site established by Utah State University (USU). Three scour chains were initially installed in September 2001. After two chains were tampered the transect was expanded in November to four chains at a 2 meter interval. Bankfull width is 13 m and average low-flow depth is 30 cm. Gradient varies between 0.003 and 0.001 depending on flow and backwater effects from the South Fork. A flood peak monitor was added in late November 2001. The site was completely re-established in July 2002 in preparation for the 2002-03 flood season. Average surface particle diameter is 21 mm. Due to the small and loose spawning gravel it was expected that significant scour would occur at this site, but during the first flood it was discovered that water from the South Fork backed up into Hutchinson Creek, lowering water velocities despite increased depth. Only slight channel shifting was recorded at this site.

16) Upper Hutchinson Creek (2002-03; tributary). The upper Hutchinson Creek site is located just downstream of the old farm bridge crossing, approximately 500 m upstream from the confluence with the South Fork mainstem. Three transects were established in mid April 2002: TR1 with 4 chains has a d_{50} of 27 mm; TR2 with 3 chains has a d_{50} of 17 mm; and TR3 with 4 chains has a d_{50} of 20 mm. Local water surface slope varies within the reach, but reach gradient encompassing all three transects is approximately 0.004. Chinook, coho, chum, and steelhead redds have been observed in the reach. Spawning gravel samples (both barrel and McNeil) were collected in early July 2002, and Lummi

Natural Resources personnel collected McNeil samples in the same reach in the mid-1980s. The site is coincident with a USU rapid assessment site for instream flows.

17) South Fork Braid (2002-03; braid). Like the North Fork braid, the South Fork braid was added in October 2002 to boost sample size for scour chains in braided habitats. The South Fork braid is located near the left bank of the South Fork downstream of the confluence with Hutchinson Creek. The Acme Farm riparian restoration site is located nearby on the right bank. The upper of two transects (TR2) is in part of the channel with substantial LWD on both banks. The lower transect (TR1) is downstream in a frequently shifting cobble bar area more indicative of a true braided channel. TR1 and TR2 median particle diameters are 48 mm and 39 mm, respectively. Reach gradient encompassing both transects is 0.004. The South Fork threatened over most of the winter to shift towards the left bank and subsume TR1, but did not capture the channel by the end of the incubation season. Disturbance at the TR2 transect has apparently been minimal over the recent past.

18) South Fork Nooksack at Larson Bridge (2002-03; mainstem, back channel, and tributary). The Larson's Bridge site encompasses five transects established in late July and early August 2002. The mainstem transect (TR1) is approximately 1800 m downstream of Larson's Bridge and contains 7 chains on a 5 m interval. Surface d_{50} is about 52 mm. The flood-prone channel at this location is wider than a single 100 m surveying tape, so a wooden hub was driven into the cobble near the left wetted edge, and it was this hub that was used for most channel surveying. The temporary mid-channel hub is 58.95 m along the transect from a more permanent hub placed higher on the left bank, and can be easily replaced when damaged by floods. TR2 is near the lower end of the Larson's right bank back channel, and contains three chains. Surface d_{50} is 34 mm. The mainstem South Fork at this location until 1990, and the chains are now in the vicinity of what was formerly referred to as "tether hole" in LNR field notes from the 1980s. TR3 is approximately 18 m upstream of TR2, contains two scour chains, and has a d_{50} of 48 mm. Water surface slope in the vicinity of TR2 and TR3 is 0.003. Spawning by chum and coho is common in the reach, and sockeye were observed spawning in the

reach in late October 2002. TR4 is on a small right bank tributary that enters the side channel approximately 200 m upstream of TR3. Three chains were installed in August 2002, all of which were later disturbed by spawning coho. Surface d_{50} is 42 mm. TR5 is located at the far upstream end of the Larson's right bank side channel, between the right valley wall and the most upstream constructed LWD jam, approximately 100 m downstream of Larson's Bridge. Five scour chains were installed in early August 2002. Surface d_{50} is 78 mm, owing in large part to the proximity with the South Fork mainstem. Water surface slope at low and medium flow is 0.001. TR5 is coincident with an LNR survey transect spanning the entire active channel.

Scour Chain Installation and Monitoring

Study sites were selected according to chinook spawning density locations as described above. At each study site transects were located to afford the best indication of redd survival. Transects were positioned orthogonal to the flow in areas where substrate, depth, and velocity were suitable for chinook spawning (Chapman 1998, Kondolf and Wolman 1993). The 2001 transects were installed in late September through October to avoid spring chinook spawning in August and early September, but every effort was made to minimize disturbance to existing redds or to fall chinook and other species. Areas of redd building were identified before entering the stream and all crew members were informed of redd locations. A fiberglass surveyors tape was strung between wooden stakes (2" x 2" hubs) on opposite banks to identify the transect location. When in the stream all crew members were restricted to a corridor within 1 m of the tape to minimize disturbance to any undetected redds. In 2002 almost all of the transects were established in June and July, before spring chinook commenced spawning, so restrictions on movement were not necessary when scour chains were being installed. No instream activity was pursued between mid-July and mid-September in 2002, to avoid disturbance to spawning spring chinook. All monitoring, surveying, and other activity after mid-September 2002 was restricted to the 1-m corridor along the transect. In cases where spawning fish placed redds over scour chains these areas were noted, all crew members

made aware, and those chains were avoided where they could not be measured without disturbance to the redd.

Chains were installed in the stream bed along the transects according to standard methods (Schuett-Hames et al. 1999a). The procedure used a three-part scour chain inserter and scour chains constructed of galvanized ¼" steel cable with 10 practice "wiffle" golf balls (Figure 2a). Field personnel pounded the three part chain inserter into the stream bed (Figure 2b) and removed the inner two driving pieces of the inserter. Next the scour chain was inserted into the hollow pipe buried vertically in the substrate (Figure 2c). Then the scour chain was held in place with a thin aluminum or bamboo rod while the outer sleeve of the inserter was extracted, leaving the scour chain in place, vertically buried in the stream bed (Figure 2d).

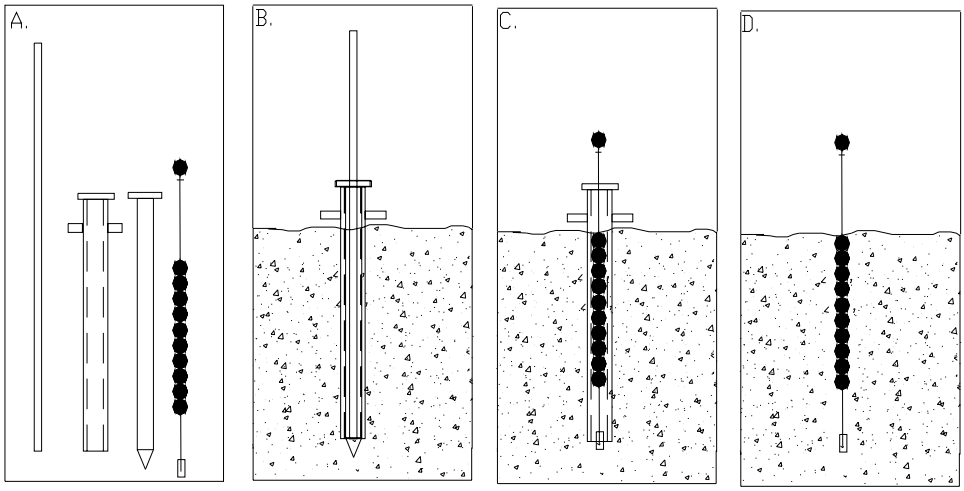

Figure 2. Procedure for installing scour chains. Panel A shows the three-part scour chain inserter and a scour chain. Panel B is the scour chain inserter after being pounded into the stream bed. Panel C shows the two inner parts of the inserter removed and a scour chain inserted. Panel D shows the scour chain in the stream bed after the inserter has been removed.

Chains were positioned at the thalweg of the stream and at regular intervals along the wetted channel, and positions noted on the transect tape. In 2001 some chains were positioned above the wetted channel and at irregular positions along the transect in order

to generate data on scour as a function of flood depth, but in 2002 this practice was discontinued. In large substrates where forcing the scour chain inserter into the stream bed was more difficult the lower anchor on the scour chain was sometimes shortened to lessen the total scour chain depth. The top of each scour chain was positioned close to the bed surface to record shallow bedload movement but deep enough to prevent premature release of a ball. In fine or medium substrate the top scour chain ball was adjusted upward to within 10 cm of the bed surface, but in large substrates the depth was greater due to greater cobble porosity, higher water velocities, and a greater tendency for the current to capture a scour ball prematurely.

Channel cross-sections were measured at each scour chain transect using standard leveling procedures (Moffitt and Bouchard 1992; Harrelson et al. 1994). At least two local reference benchmarks were positioned on the streambanks, above the floodway where they would not be damaged. Using a 32x surveyors level (Berger CST M22818) and a metric stadia rod, a level loop was conducted which encompassed all benchmarks and hubs at a site. After accurate vertical positions and proper autolevel operation had been verified the transects were surveyed (Figure 3).

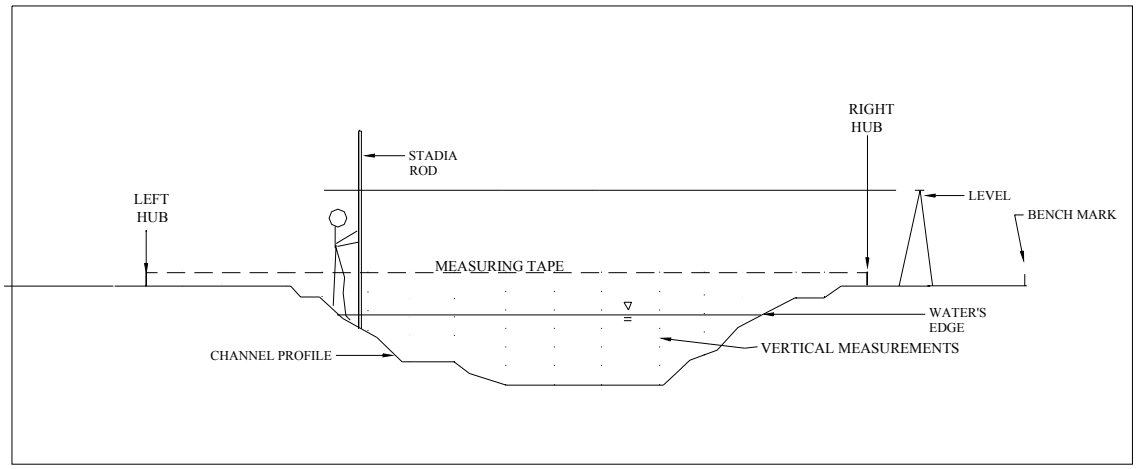

Figure 3. Surveying channel cross-sectional transects with a autolevel and stadia rod.

All transects were established with Station 0 at the left bank (looking downstream) hub. Ground elevations were measured on channel banks at all breaks in slope and on other

features (e.g. large logs) that would have an effect on the hydraulics at the cross-section. The edge of vegetation, bankfull indicators, and other hydraulic influences were noted in the field books. Left and right water surface elevations were measured and verified to be within 2 cm, except where turbulence or local influence created a difference in cross-channel water elevation. Survey point spacing across the channel was determined by channel width, topographical variation, and spacing between scour chains, but generally did not exceed 2.5 meters between points.

At each scour chain several measurements were taken simultaneously. A metric stadia rod was fitted with a 12.7 cm (5 inch) diameter aluminum disc at the base to minimize variation in bed elevation readings on large and medium cobble (DeVries and Goold 1999). A 2.5 cm notch was cut in the base plate to accommodate a gravel depth measuring pipe (Figure 4). The gravel depth pipe was cut from 2 cm diameter (3/4 inch) schedule 40 PVC plumbing material with a 5 mm gap cut lengthwise and 0.5 cm notches marked at intervals up to 20 cm. At each scour chain the gravel depth pipe was fit around the exposed cable and then forced with a twisting motion into the gravel until it was firmly seated on the top wiffle ball on the scour chain. The notch on the stadia rod base was then fit around the gravel depth pipe so that the bed elevation (measured with the autolevel) and the depth to the top ball (measured with the gravel pipe) were measured relative to the same datum on the stream bed. Early scour chain measurements in 2001 noted discrepancies-- sometimes exceeding 10 cm-- in the location of the top ball. These discrepancies varied according to the size of the substrate and the relative positions of the stadia rod and the ruler that were used to measure chain depth. The gravel measuring pipe reduced these discrepancies to generally less than 2 cm.

Figure 4. Simultaneous field measurement of gravel depth, channel bed, and washer height from the same datum. Stadia rod is modified with an aluminum disk to minimize variance in bed topography on cobbles. Gravel depth pipe is fitted around scour chain cable and seated on the (buried) top scour chain wiffle ball, and depth to the top ball measured relative to the aluminum plate. Bed elevation is measured with an autolevel and all vertical measurements are tied to the site benchmark.

During the 2002-03 flood season a further refinement was added. At each scour chain two measurements were taken to relate the bed elevation to the elevation of the washer at the exposed end of the scour chain (Figure 5). While the stadia rod was positioned over the scour chain with the gravel depth pipe inserted into the bed, the length of exposed scour chain was measured against the stadia rod (washer height). This measure gave a distance from the washer at the end of the chain to the stream bed surface. The stadia rod was then lifted and the scour chain washer was fit into the base plate notch, and the elevation of the washer measured with the autolevel (washer foresight).

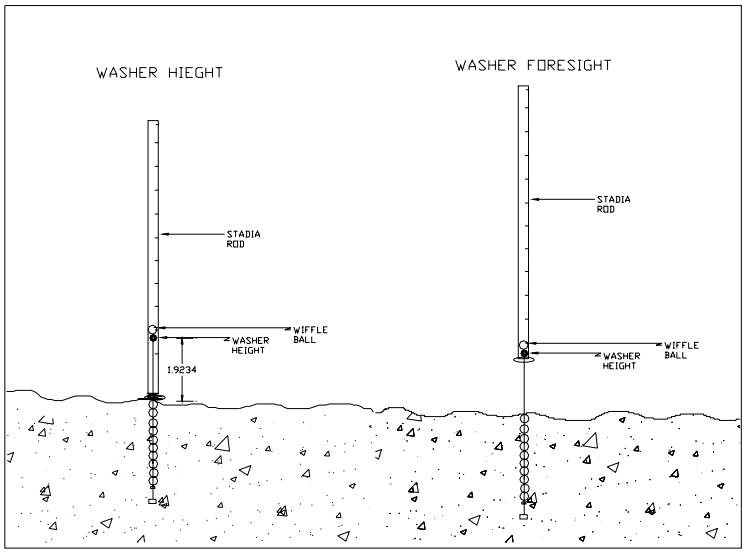

Figure 5. Measuring washer height and washer foresight with a stadia rod and autolevel. Documenting the distance between the top of the scour chain and the initial bed elevation allowed a quick assessment of bed aggradation. This, combined with the number of escaped wiffle balls, documented the scour and fill at a scour chain without the necessity of an autolevel or two-person crew. Significant bed changes were measured with the autolevel on subsequent site visits.

Knowing the two washer measurements allowed a quick assessment of scour and fill without using a two-person crew or autolevel. On intermediate field visits the exposed length of scour chain cable (washer height) and the number of escaped balls was noted for each chain. Subtracting the number of escaped balls (multiplied by 4 cm each) from the original top ball, and further subtracting the initial gravel depth (overburden) over the top ball gave a depth of scour from the bed elevation during the spawning season. Subtracting washer height from washer elevation gave a reading of bed elevation, which was used to measure aggradation or fill over each chain. Thus the scour and fill at each chain could be assessed quickly, and all 169 scour chains could be measured in two or three days, depending on weather, flows, and access. By contrast a full re-survey of each chain using the autolevel required approximately 7-10 working days. By using the washer measurements it was possible to monitor scour and fill between successive floods, which was not always possible during the 2001-02 season. A further advantage was that it was possible to determine if a scour chain had been tampered. If the washer elevation did not change over the flood season it was assumed that all exposed balls were a result of bed

scour or spawning activity, instead of the chain being pulled by curious fishermen, rafters, and local residents. Any washer height that changed more than 2 cm over the incubation season was assumed to have been tampered, and scour calculations were adjusted accordingly.

Monitoring surveys were conducted on all chains after each significant flood, as soon afterward as river conditions permitted. Significant floods were those that reached 5000 cfs or greater on the North Fork at Glacier (USGS 12205000) or the South Fork at Wickersham (USGS 12209000) gauges. Monitoring commenced on the smallest tributaries and proceeded to larger channels as flows dissipated. After all chains at all sites were measured the transects with significant bed changes would be fully re-surveyed on a return visit with an autolevel. Chains buried by redd building activity were left undisturbed until the end of the incubation season. In isolated cases chains that were tampered were replaced and fully re-surveyed, with appropriate notations in the field books and adjustments in the data tables.

Pebble counts were conducted at each transect at the time the transect was established, following standard procedures (Wolman 1954, Kondolf and Li 1992). One or two observers paced the transect selecting the particle first touched by a finger tip extended forward from a boot toe, with eyes averted to avoid biasing the selection. A crew member tallied at least 100 pebbles from each transect according to the Wentworth scale (i.e. 0-2, 2-4, 4-8 mm, etc.). Pebble counts were entered in spreadsheets and the percent bed composition at various particle diameters calculated.

In addition to pebble counts, surface counts around each scour chain were added in 2002. Calculations on 2001-02 data were not successful in differentiating scour effects among chains in the same transect, largely due to the aggregation of pebble data across the all chains in the transect. In 2002 a barrel sampler was used to collect surface particles separately from around each scour chain. The 40 cm diameter barrel was centered on each chain and driven shallowly into the bed to isolate the surface layer in a 20 cm radius around the chain. The surface layer was extracted by hand and placed in a bucket, and

each particle was measured on the b-axis (Harrelson et al 1994) as it was redeposited into the barrel. Initial analyses indicated that the largest 10 particles would have the greatest influence in explaining scour at a chain, so the particle count was capped at the largest 30 particles to assure that the largest 10 were included in the sample. After measurement the particles were replaced around the chain and the barrel removed. Most surface counts were conducted in June and July, providing ample time for the surface particles to become re-embedded by fine sediment before the flood season commenced. In a few cases surface counts were conducted in September, one month before the first flood.

Peak flow monitors were constructed in 2001 to record the maximum flood stage at each site. Peak monitors consisted of an outer stilling well and an inner recording staff, both made of PVC pipe, and a steel support fencepost with an anchoring cable (Figure 6). The recording staff was held level with the top of the stilling well by a bolt fit into a drilled groove, and the elevation of the top of the monitor was surveyed relative to the site benchmark.

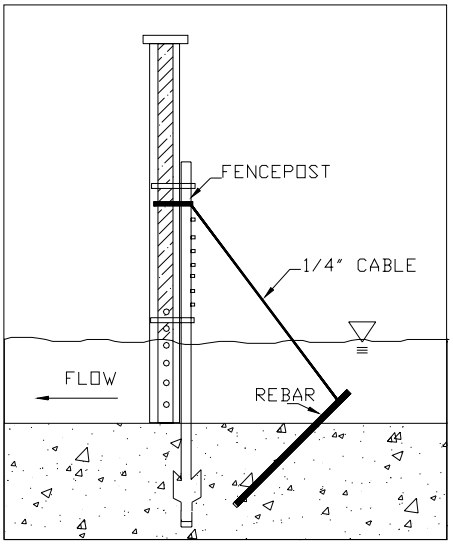

Figure 6. Peak flow monitor with steel support fencepost and anchor. The inner PVC pipe was coated with powdered chalk and fit inside a larger PVC stilling well. Water entered through the open bottom and washed away the chalk, marking the highest extent of each flood. Flood elevations were tied to local benchmarks and used in bed movement calculations.

The inner staff was roughened with sandpaper and covered in blue powdered chalk and placed in the stilling well, with a cap over both. The stilling well was open at the bottom with holes drilled in the downstream side. The entire apparatus was installed in a protected area near the waters edge and reinforced against flood damage. When flood waters rose in the stilling well the chalk was washed away, and after floods subsided the chalk line level was measured relative to the top of the rod. Subtracting the distance to the chalk line from the elevation of the monitor top gave the peak flood elevation at the site. In combination with other survey data the depth of floods over each chain was calculated for each flood. Depth at each chain was used in calculating bed shear stress and other hydraulic and geomorphic variables.

Spawning Gravel Sampling

Site selection for McNeil samples, conducted in summer and fall of 2001, was based on random selection of stream reaches with directed selection of spawning gravel patches within each reach. The chinook-bearing waters of the Nooksack River mainstems and tributaries were depicted in a GIS and subdivided into 160 m (0.1 mile) reaches, according to the river mile stations used during spawning surveys. Of the 19 randomly selected sites only one was in a tributary (Gallup Creek), two were in side channels (Boyd Creek and Boulder Creek) and the remaining 16 were in the North and South Fork mainstems. The procedure for selecting the sampled gravels was to arrive at the point that was randomly chosen in the GIS, then proceed downstream to the first area where the substrate, depth, and velocity were suitable for both chinook spawning and the limits of the sampling equipment. A McNeil sampler can not operate effectively in water depths greater than about 40 cm, nor can it accept any substrate particles greater than 150 mm. In practice the McNeil samplers should not be used in gravels where the maximum particles are greater than twice the sampler diameter ($2D_{max}$), or about 75 mm.

Once a gravel patch had been chosen for sampling the collection methods followed standard procedures (Schuett-Hames et al. 1999b, Bunte and Abt 2001). The McNeil sampler was positioned over a suitable gravel patch and forced into the stream bed with a

twisting motion. The McNeil sampler is designed to extract gravel from a cylinder 15 cm in diameter and 23 cm deep (Figure 7). In larger, compacted, and embedded substrates considerable effort is necessary to force the sampler into the bed. Medium to large cobbles (75 – 150 mm) on the cylinder edge can prevent the sampler from penetrating the bed, and must be extracted individually. Cobbles more than halfway outside the cylinder were extracted and excluded from the sample; cobbles at least halfway in the cylinder were retained. With the McNeil sampler firmly seated in the stream bed the gravel from inside the cylinder was extracted by hand and placed in the sampler's collection basin. A plunger was then inserted into the cylinder and closed so that water and fine sediment in the sampler were retained as the sampler was lifted from the stream bed. The sampler contents were poured into freshly rinsed 5-gallon buckets, and then the sampler itself was rinsed into the buckets to assure that all fine sediment in the sampler was retained. The capped and numbered buckets were entered in the field notes, along with site information and any sampling abnormalities, and transported to the laboratory for sieving.

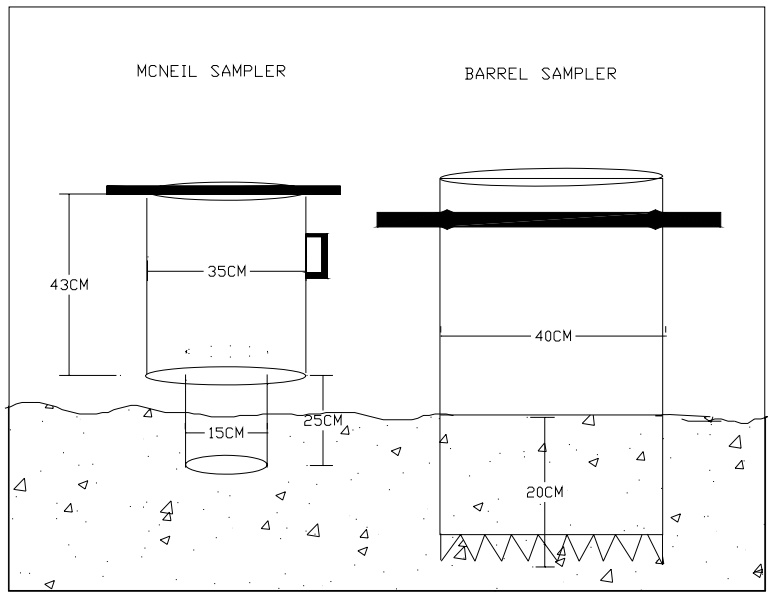

Figure 7. Bulk samplers used for collecting spawning gravels. A McNeil sampler was used in 2001, but was limited to shallow water depths and smaller gravels than were frequently encountered, so the larger barrel sampler was used in 2002.

Barrel samples in the summer 2002 field season were collected at the same sites as the scour chain transects. In general, one barrel sample was collected at each transect, although duplicate samples were collected in some sites to assess variation in the gravel composition within a site or between samplers (barrel vs. McNeil). The barrel sampler was cut from stainless steel pipe 40 cm in diameter (16 inch outside diameter) and 60 cm in length (Figure 7). Teeth (2.5 cm) were cut along the bottom of the sampler to increase streambed penetration, and diametrically opposed holes were cut near the top to accommodate a 2 cm diameter "cheater" pipe used to twist the barrel into the streambed. The barrel sampler was placed over a patch of suitable spawning gravel near the transect and the position relative to the nearest scour chains noted. Typical procedure was to have one crew member sit on the barrel top, partially supported by the cheater pipe, and two other crew members would rotate the sampler, which would sink into position through a combination of friction and gravity. The sampler was forced into the streambed to a depth of 20 cm, and the gravel was extracted by hand scoop and placed in rinsed and numbered 5-gallon plastic buckets. The last bucket was filled with supernatant (sediment-laden water) using a hand pump capable of passing fine sediment. The supernatant was processed with the sediment samples as an analog to the water retained with the McNeil sampler, which allowed comparison between the two sample methods.

Sample processing for the McNeil and barrel samples differed only slightly, to accommodate the larger bulk for the barrel samples. McNeil samples typically filled only one five-gallon bucket; two if excess water was collected in the deeper sampling areas. McNeil sample cylinder volume is 4 liters, all of which was processed as a single sample. Barrel sample volume averaged 25 liters, and each barrel sample typically filled three or four five-gallon buckets (with supernatant). Barrel samples were processed by individual bucket to avoid overfilling the sieves, and the sediment volumes from multiple buckets were summed for a sample.

Volumetric measurement followed standard TFW procedures (Schuett-Hames et al. 1994, 1999b). Buckets of sediment were wet-sieved through a series of eight increasingly finer sieves (75, 26.5, 9.5, 3.35, 1.7, 0.85, 0.425, and 0.125 mm) with a 6.7 mm sieve added for

the 2002 samples to facilitate comparison with other studies (Figure 8). Contents of each sieve were allowed to drain for approximately 20 minutes before volume measurement. A stainless steel volumetric carafe and a 5- gallon bucket fitted with a spigot were used to measure the volume of sediment retained on each sieve, depending on sediment particle size and volume. All McNeil samples and smaller particles and volumes from the barrel samples were measured with the carafe. Larger sediments from the barrel samples were

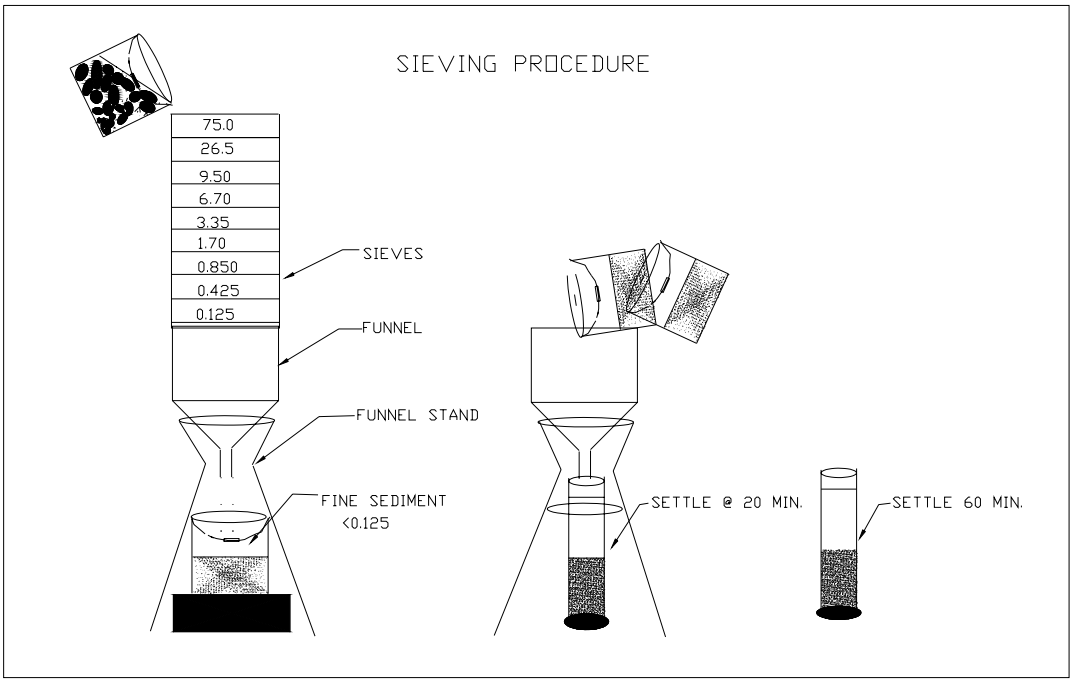

Figure 8. Sieving procedure showing the stack of nine sieves and the settling cylinder.

measured with the bucket. The procedure for both devices was to open the stopcock or spigot until the water level equilibrated inside the vessel, close the valve, add the contents of a sieve to the vessel, then drain the vessel into graduated cylinders and note the collected volume. After the gravel rinsing, all supernatant and rinse water was collected into a 300 liter funnel to which a graduated cylinder had been fitted with leak-proof seals. Fine sediment was allowed to settle from the funnel into the graduated cylinder, and the volume of sediment recorded at 20 minute and 60 minute intervals. The volume of sediment after 60 minutes was recorded as a particle fraction finer than 0.125 mm and

added to the total volume of the sample. Volumetric data were recorded on forms and entered into spreadsheets for analysis.

Data reduction

Several variables were calculated for gravel analysis and site comparisons. The sample median, or d_{50}, is the particle size for which 50% of the sample (in this case by volume) is finer and 50% is coarser. The median particle diameter is frequently used in gravel studies as a single indicator of sediment size, in particular in the central portions of the sample. The d_{84} is the particle for which 84% of the sample is finer, and is often used to indicate the upper margin of particles in a sample, as well as the bed roughness for surface samples. The d_{75}, d_{25}, and d_{16} are likewise the particle sizes for which 75, 25, and 16 percent of the sample is smaller, respectively.

Graphic assessment methods compute gravel size distribution parameters from a few percentile values that are obtained from a cumulative frequency distribution. Percentile values can be calculated by linear interpolation between cumulative proportions of sediment retained on each sieve, when sieve sizes are in Wentworth (ψ) units and proportions are $\log_2$ transformed. Percentile values were interpolated for the d_{16}, d_{25}, d_{50}, d_{75}, and d_{84} size fractions using the formula:

$$\psi_x = (x_2 - x_1) \cdot \left(\frac{y_x - y_1}{y_2 - y_1} \right) + x_1 \qquad \text{(Eq. 1)}$$

where ψ_x is the *x* percentile particle size in Wentworth (ψ , $\log_2$) units, y_2 and y_1 are the values of the cumulative frequency just below and above the desired cumulative frequency y_x, and x_2 and x_1 are the particle (sieve) sizes in ψ units associated with the cumulative frequencies y_2 and y_1.

In samples where 100% of the sediment did not pass the 75 mm sieve, the b-axis of the largest particle in each sample was measured directly and recorded. In many of these

samples, particularly barrel samples, the 84th percentile was larger than the coarsest sieve (75 mm), so the largest particle for all samples combined was used as an upper limit in calculating the d_{84} and d_{75}. In practice this upper limit was set at 150 mm for NNR McNeil cores and 200 mm for barrel samples, which had the same effect as placing a coarser (150 mm or 200 mm) sieve at the top of each stack. The largest particle for LNR samples was not recorded, but few of those samples had a d_{84} larger than the coarsest (77 mm) sieve, most of which exhibited smaller average diameters and narrower variance than NNR samples. LNR samples were therefore assumed smaller than NNR samples and were also given a 150 mm upper size class.

In addition to, or as a substitute for, the d_{50}, or median particle diameter, some studies recommend the geometric mean diameter d_g, as a measure of central tendency of grain size. The geometric mean particle diameter was calculated as:

$$d_g = \sqrt{d_{16} \cdot d_{84}} \qquad \text{(Eq. 2)}$$

The geometric mean is normally calculated as the nth root of n factors (Zar 1996) but for gravel samples the geometric mean particle diameter (d_g) is calculated in a number of different ways, and is often used as a more robust estimate of central tendency than the d_{50} (Platts et al. 1983, Kondolf and Wolman 1993, Bunte and Abt 2001). The Fredle Index (*Fi*) is a measure of skewness with the geometric mean diameter as its numerator. The *Fi* is essentially the coefficient of variation of a sample with units in mm (Kondolf 2000). The *Fi* is calculated as:

$$Fi = \sqrt{\frac{d_{16} \cdot d_{84}}{d_{75} / \ d_{25}}} \qquad \text{(Eq. 3)}$$

Lotspeich and Everest (1981) used the *Fi* as an indicator of the porosity and permeability of spawning gravel, and were able to effectively correlate it to emergence success. The Fredle index showed a marked ability to discriminate spawning gravels that were well sorted and free of fine sediments. The higher the *Fi* the better the spawning gravel.

Church et al. (1987) specified that the largest particle in the sample should encompass no more than 1% of the sample by weight. In samples with 100 mm particles this equates to a sample size of approximately 300 kg. Due to the prohibitively large sample sizes required to satisfy the 1% rule, all samples were instead re-calculated using the 26.5 mm sieve as the upper sample limit. This had the effect of limiting the sample to particles less than about 1 inch, which dramatically increased the representation of the finest particles. However, the truncated samples allowed more statistically valid comparisons between sites and sampling protocols, and were similar to gravel mixtures used in several incubation studies. The median particle diameter, as well as the d_{16} through d_{84}, the d_g and the Fredle Index, were all re-calculated for the truncated samples.

RESULTS

This section, as with the methods section, has been divided into separate discussions of the spawning gravel composition results and the scour results. An assessment of normality for the spawning gravel is first, since many statistical tests are predicated on, and require, the samples being drawn from a normally distributed population. The normality assessment is followed by discussions of the gravel characteristics throughout the basin, which are in turn followed by the scour results.

Assessment of normality

Some gravel samples with strong positive skewness tended toward a high proportion of fine (<0.85 mm) sediment. Across all samples the untransformed percent fines exhibited only slight positive skewness (Figure 9), but due to the high number of samples (n = 467) the distribution of fine sediment was assumed to be approximately normal (Zar 1996). Comparisons between samples of untransformed cumulative frequencies (i.e., d_{16} - d_{84})

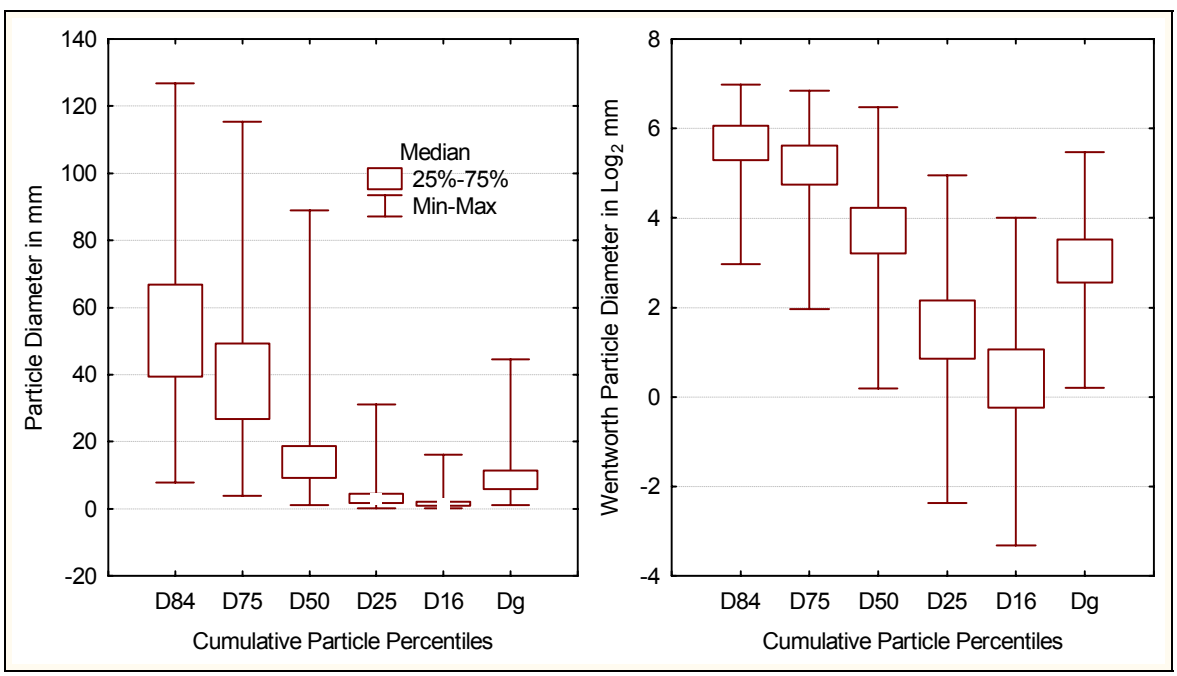

Figure 9. Comparison of bulk samples on an arithmetic vs. Wentworth (log_2) scale. Parameters calculated on an arithmetic scale (left figure) show extreme skewness, especially in the smaller diameters, whereas log transformed (right figure) parameters show only slight skewness in the larger diameters.

were not normally distributed (Figure 9), so each value was log transformed (base 2, ψ scale) for comparisons between samplers and between sites (Figure 9). The ψ scale variables were normally distributed except for slight positive skewness in the larger (d_{75} and d_{84}) categories. Again, due to large sample sizes these departures were considered acceptable.

Bulk gravel samples exhibited a strong positive skewness in arithmetic units and were log transformed to allow comparison between samples and among sites. Departures from normality were evidenced by the tendency of the median away from the center of the distribution, and tails or "whiskers" of unequal length (Figures 10-12). Thus samples measured in arithmetic units could not be statistically compared and were transformed to logarithmic units for analysis. Some samples still had long tails, but this was considered evidence of high fine sediment concentrations in the sample rather than an artifact of the measurement method.

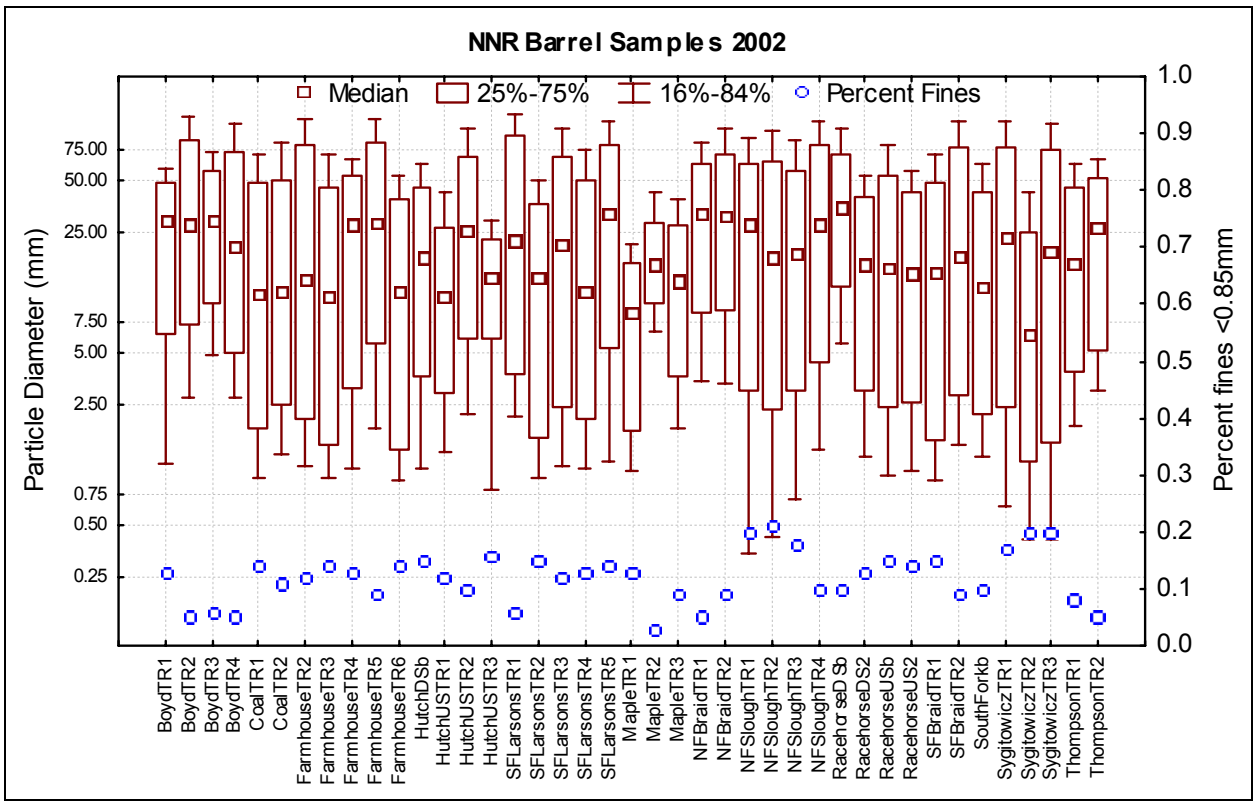

Figure 10. Log transformed, untruncated spawning gravel bulk samples from 2002, using a 40 cm barrel sampler. Boxes and whiskers (left axis) present the d_{16}, d_{25}, d_{50}, d_{75}, and d_{84} for each sample, while the open dots (right axis) represent the proportion of the sample finer than 0.85 mm.

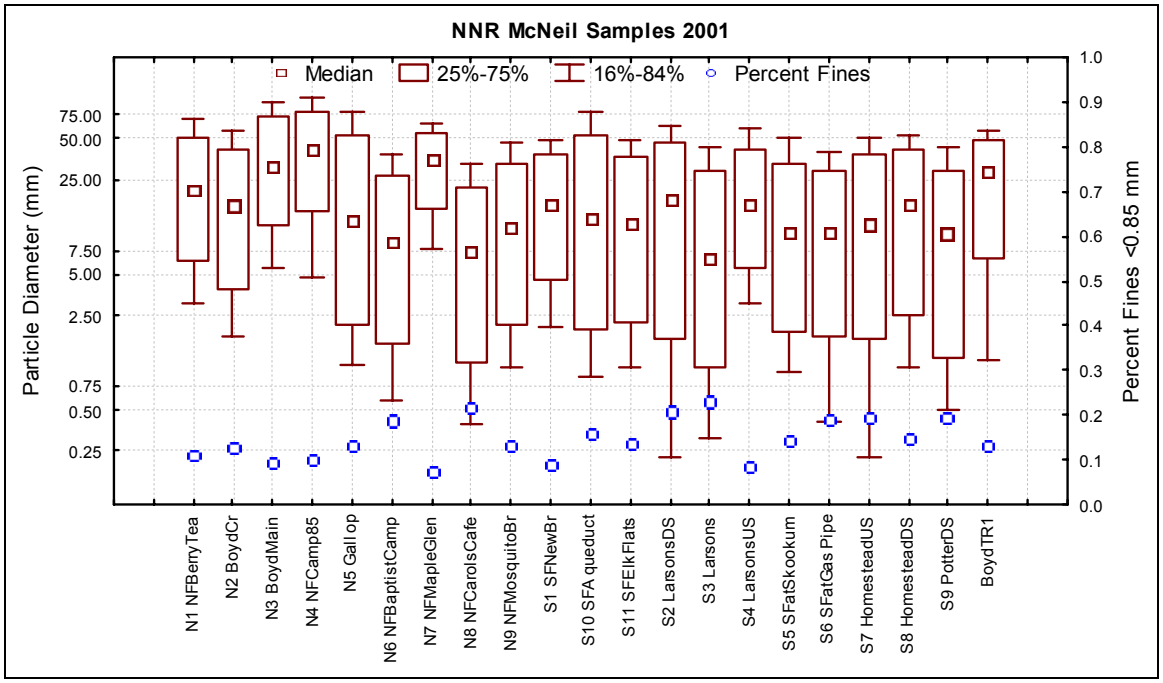

Figure 11. Spawning gravel bulk samples from 2001, using a McNeil sampler. Legend is the same as in Figure 10. Triplicate samples were taken at 20 sites (n = 60), with Boyd Cr TR1 added in 2002 for comparison. Average sample volume was 3.6 l.

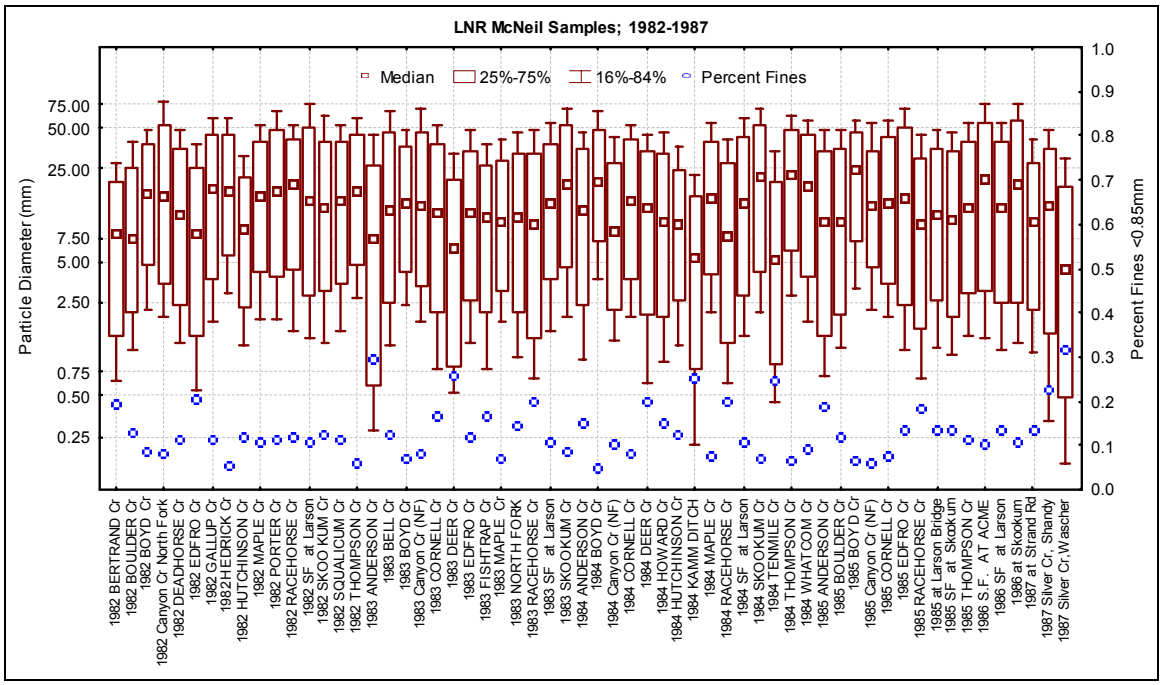

Figure 12. Spawning gravel bulk samples from Lummi Natural Resources (LNR) in the mid-1980s. Legend is the same as in Figure 10. A total of 359 samples were collected at 36 sites over five years. Comparisons across sites and over time are discussed in the text.

In Figures 10-12 (which have been log transformed), when the lower whisker is long relative to the box and the upper whisker, a sample with high fine sediment concentration is indicated. Blue circles depicting the proportion of sediment finer than 0.85 mm are plotted for each sample as well. Upper box limits reaching above the 75 mm mark on the left axis indicate a high proportion of large cobbles in the sample. The shorter the box for each sample the better sorted the gravel, meaning that the gravel is all nearly the same size. After log-transformation the individual samples showed approximately normal distributions of gravel sizes, although a few samples retained a skewness towards the finer sediments.

Significant differences between bulk sampler types (Figure 13) was evident when all untransformed bulk samples were compared. Untransformed (i.e. full, non-truncated) spawning gravel samples collected by LNR in the mid-1980s (Schuett-Hames et al. 1988), and samples collected by NNR in 2001 and 2002 differed significantly in composition (One-way ANOVA, $p<0.001$, $F=8.5$, $n=467$), making direct comparison

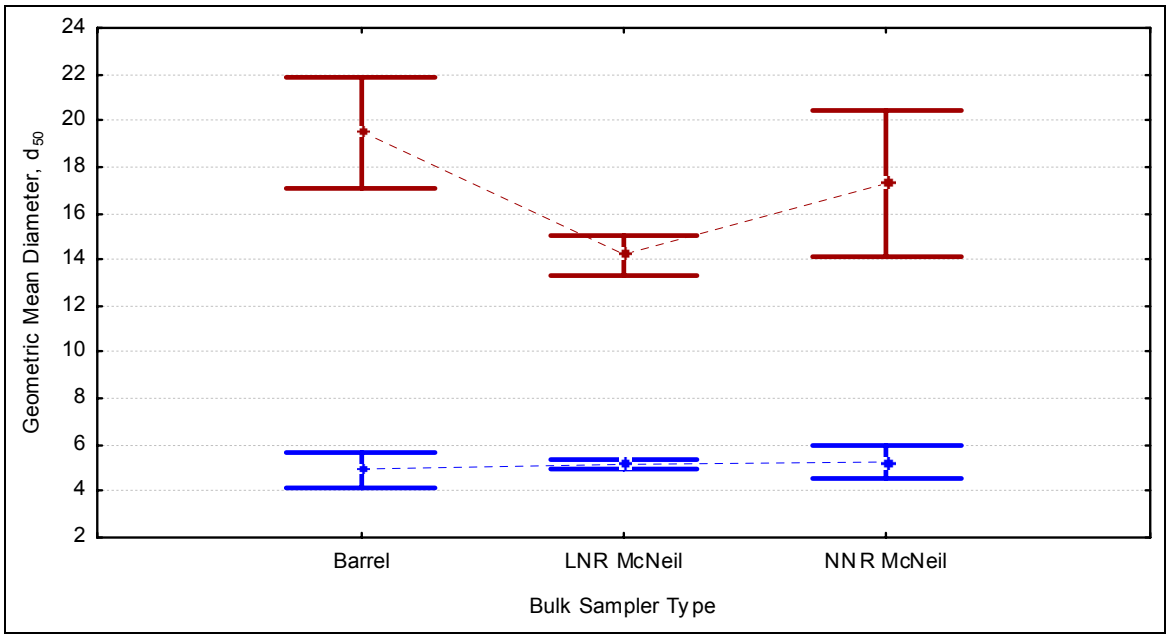

Figure 13. Plot of geometric mean particle diameter (d_{50}) and standard deviation for each of three bulk samplers (n=467). Differences in samplers and sampling protocols are discussed in the methods section. Full samples (red) showed significant differences between samplers ($p<0.001$) but samples truncated at 26.5 mm (blue) did not ($p=0.51$).

difficult. However, when samples were truncated to exclude particles >26.5 mm the variance within and between sample types diminished, and no significant differences remained in the median particle diameter (d_{50}) between sample types ($p=0.51$, $F=0.77$, $n=467$). By removing the largest particles from each sample, truncation lowered the median particle size of each sample, as well as the d_{16} through d_{84}. Percent fines in truncated samples were significantly higher ($t = -12.8$, $dF=968$, $p<0.01$), with all truncated and untruncated samples averaging 19% and 13% fines, respectively.

Differences in gravel composition for the full samples are most likely due to differences in study design. Field notes from LNR reveal that sampling was directed at spawning gravels for all salmon, whereas NNR sampling was directed exclusively at chinook spawning gravel. LNR staff often collected five or more McNeil samples from each reach, and most reaches extended for several hundred meters. McNeil samples collected by NNR were taken in triplicate from a single riffle at a site, the sites being chosen randomly and then narrowed in the field to exemplify chinook spawning characteristics. Even though collected over a larger area, LNR McNeil samples showed a narrower variance (CV=68, n=359) than NNR McNeil samples (CV=114, n=60). This again may be explained by the LNR focus on ideal spawning gravels rather than the larger and more varied gravels used by chinook. Both LNR and NNR McNeil samples used a plunger device to retain the sediment-laden supernatant with the gravel samples, and Nooksack barrel samples included 5 gallons of supernatant for processing with the gravel sieving. All LNR and NNR samples were wet sieved and measured volumetrically. Average volumes of samples are presented in Table 1.

Table 1. Sample characteristics for three bulk sampler types. NNR samples collected by Nooksack Natural Resources, LNR samples collected by Lummi Nation.

Sampler Type	Sampling Years	Number of Samples	Number of Sites	Average Vol (l) ± 1 SD	Average % fines <0.85 mm ± 1SD
NNR Barrel	2002	41	15	33.2 ± 9.8	0.12 ± 0.04
NNR McNeil	2001	60	20	3.7 ± 0.6	0.14 ± 0.06
LNR McNeil	1982-87	359	36	3.2 ± 0.4	0.13 ± 0.08

Comparison between bulk samplers on log-transformed ψ scale variables showed significant differences (one way ANOVA, $p<0.01$, $n=481$) in the larger size classes (d_{50} – d_{84}) but no significant differences in the smaller size fractions or the percentage of fine sediment (Figure 14). Fisher's least significant difference (LSD) test showed differences between the barrel sampler and the McNeil samplers, but no difference between the two (LNR and NNR) McNeil samplers (dF = 478, MS error=0.387).

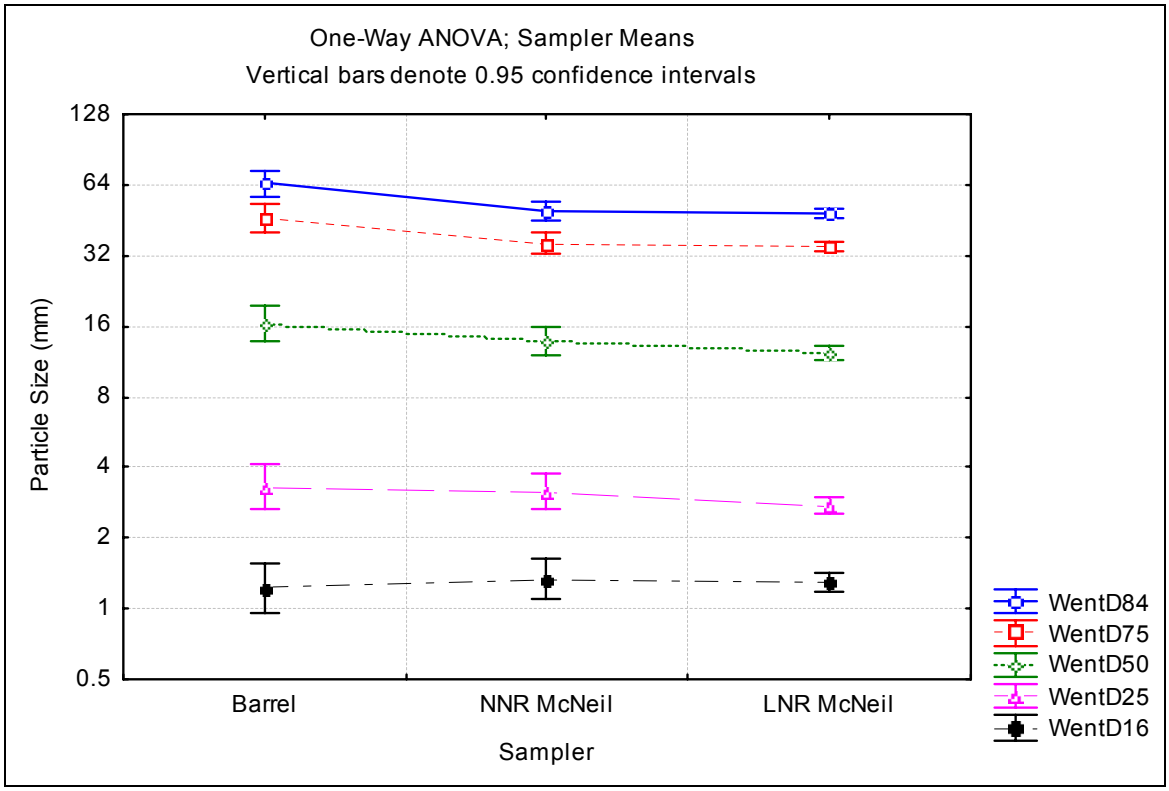

Figure 14. Comparison of three bulk sampler types, by gravel size fraction. Larger size fractions tend to show significant differences between samplers, whereas smaller size fractions do not. McNeil samples collected by Lummi Natural Resources (LNR) targeted spawning gravels for all salmonids and showed smaller diameters and lower variability than Nooksack Natural Resources (NNR) barrel and McNeil sampling that specifically targeted chinook spawning areas.

Differences between sites

Differences in gravel samples are evident between sites and between groups of sites, although many exceptions prevent distinct classification of sites or identification of clear trends. Among the LNR McNeil samples in the mid-1980s the sites with the highest

percent fines were those in the agricultural lowlands, while those with the most suitable spawning gravels were generally in the upper watershed. Bertrand Creek, Kamm Ditch, Tenmile Creek, and two sites on Silver Creek were all well above the 20% fine sediment threshold (Figure 10). Only a few forested reaches had consistently high fine sediment content, namely Edfro, Deer, and Anderson Creeks. Edfro Creek was above the 20% threshold in 1982, then fell below it in 1983 and 1985. Anderson Creek showed a similar pattern. Squalicum Creek and Fishtrap Creek, sampled in 1982 and 1983, respectively, had fines well below 20% despite their location low-lying in agricultural areas.

In 2001 and 2002 NNR did not sample the lower agricultural areas due to the intentional focus on spring chinook, but several reaches in the upper forks had high fine sediment concentrations nonetheless (Figs. 10-12). The Larson's Bridge reach, in particular, had fine sediments in excess of 20% in 2001, but only at locations downstream of the LWD logjam construction under way that year. Immediately downstream of the largest constructed logjam, and downstream of a large slide of clay deposits, the fine sediment concentration averaged 23% (when three samples at 30%, 24% and 13% fines were combined). Upstream of the project, and immediately upstream of Larson's Bridge, fine sediments averaged only 9%, while 800 m downstream of the project fine sediment averaged 21%. By 2002 the fine sediment levels appeared to have recovered. Average fines from six barrel samples in the vicinity (two mainstem, three side channel, and one tributary sample) averaged 8% and ranged from 6% to 14.5%. Spawning was observed at most 2002 sampling sites.

In the 2001 McNeil samples the sites with the highest fine sediment concentrations were on the North Fork near the Truck Road County Park, the South Fork below Potter Bridge; and the South Fork above Homesteader Road. In the 2002 barrel samples the highest fine sediment concentrations were detected in the North Fork Slough and in Sygitowicz Creek.

Stream reaches that had consistently good spawning gravels (i.e., <10% fines) in the mid-1980s were several North Fork tributaries in the vicinity of Glacier, Washington, and

Skookum Creek on the South Fork. Boyd, Thompson, Hedrick, Cornell, Canyon, Gallup, and Maple Creeks consistently were at or below 10% fines, although slight exceedences on a few of these creeks occurred. Field notes reveal that in several of these tributaries, particularly Canyon and Cornell Creeks, sampling was in distinct and limited patches in the lee of large boulders. Large spawning beds were not present in many of these creeks, as they are in Thompson and Maple Creeks, for instance. Many of the Glacier tributaries were not re-sampled in 2001 and 2002 due to differences in study design. Some tributaries however were coincident between the two studies. The Boyd Creek side channel, for instance, had three 2001 McNeil samples with 8%, 9%, and 19% fines, and three 2002 barrel samples all with 5%-6% fines. A North Fork mainstem braid at Boyd Creek had similar low levels of fine sediments, as did a mainstem braid upstream of Boyd Creek. Four LNR gravel samples from Boyd Creek taken annually from 1982-1985 averaged 7% fines. The North Fork near the Maple Glen spawning channel had low fine sediments, although the North Fork just downstream near the Baptist Camp had high fines. Figures 10-12 show details of spawning gravel characteristics by site.

LNR data from the mid-1980s show that nearly all the mainstem reaches and several tributaries (Hutchinson, Racehorse, Boulder, Bell, and Howard Creeks) had moderate levels of fine sediment (i.e. between 10% and 20% fines). Mainstem reaches were generally the most consistent over time, fluctuating within a narrow range of 10-13% fines. Survival in these sites (as a function of fine sediment only and regardless of redd scour mortality) would be moderate according to published relationships (Tappel and Bjornn, 1983).

Differences over time

Despite the uncertainties in comparing study results and between sampling sites, the inclusion of LNR data from the mid-1980s (Schuett-Hames et al. 1988) offers a rare opportunity to look at changes in spawning gravel over time. However, no clear temporal trend could be ascertained from the available data, after the anomalies between sampling sites and sampling protocols had been taken into account. The obvious peak in fine

sediments in 1987 (Figure 15) is attributable to only three sites sampled that year: the South Fork at Strand Road, and Silver Creek at Wascher Road and Shandy Road. The exceptionally high fine sediment concentrations in Silver Creek-- a low, marshy Nooksack tributary near the tidal zone—seem sufficient to explain the peak in fine sediments that year. When the 1987 samples are excluded from analysis the 1983 and 2001 samples are significantly different from the data set as a whole (Tukey HSD, n=467, $p<0.05$), although the slope of the regression line over time was essentially zero and no basin-wide increase or decrease in fine sediments is evident.

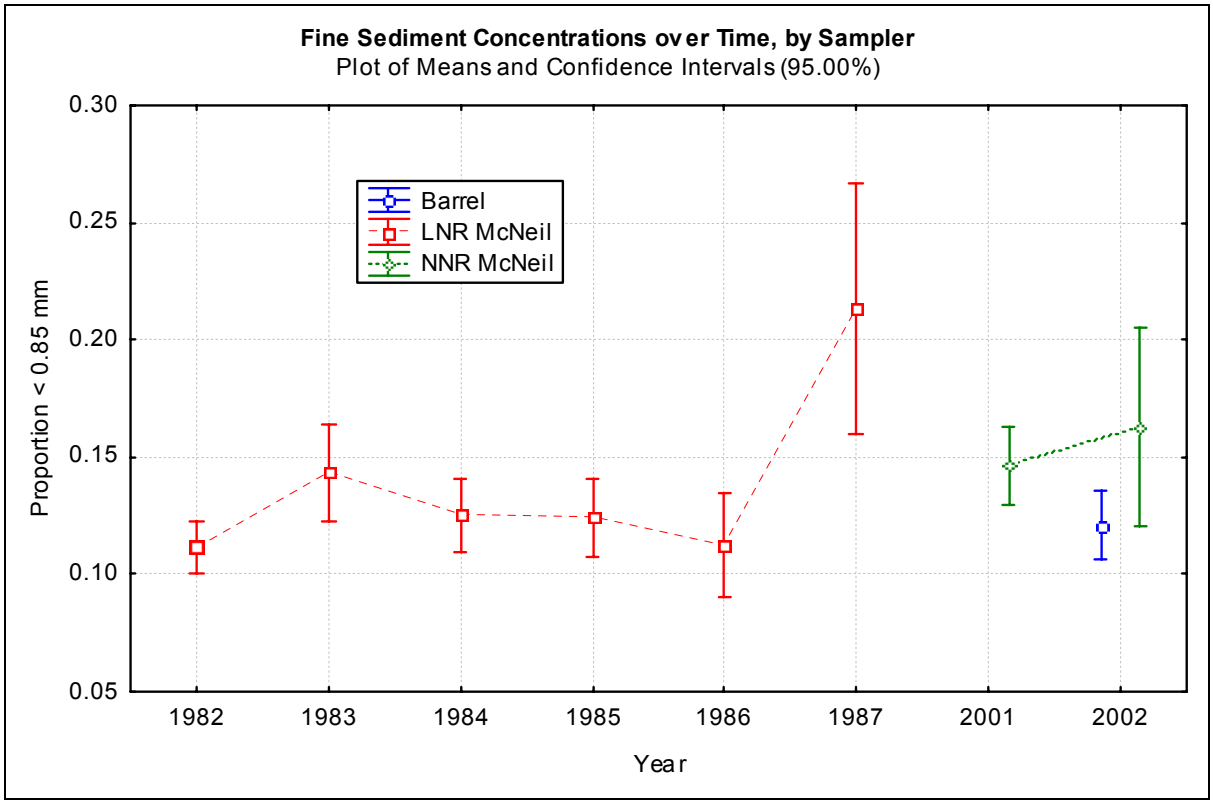

Figure 15. Fine sediment concentrations over time, grouped by sampler type and averaged for all samples in each year. High fine sediments in 1987 are due to sampling anomalies in a marshy tributary. Although 1983 and 2001 are significantly different from all years (when 1987 has been excluded from the analysis) no clear trend over time is detectable from the data.

Differences over time can easily be obscured by changes in sampling sites and protocols, but eight sites (Boyd, Thompson, Gallop, Maple, Racehorse, and Hutchinson Creeks, and the South Fork at Skookum Creek and at Larson's Bridge) were sampled repetitively by

both LNR in the mid-1980s and by NNR in 2001-02, using only slightly different protocols. Sampling months, site locations, number of replicates, and sampling instruments varied over the years, but at these eight sites the same reaches were targeted, the same sieving procedures were used, and differences in fine sediment concentrations are not apparent between the McNeil and barrel samplers. Paired t-tests from these eight sites, with averaged LNR samples from the mid-1980s compared to NNR samples from 2001-02, indicate that no major difference is detectable in spawning gravels over time ($n = 8$, $t = -1.49$; $p = 0.18$).

Individual sites in the basin show a similar stability in fine sediments over time. Boyd Creek and its associated side channel were sampled over four consecutive years (1982-85) by LNR, and then again in 2001 and 2002 by NNR. Five of the six fine sediment concentrations were less than or equal to 8%, and the sixth sample, in 2001, was 12% (still lower than the lethal threshold). Racehorse Creek was sampled by LNR in the same four consecutive years using a McNeil sampler and then in 2002 by NNR using a barrel sampler. The concentrations in Racehorse appear to have declined from 17% (SD=0.08) to 13% (SD=0.02), although some variance is expected between the two samplers. Hutchinson Creek in the vicinity of the old farm bridge was sampled in 1982, 1984, and 2002, and appears to be stable at about 13% (SD=0.04) fines. As discussed above, the South Fork near Larson's Bridge has shifted widely over several years, due in part to instream logjam construction in 2001. LNR McNeil samples from the Larson's Bridge vicinity over five consecutive years (1982-1986) show an annually consistent 12% fines (SD=0.04) averaged over several spawning sites. Fine sediment concentrations in the Larson's reach in 2001, both adjacent to and downstream of the construction, jumped to 17% fines (SD=0.09), but fell again to 12% (SD=0.04) in 2002, in barrel samples from 5 sites on the mainstem, back channel, and a small tributary. Although fine sediment reached a peak of nearly 30% in certain spawning gravel patches immediately downstream of the Larson's construction in 2001, those gravels had mostly recovered by the following year, so the effects of construction on spawning gravels should be interpreted accordingly.

Longitudinal Trends

Only the South Fork Nooksack mainstem had an adequate number of gravel sample sites to assess changes in fine sediment concentration on an upstream/downstream continuum. A slight downstream increase in fine sediment was detectable in spawning gravel samples taken over several years, although scatter in the data was high and the data should be interpreted cautiously. A simple linear regression between river mile and fine sediment concentration was significant at $\alpha<0.05$, but both the slope and the coefficient of determination ($r^2 = 0.03$) were low and the relationship is not dependable for comparisons or predicting gravel concentrations at other sites (Figure 16). It is however possible that future samples from higher in the watershed could expand the range across which samples were compared, with more significant results. A study specifically designed to sample longitudinally and conducted in a single year using a single consistent protocol might reduce the variation and increase the precision depicted in Figure 16.

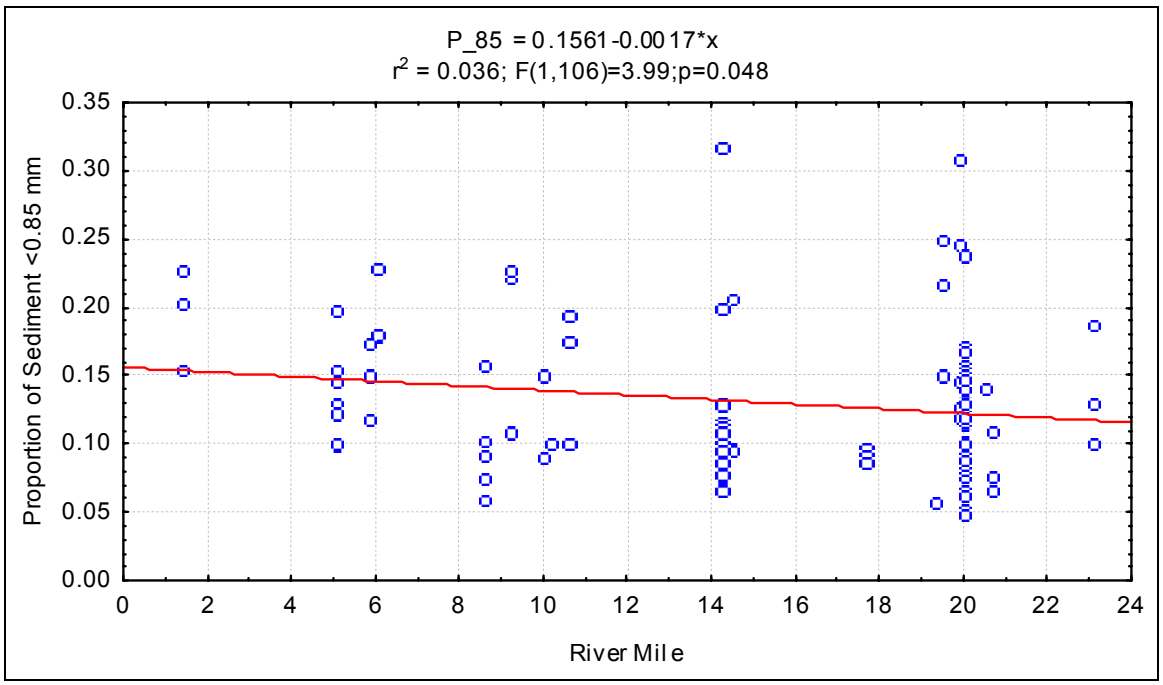

Figure 16. Longitudinal comparison of fine sediment concentrations in the South Fork Nooksack. Wide scatter in the Larson's Bridge vicinity (river mile 20) and at Skookum Creek (river mile 14.5) prevent clear conclusions on downstream fining of sediments, although the linear relationship was significant at $\alpha=0.05$.

Like the sediment concentrations by river length, sediment composition by watershed area does not show a strong trend from which clear conclusions can be drawn (Figure 17). Watershed areas, elevations, and other basin parameters were calculated for each of the identifiable sample sites. Some of the LNR sites could not be precisely located, and were not included in the analysis. Neither the percent fines nor the Fredle index were

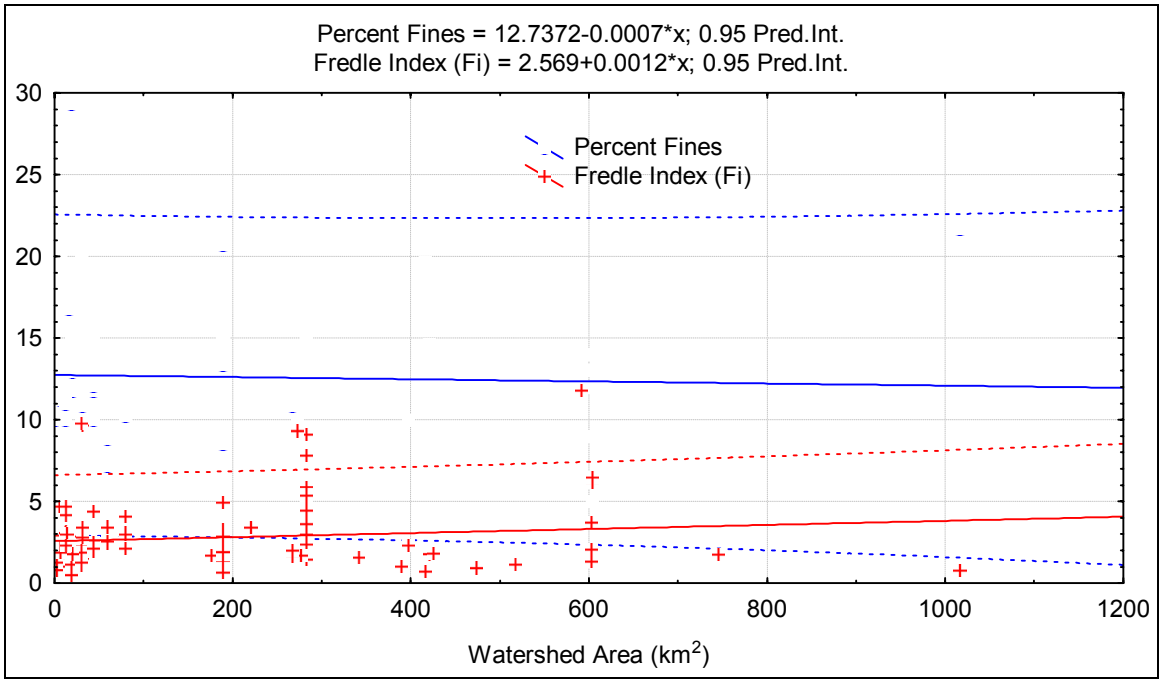

Figure 16. Percent fine sediment and Fredle Index (Fi) as a function of watershed area. Neither regression is significant. Basin area, and hence other watershed variables strongly related to area such as road miles, clearcut area, and discharge, does not appear to have a strong deterministic effect on spawning gravel composition. Note the higher sampling density at Larson's Bridge (189 km^2), Boyd Creek (282 km^2), and the Farmhouse Reach (~600 km^2).

significantly correlated with watershed area. Three sites: Larson's Bridge (189 km^2), Boyd Creek (282 km^2), and the Farmhouse reach (600 km^2) all had high sample numbers and thus strongly influenced the regression outcome, although results would not have been substantially different with those three sites removed. The high sampling density over several years at these three sites, and the wide variation in sediment composition, were largely responsible for the wide scatter of points along the y-axis, and hence the low correlation. Watershed area is highly correlated with several other basin parameters such

as total road miles, clearcut area, landslide area, and discharge, so it is unlikely that these other factors have any influence on sediment composition over the basin as a whole.

Comparisons with other studies

Platts et al. (1989) documented fine sediments (<4.75 mm) in chinook spawning gravels in the South Fork Salmon River of Idaho, which had been heavily impacted by timber harvest, road building, fires, and mass wasting. After a logging moratorium in 1965, sub-surface fine sediment concentrations peaked at an average of 46% in 1969, dropped steeply to 27% in 1975, and leveled off at about 25% fines through 1985. In the Nooksack samples a 3.35 mm sieve was used instead of 4.75 mm, so exact comparisons with the Platts (1989) study are not possible. For Nooksack spawning gravels the percentage of sediment finer than 3.35 mm was 25% ± 7% for 2002 barrel samples, 27% ± 11% for 2001 NNR McNeil samples, and 28% ± 10% for 1982-1987 LNR McNeil samples. Overall it appears that Nooksack gravels are roughly equivalent or somewhat finer than the Idaho samples after several years of flushing had allowed the Idaho gravels to reach equilibrium with sediment inputs.

Tappel and Bjornn (1983) measured chinook and steelhead egg survival in laboratory flumes and developed linear equations for predicting egg survival based on gravel composition. For chinook salmon the equation with the highest explanatory power was:

$$\% \text{ survival} = 93.4 - 0.17 s_{9.5} \cdot s_{0.85} + 3.87 s_{0.85} \qquad r^2 = 0.93 \qquad \text{(Eq. 4)}$$

where $s_{9.5}$ and $s_{0.85}$ are the cumulative percentages of sediment finer than 9.5 mm and 0.85 mm, respectively. When the equation was applied to NNR McNeil data some of the values were <0% or >100%, indicating that Nooksack gravel mixtures sometimes fell outside the range of gravels used to derive the equation. For assessment purposes those values were changed to 0% and 100% survival, respectively. For NNR barrel samples only 1 value (out of 41) was outside the 1-100% range. LNR McNeil samples were not sieved with a 9.5 mm sieve, and could not be evaluated with Equation 4. NNR McNeil

samples averaged 46% survival. Survival rates often varied widely among the three samples at each site, in one case from 0-74% (Skookum Creek). Barrel samples ranged from 0 to 97%, and averaged 60%, but variance between samples at the same sites was much lower than for McNeil samples. Fredle Index values were computed for each site and appear in Appendix I.

Tripp and Poulin (1986) measured fine sediment concentrations in spawning gravels in the Queen Charlotte Islands and reported increases from 4.3% (± 1.5 SD) fines <0.85 mm in unlogged basins with no mass wasting to 7.1% fines (± 2.2 SD) in logged basins with upstream mass wasting. Both figures were substantially lower and exhibited less variance than spawning gravel samples in the Nooksack basin. For untruncated (full) Nooksack samples the percent fine (<0.85 mm) sediment was 12% (± 4% SD, n=48) for 2002 barrel samples, 14% (± 6% SD, n=74) for 2001 McNeil samples, and 13% (±8% SD, n=359) for 1982-87 LNR McNeil samples. Overall fine sediment content was 13% (± 7% SD, n=481) for all samples combined. Nooksack gravel samples appear to be roughly equivalent in fine sediment concentration to the stream gravels subjected to extensive logging impacts in the Queen Charlotte Islands.

Scour Results and Discussion

Redd scour during the incubation season does appear to be a significant factor limiting the population of Nooksack early chinook, and the number of potential redds that are scoured to lethal depth varies according to habitat type and the intensity of seasonal floods.

During the 2000-01 flood season both the North and South Fork Nooksack branches exceeded their bankfull flood thresholds (approximately 4800 and 7300 cfs respectively) three times, although the first two floods were not bankfull events in both forks (Figure 18). Substantial flooding (8-10 year recurrence intervals) occurred in the first week of January 2002. The 2001-02 flood season was much milder, with neither fork exceeding the annual flow threshold. Scour was commensurately heavier in 2001 than 2002.

Subsequent to the field portion of this study, in October 2003, the North Fork exceeded its highest flow on record, peaking at 13,500 cfs, while the South Fork achieved its third highest flow on record at 21,800 cfs (preliminary USGS figures).

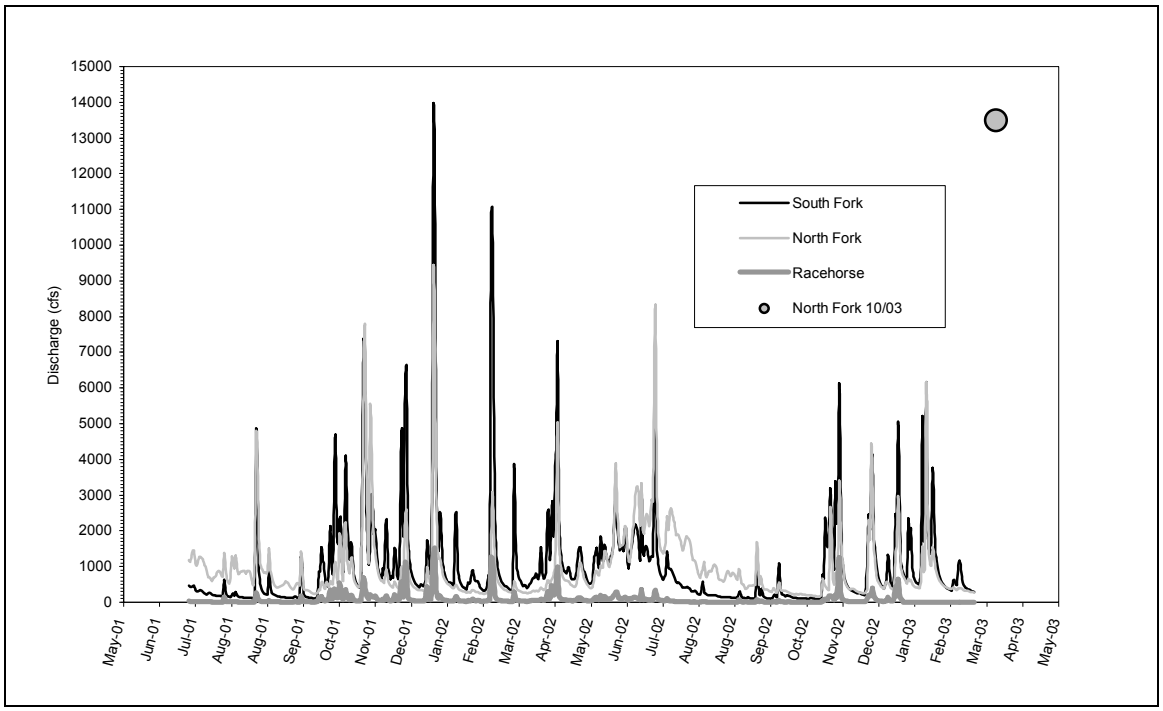

Figure 18. Hydrographs for the study period at three USGS stream gauges. South Fork Nooksack at Wickersham (USGS #12209000; North Fork at Glacier (#12205000; and Racehorse Creek (USGS# 12206900). A flood in October 2003 was the highest recorded in the North Fork, at 13,500 cubic feet per second.

For the purposes of this report, "redd failure" occurred when scour chains recorded bedload scour in excess of 20 cm, net aggradation over the initial bed elevation exceeded 30 cm, or the bed surface at the time of emergence had been completely dewatered. The rationale for these thresholds is that chinook redd pockets average about 20 cm depth (DeVries 1997) and would be at least partially destroyed by bedload movements to that depth, and that 30 cm of fill over a 20 cm pocket depth would create an impenetrable barrier for emerging alevins. The latter assertion has yet to be shown in the research literature, but some accommodation for excess aggradation was necessary, if somewhat arbitrary. Further, while developing alevins in the gravel can often survive partial

dewatering (Reiser and White 1983) egg-to-smolt survival requires that surface flows are present above the redds when the alevins swim up to enter the channel.

Based on the 20 cm scour or 30 cm fill criteria, during the 2001 water year nearly half (55%) of all scour chains recorded a redd failure. During the milder 2002 water year 27% of scour chains recorded a redd failure. The failure rate was approximately 36% for both years combined. The majority of redd failures were in the mainstems and braids, with few failures occurring in the tributaries and sloughs (Table 2). An intermediate number of failures occurred in the back channels.

Table 2. Percentage of mean redd (scour chain) failures by habitat type. Using all (2001-03) data combined, back channels were indistinguishable from low-scour or high-scour habitats, but in the heavier 2001-02 flood year tributaries and back channels were low-scour habitats, while braids and mainstems were high-scour habitats.

Year(s)	All Habitats	Slough	Tributary	Back Chan	Braid	Mainstem
2001-03 combined	36	5	13	32	56	64
2001-02	55		27	25	75	72
2002-03	27	5	10	34	40	56

As depicted in Table 2, redd failure varied widely by habitat type. A one-way ANOVA of failure rates over both years combined found distinct differences between habitat types ($F = 4.56$; $p=0.003$). Fisher's least significant difference (LSD) test (at $\alpha = .01$) showed that sloughs and tributaries had significantly lower redd failure rates than braids and mainstems. It was not possible, however, to group back channels with either the lower or higher failure rate categories. In 2001 tributaries and back channels were similar to each other in having relatively low levels of potential redd failure, and braids and mainstems had similar levels of relatively high redd failure. Sloughs were not measured in 2001. Results from 2001 were used to shift the sampling design for 2002 to emphasize the differences in scour rates among channel types. In 2002 back channels had higher failures than in 2001, due primarily to avulsions and high sediment deposition in upstream

reaches of the Bear Creek back channel, where 7 scour chains were located. In 2002 the back channel failure rates were intermediate between sloughs and tributaries on the low end, and mainstems and braids on the high end, and hence obscured the differences between these two groups. A Fisher's LSD test on 2002 results was able to classify sloughs and tributaries in a low-failure group and mainstems in a high-failure group, but back channels and braids were more ambiguous and could not be placed in either the high- or low-failure groups.

Not all of the scour chains installed at the beginning of the incubation season were recovered at the end of the season. Scour, burial, and tampering all contributed to chains being lost. In the 2001-02 flood season 40 out of 79 chains were not recovered (50%), and in the lighter 2002-03 flood year a much more favorable 38 out of 159 chains (24%) were lost. In most situations when chains were lost or destroyed it was possible to ascertain in the field if the loss represented a redd failure or not. The data presented in the preceding discussion pertains to *numbers of chains* and includes all chains where such a determination could be made. The following discussion of scour *depth* is based only on the scour chains that could be recovered, and therefore measured.

When average scour *depths* are considered, as opposed to average failure rates, a similar pattern of differential scour by habitat type emerges. As Figure 19 shows, the greatest average scour was in mainstem habitats, followed by braids, tributaries, sloughs, and back channels. A simple one-way ANOVA found significant differences between groups (at α=0.05), and a post-hoc LSD test was able to distinguish mainstem habitats from tributaries, back channels, and sloughs. Braids were intermediate in scour depth between mainstems and tributaries, and the variation in braided channels was high, so the braided habitat type was ambiguous when assessed over both flood years. In the higher 2001-02 flood year scour depths were on average greater in all habitat types, variation in scour depth was higher, and no significant differences in average scour depths between habitats were observed, although significant differences in redd failure rates were distinguishable by habitat type, as previously discussed.

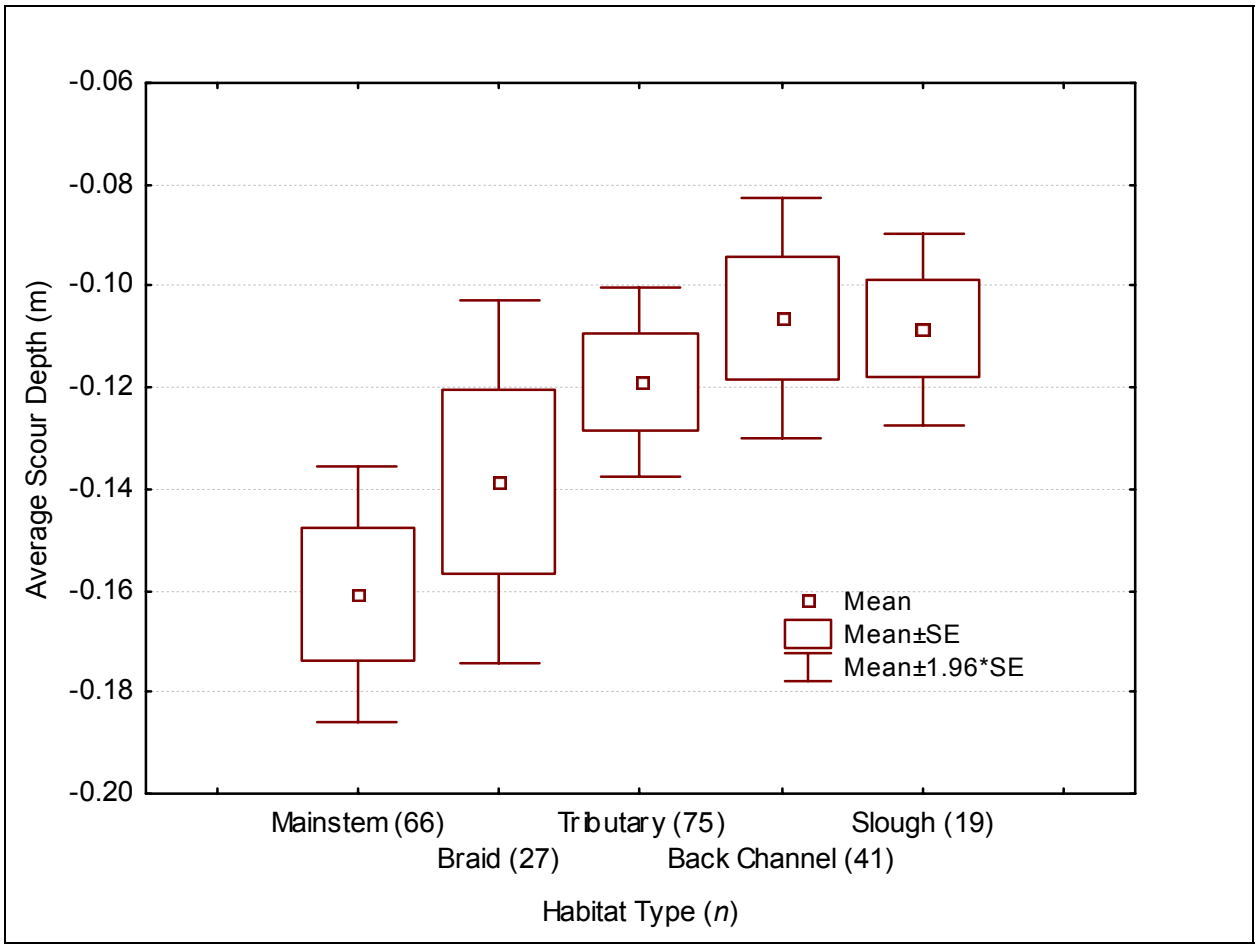

Figure 19. Average scour depth by habitat type. Despite wide variation in scour depths at each transect, mainstem scour chains scoured significantly deeper than tributaries, sloughs, and back channels. Scour depths in braided channels were intermediate between mainstems and the other habitat types. Data are for both flood years (2001-02 and 2002-03) combined

Despite the differences in redd failure by habitat types, in the field habitat types are somewhat arbitrary groupings along a continuum of varying habitat conditions (habitat definitions were described in the methods section of this report). In essence, tributaries differ from mainstems only in size and watershed area. Larger tributaries function in similar ways to headwater reaches of mainstems. Back channels are often indistinct from braids except that they are separated from the mainstem by persistent woody vegetation. Mainstems differ from braids only in the proportion of discharge that they carry, and in some reaches, particularly in the North Fork, channels can shift between a mainstem and braid multiple times in the same flood year. Thus while it is useful to identify differences

in redd failure by habitat type, those habitat types are by no means permanent (or even, sometimes, are the differences clear), so the ability or inability of certain statistical tests to delineate significant differences should not be over emphasized.

Taken over both flood seasons and all habitat types, 36% of scour chains (including those not recovered) recorded scour depths that could be interpreted as redd failures (Table 2). Taken from the recovered and measurable scour chains only, 19% (40 out of 207 chains) scoured to lethal depth. Figure 20 shows the numbers of chains that scoured to lethal and non-lethal depths over one flood season. The pattern of scour depths clearly follows a lognormal distribution, which could be used to predict the number of redds that can be expected to scour to lethal depths in a given year. However, it is likely that the shape of the histogram changes according to the intensity of the flood year, and two years of scour data are inadequate to determine how that shape changes. Although Haschenberger (1999) was able to fit exponential curves to scour data from three sites over several years, a similar analysis would be beyond the scope of this study.

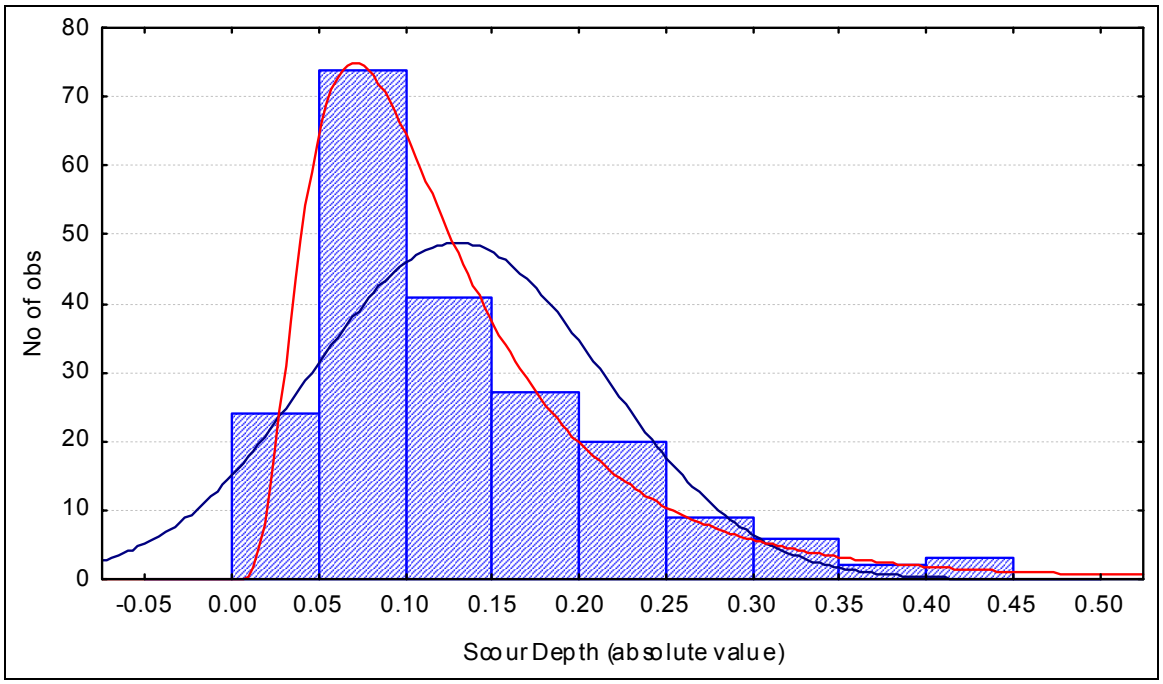

Figure 20. Distribution of scour results follows a lognormal distribution (red line) rather than a normal distribution (blue line). Over both study years and all habitats, and for the chains that were recovered and measurable at the end of the flood year, 19% of scour chains scoured to a potentially lethal depth.

Finally, a multiple linear regression approach was used to determine if the conditions that promote or determine scour could be detected *a priory* in the field. Several hypotheses were tested, all of which related to the contributions of local and watershed variables in determining scour. The dependent variable in the regression was scour depth (during the incubation season). The independent variables tested were maximum water depth during flood peaks, maximum flood intensity (recurrence interval), water surface slope at each site, total watershed area upstream, average particle diameter (d50) at each scour chain transect, and average diameter of the ten largest particles within a 20 cm radius around each chain. Additionally, each habitat type was tested as a binomial variable to determine significance in the regression outcome.

Water surface slope had surprisingly little effect on the regression, and was insignificant at the $\alpha = 0.05$ level. Flood intensity was highly correlated with flood water depth, so flood depth was chosen for the final regression due to its greater predictive power ($p<0.001$). Likewise with average particle size at each transect and average particle size at each chain, where particle size at each chain was chosen. Of the five habitat types only mainstems were significant in the regression. The three significant variables—flood depth, particle size, and mainstem habitat—are plotted in Figure 21.

Figure 21 demonstrates several important determinants of redd scour. The overall multiple regression was highly significant ($F(4,104)=13.3$; $p<0.000$; $R^2=.34$) and showed flood depth, particle size, and habitat type to each be significant factors in the final stepwise regression. Although the data points in Figure 21 are scattered widely about their regression lines, the slope of the flood depth (blue) line is clearly not horizontal, whereas the slope of the brown line is nearly flat, demonstrating that flood depth has a clear relationship with scour depth ($p=0.000012$) but particle size is less important. The deeper the flood, the deeper the scour, in general. However, the wide scatter in the data (Pearson's $r=0.51$) make predictions about redd scour highly imprecise. The relationship between scour depth and particle size is more tenuous, with a regression slope that is, again, almost horizontal, indicating that even a relatively large change in particle size

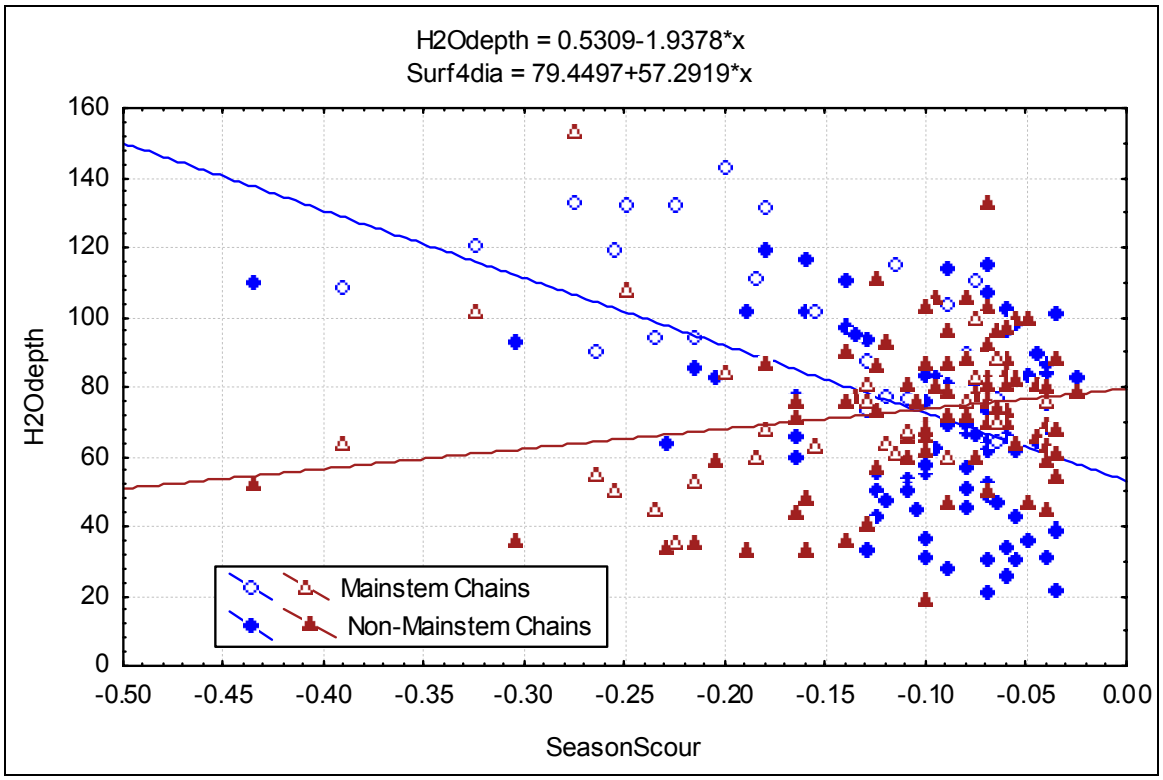

Figure 21. The three most significant determinants of redd scour are flood depth, particle size, and habitat type. The abscissa (X-axis) pertains to the depth of scour at each chain over one incubation period (both 2001 and 2002 data are plotted). The left ordinate (Y-axis) pertains to the surface particle diameter around each chain, and is represented by the brown data points and the brown line in the graph. The right ordinate pertains to the maximum flood depth over each chain in a given flood season, and is represented by the blue points and blue line in the graph. Open squares represent mainstem scour chains and closed dots represent non-mainstem chains. Each chain in the data set is plotted twice, once on the left ordinate and once on the right ordinate.

effects only a small change in scour depth. The relationship in the multiple regression between particle size and scour depth was however significant, with a p-value of 0.008 and a Pearson's r (univariate correlation coefficient) value of only 0.20. Despite an unimpressive significance level for habitat type in the multiple regression (p=0.019), most of the scour chains that scoured deeper than lethal depth (20 cm) were in mainstem habitats.

Comparisons with other scour studies

Few other studies have identified differences in scour depth by macro-habitat type (tributaries, mainstems, sloughs, etc.), although several have concentrated scour chains in river or tributary reaches and examined scour depth as a function of local variables such as gradient and reach-scale habitat type (pools, riffles, glides, etc.). Rennie and Millar (2000) found bedload scour to be so highly variable that scour at one monitor gave no statistical indication of the depth of scour at adjacent monitors. Similar findings are common in the field notes for this study, and are fully demonstrated by examination in Appendix II. DeVries (2000) found that during an equilibrium bedload movement event (that is, absent local imbalances between sediment supply and transport, and irrespective of channel shifting) the depth of the bedload layer approaches and rarely exceeds two times the d_{90} (the 90th percentile particle size) of the surface layer. The d_{90} was not calculated for this study, due to uncertainty at the extremes of the sample distribution, but the d_{84} was calculated from pebble counts at each scour transect. Substituting the d_{84} for the d_{90}, approximately 22% of scour chains recorded depths greater than 2 d_{90}, usually in channels with fine gravels or in areas of excess (>~ 25 cm) scour.

Results of a study of chum salmon redd scour in a single tributary to lower Puget Sound (Kennedy Creek) by Schuett-Hames et al (2000), compares favorably to this study. In Kennedy Creek, a 1.4 year flood event scoured 20 percent of chum redds to a lethal (20 cm) depth, and scour was more prevalent and deeper in pools than in riffles. In this study the tributary redd failure rates were 27% in 2001-02, 10% in 2002-03, and 13% overall. In Kennedy Creek, as in the Nooksack, substantial variation in scour and fill was apparent between reaches, among habitat types, and between chains in the same transect (Schuett-Hames et al 2000). Using the same data from Kennedy Creek, Montgomery et al (1996) showed that chum spawning coarsened the gravel layer in spawning reaches from 22 to 30 mm, and that gravels disturbed by spawning were more loosely packed than unspawned portions of the stream bed. Unlike the Nooksack though, the distribution of scour depths followed a steep exponential decay curve rather than the lognormal distribution shown in Figure 20. Rennie and Millar (2000) point out that scour histograms

resemble negative exponential curves if zero scour values are included, and lognormal curves if zero values are excluded, as in this study. Haschenberger (1999) observed and modeled a similar distribution pattern. Drawing on the pattern of scour results, as demonstrated by histograms such as Figure 20, Montgomery et al (1996) point out that even a minor shift towards deeper scour could destroy the redds of a significant number of fish, and possibly jeopardize the entire population. This concept was elaborated later, when Montgomery et al (1999) hypothesized that depth of egg burial and choice of spawning habitat was an evolutionary adaptation to scour depth.

On a less theoretical level, at least three separate studies of redd scour have been conducted in the Nooksack basin, all by the Lummi Natural Resources (LNR) department in the mid-1980s to early 1990s. Schuett-Hames et al (1988b) briefly describe results from eight scour monitors installed on the mainstem of the South Fork Nooksack between river miles 14.8 and 15.5 (from about Saxon Bridge to just above Skookum Creek). The scour monitors (the type was not specified) were placed in December 1984 and recovered in August 1985. None of the scour monitors recorded significant scour (max 10 cm), but three monitors were buried by more than 60 cm (24 inches) of gravel fill when the channel shifted (Schuett-Hames et al 1988b). This report has been widely cited as evidence of widespread and debilitating "scour" in the South Fork (Smith 2002).

Schuett-Hames et al (1988c) marked spring chinook redds in Canyon Creek, Kendall Creek, and a side channel of the North Fork. They surveyed cross-sections and redd point locations in August and September 1987. Field observations and resurveying the at the end of the incubation season revealed that none of the redds appeared to have been affected, although no scour monitors were installed and scour could have been equal to fill over the incubation period (Schuett-Hames et al 1988c).

Neff and Edwards (1992) placed rebar scour monitors in the South Fork and Middle Fork mainstems, as well as the Hutchinson, Porter, Canyon Lake, and Bells Creek tributaries and one unnamed (01.0412) tributary. The scour monitors were placed in September 1991, and 32 of the 46 monitors (69%) were reportedly recovered in March 1992. Only a

handful (5 out of 17) of the mainstem scour monitors were recovered. Of the 24 scour monitors that were both recovered and remeasured, the average scour depth was 10 cm, the max scour depth was 37 cm, and three of the 24 recovered monitors scoured to greater than 20 cm, for a redd destruction rate of 0.13, mostly in tributary habitats (Neff and Edwards 1992). It is likely that unrecovered scour monitors in the mainstems were scoured to lethal depths as well, but field conditions described in the report prevent any such assertion from being made with any degree of confidence.

Conclusions and Recommendations

Wide local variation in spawning gravel quality obscured differences between sites and over time. In general the best spawning gravels were found in upper watershed areas rather than lower in the basin, although many exceptions to this generalization were evident. Often within-site variation exceeded between-site variation, meaning that the placement of the gravel sampler (barrel or McNeil) within a habitat type often changed the fine sediment composition as much or more than moving downstream or to another stream. However, several tributaries close to the mainstem North and South Forks, especially Boyd Creek, Thompson Creek, Maple Creek, and Skookum Creek, as well as the upper North and South Fork mainstems, consistently showed adequate or highly productive spawning gravels. The distribution of high-quality spawning gravels seems to be largely determined by local characteristics and short-term fluctuations in sediment delivery and transport, so basin-wide restoration strategies for spawning gravel quality are so far unclear. However, several important spawning areas provide clean spawning gravels and consistently attract returning fish, and clearly deserve protection from future degradation.

A restoration strategy for improving spawning gravel *composition* may not be a direct outcome of this study, but a strategy for reducing redd *scour* is nevertheless apparent. The scour chain results in Table 2 provide at least one clear direction for habitat restoration in reaches used by spawning chinook salmon. The embryos of fish spawning in mainstem channels and braids seem to be at a clear disadvantage relative to the eggs

buried in tributaries and sloughs. Despite the 2002 avulsions that led to some higher than expected failure rates, it is still likely that back channels and tributaries provide a more protected incubation environment compared to mainstems and braids. Coincidentally, tributaries, sloughs, and back channels are also more likely to provide suitable rearing habitat for juvenile salmonids of several species (Sedell et al. 1984; Murphy et al. 1989; Cunjak 1996). Given these findings, it seems clear that spawnable tributaries, sloughs, and back channels should receive the highest priority for acquisition and habitat protection. Conversely, mainstems and braids provide the greatest opportunities for restoration and enhancement. Instream structures, such as constructed logjams, combined with appropriate riparian plantings, could conceivably be designed to shift braid habitat into back channel, or even slough, habitats.

Logjams at the upstream ends of channel islands frequently anchor and protect downstream vegetation and encourage the formation and stability of mid-channel islands (Abbe and Montgomery 1996, 2003). As these islands form and coalesce they could potentially transform braided channels into anastomosing channels or an *island braided* habitat type (Fetherston et al. 1995, Collins and Montgomery 2002). Anastomosing and island braided channels would provide more allochthonous inputs, more LWD contributions, more stream shading, more undercut banks, and more instream cover than what is currently provided in braided reaches (Sedell and Froggatt 1984, Collins and Montgomery 2002). As this study has made clear, reaches with persistent woody vegetation in the riparian zone (tributaries, sloughs, and back channels) are correlated with higher spawning gravel stability than reaches with little or no vegetation (braids and mainstems). Several life stages of chinook (and other) species would be enhanced if logjams or other techniques were successful in creating stable back channels, sloughs, channel islands, and anastomosing reaches. Sloughs and tributaries rarely exhibit redd failure rates greater than 20%, while mainstems and braids rarely exhibit redd failure rates less than 50%. Thus the judicious placement of logjams might be used to deliberately modify braids into more stable habitat types, and could conceivably increase local incubation survival by a factor of two or more. Spread over several carefully-chosen

sites, such an increase could show measurable escapement increases in only one or two generations of the targeted species.

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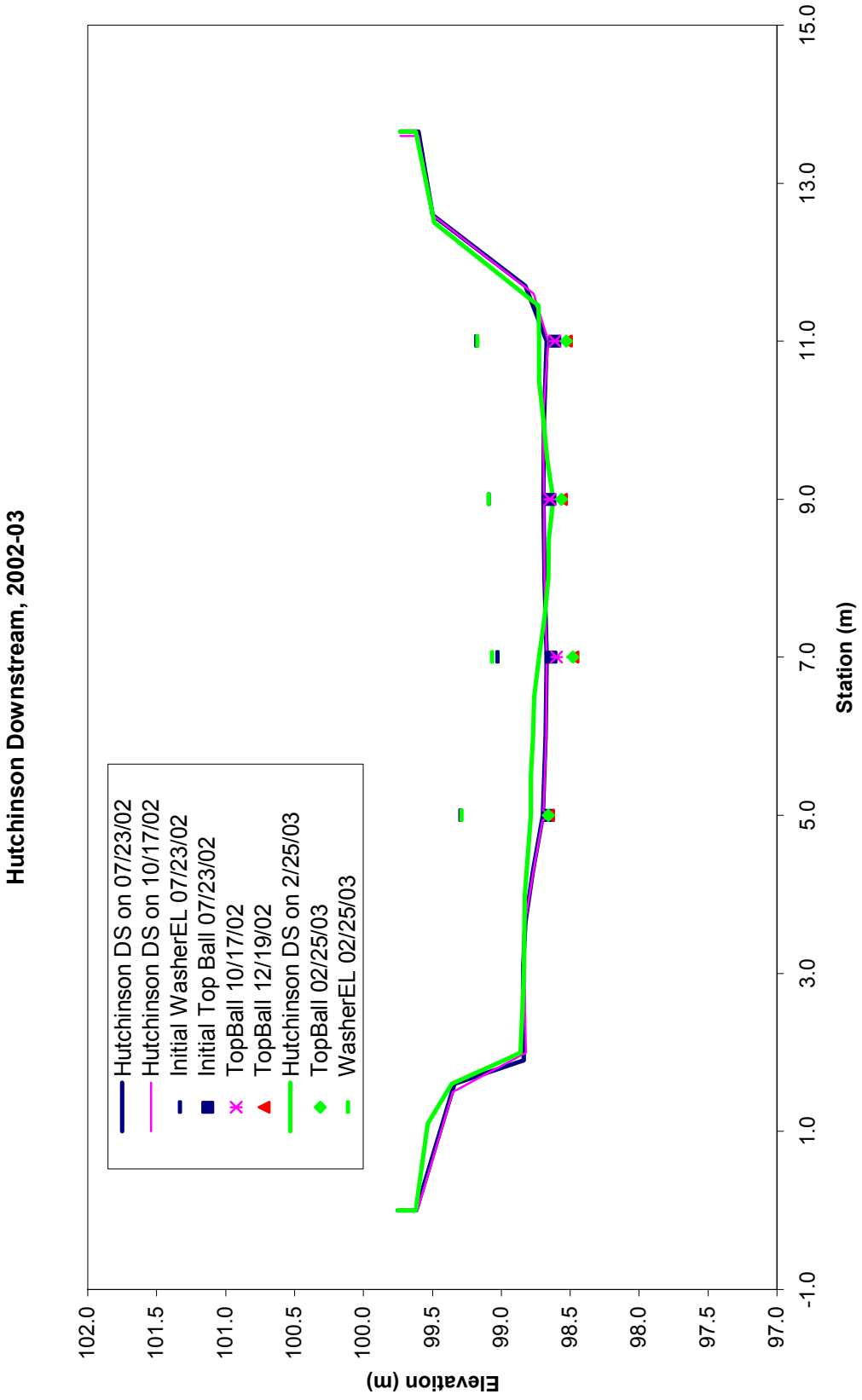
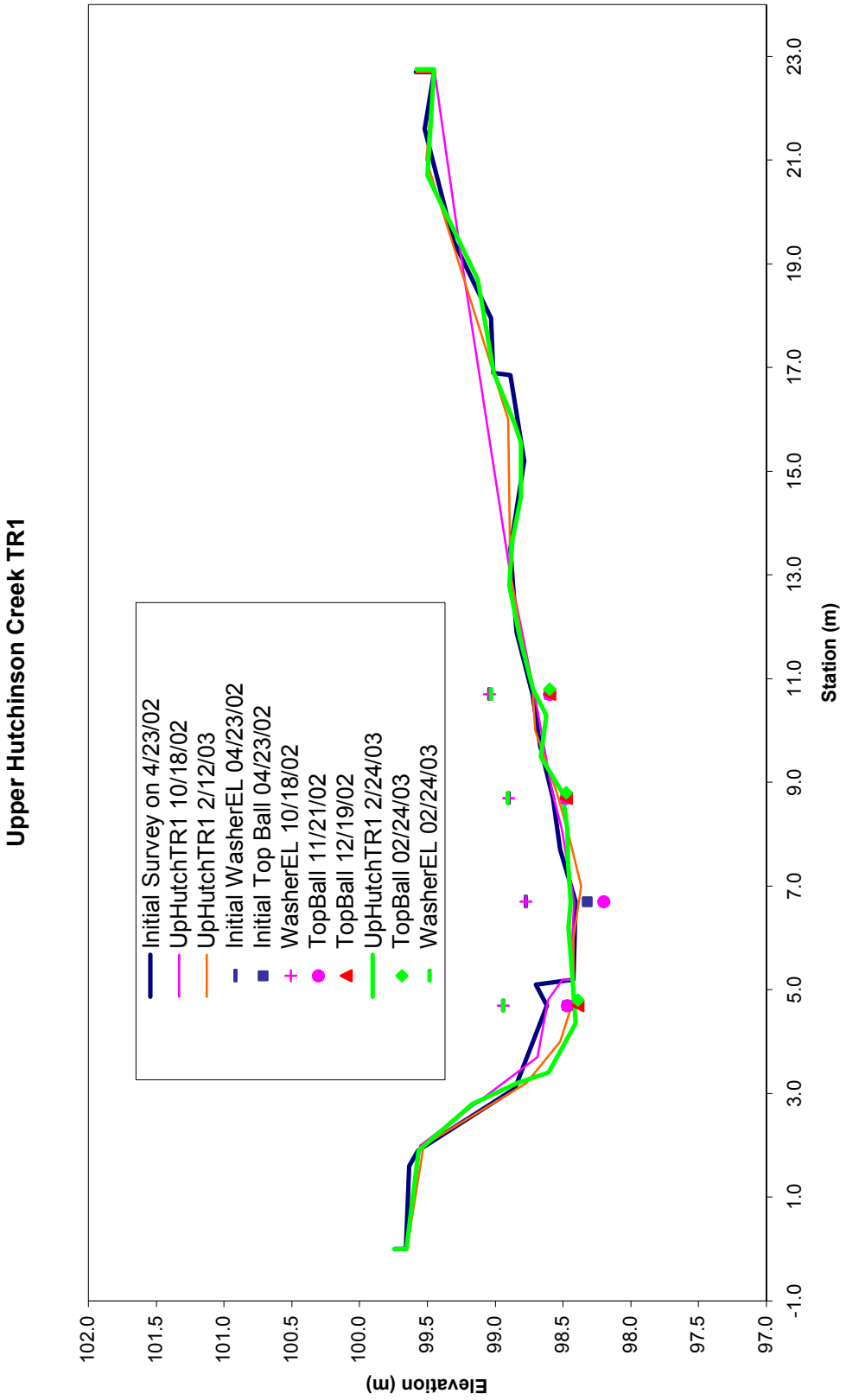
Appendix A. Cross-Section Plots.

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UpHutchTR1 10/18/02
UpHutchTR1 2/12/03
Initial WasherEL 04/23/02
Initial Top Ball 04/23/02
WasherEL 10/18/02
TopBall 11/21/02
TopBall 12/19/02
UpHutchTR1 2/24/03
TopBall 02/24/03
WasherEL 02/24/03
Elevation (m)
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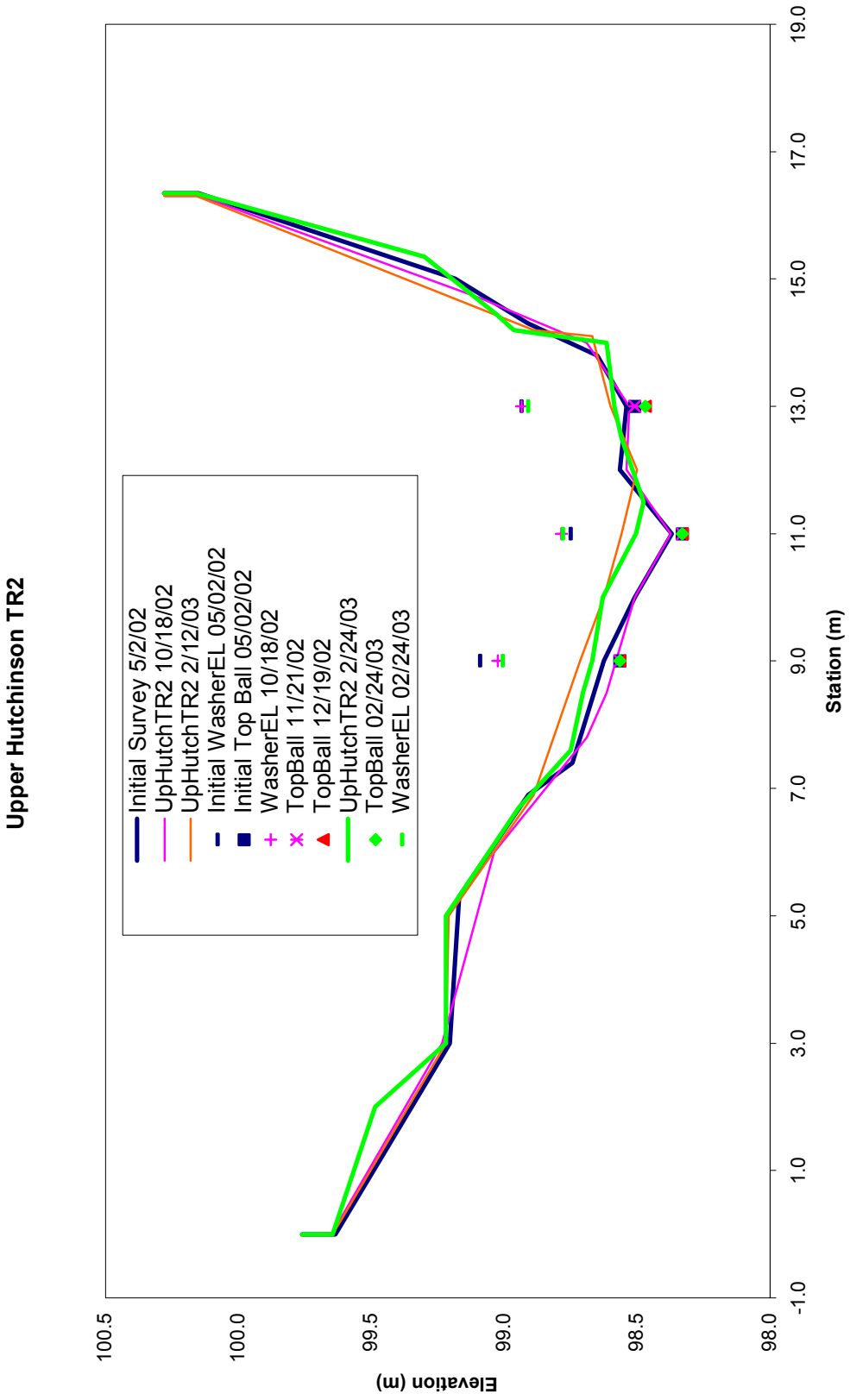
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Initial Survey 5/2/02
UpHutchTR2 10/18/02
UpHutchTR2 2/12/03
Initial WasherEL 05/02/02
Initial Top Ball 05/02/02
WasherEL 10/18/02
TopBall 11/21/02
TopBall 12/19/02
UpHutchTR2 2/24/03
TopBall 02/24/03
WasherEL 02/24/03
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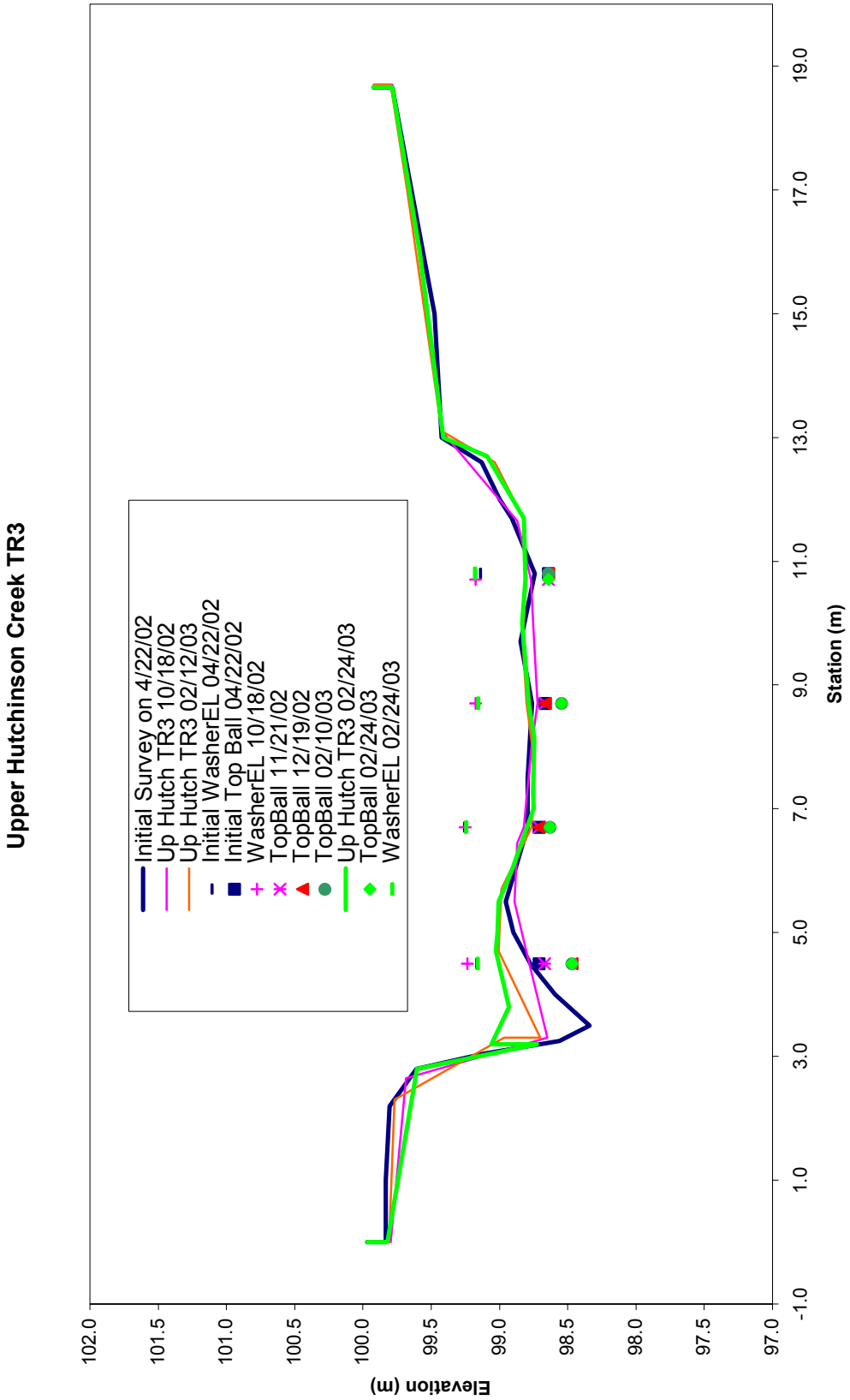
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Initial Survey on 4/22/02
Up Hutch TR3 10/18/02
Up Hutch TR3 02/12/03
Initial WasherEL 04/22/02
Initial Top Ball 04/22/02
WasherEL 10/18/02
TopBall 11/21/02
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TopBall 02/10/03
Up Hutch TR3 02/24/03
TopBall 02/24/03
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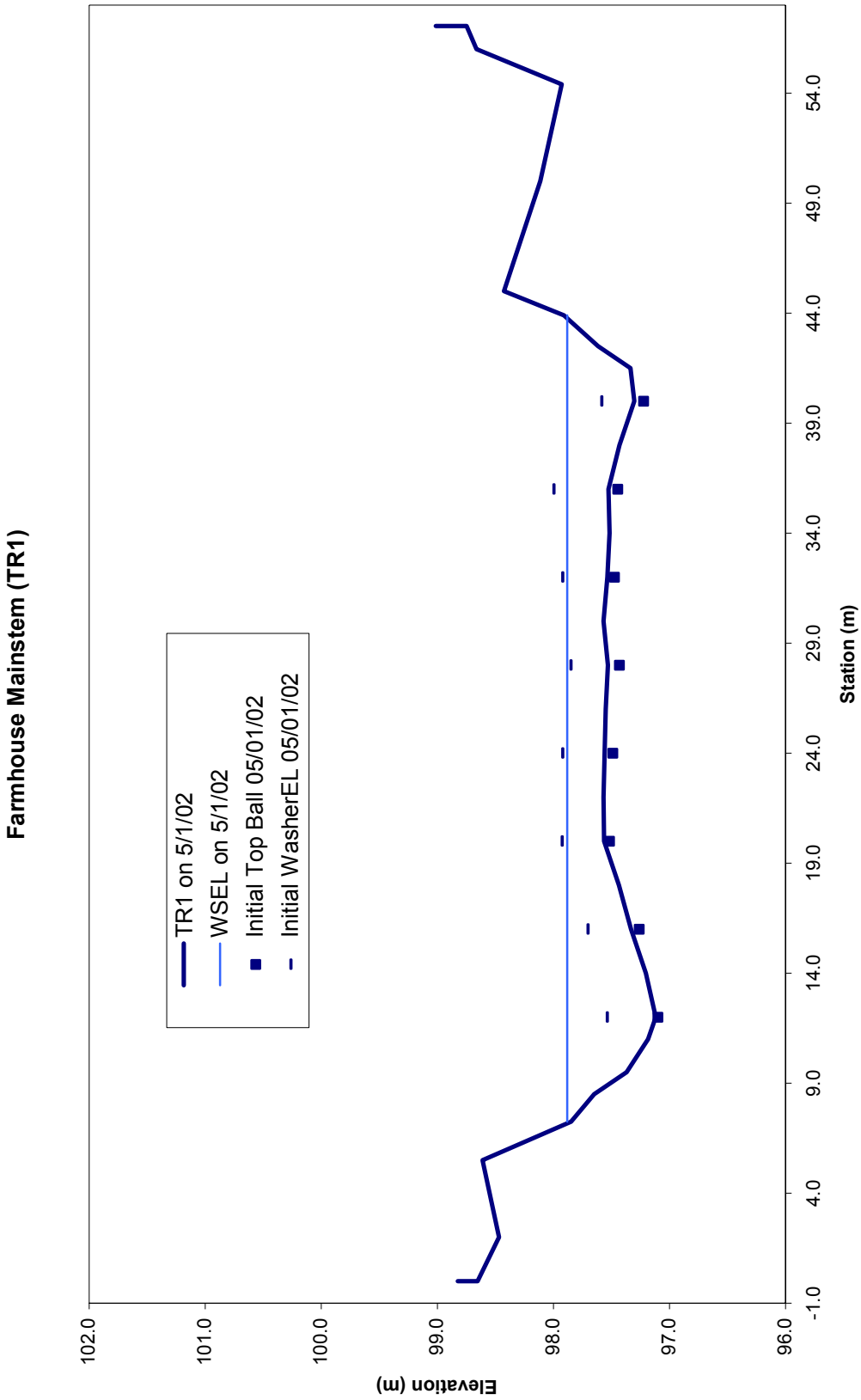
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TR1 on 5/1/02
WSEL on 5/1/02
Initial Top Ball 05/01/02
Initial WasherEL 05/01/02
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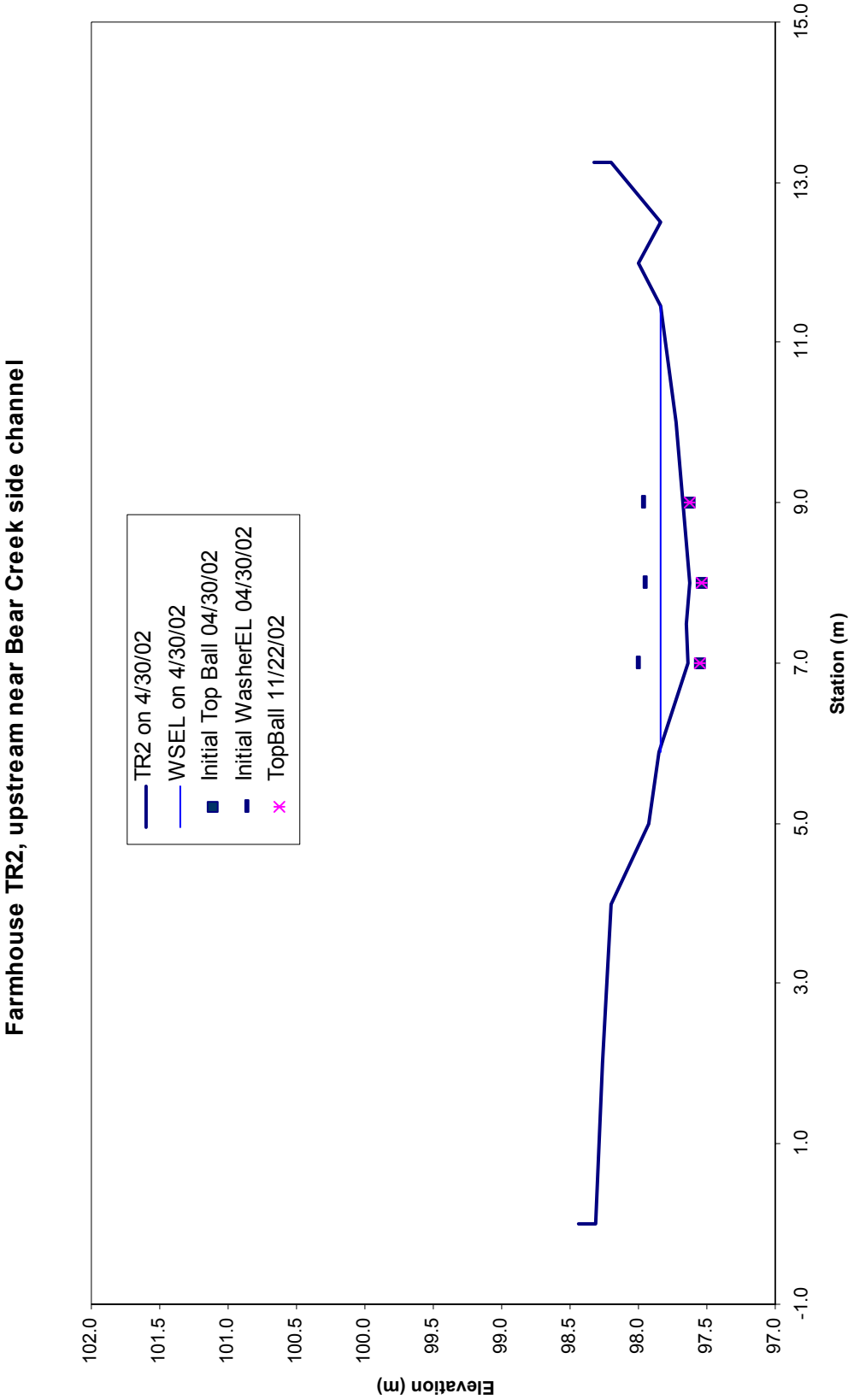
Farmhouse TR2, upstream near Bear Creek side channel
TR2 on 4/30/02
WSEL on 4/30/02
Initial Top Ball 04/30/02
Initial WasherEL 04/30/02
TopBall 11/22/02
Elevation (m)
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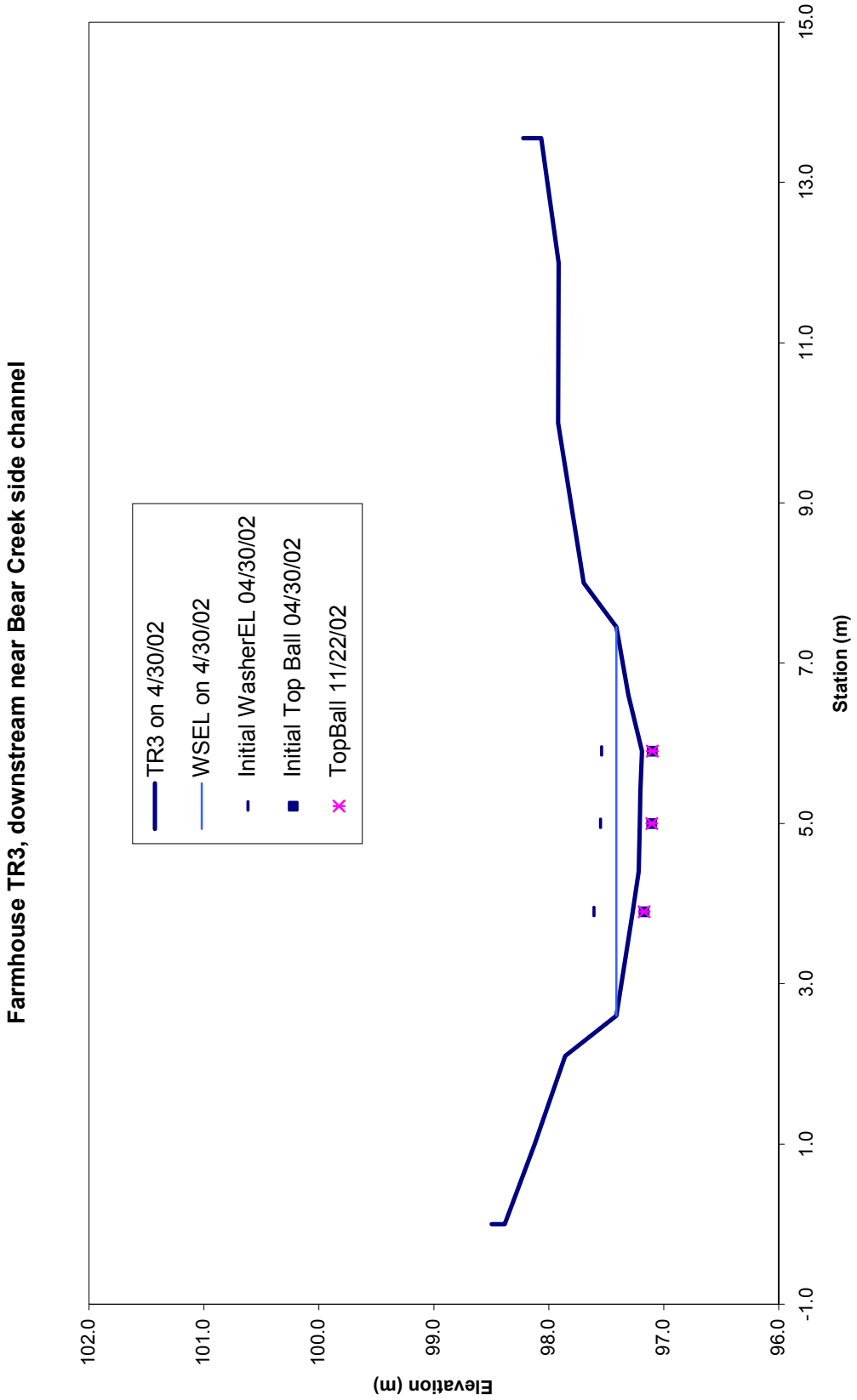
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TR3 on 4/30/02
WSEL on 4/30/02
Initial WasherEL 04/30/02
Initial Top Ball 04/30/02
TopBall 11/22/02
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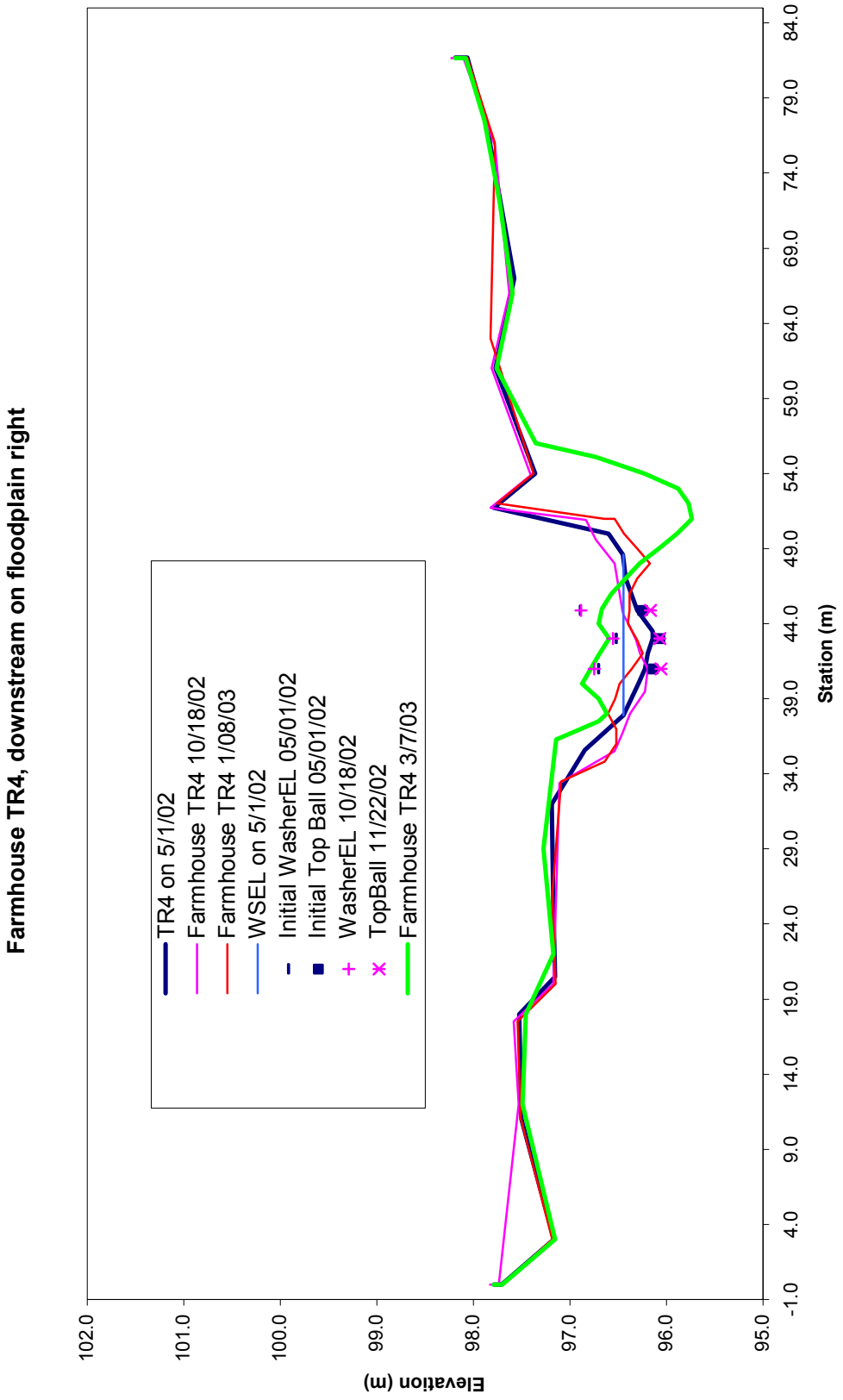
Farmhouse TR4, downstream on floodplain right
TR4 on 5/1/02
Farmhouse TR4 10/18/02
Farmhouse TR4 1/08/03
WSEL on 5/1/02
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Initial Top Ball 05/01/02
WasherEL 10/18/02
TopBall 11/22/02
Farmhouse TR4 3/7/03
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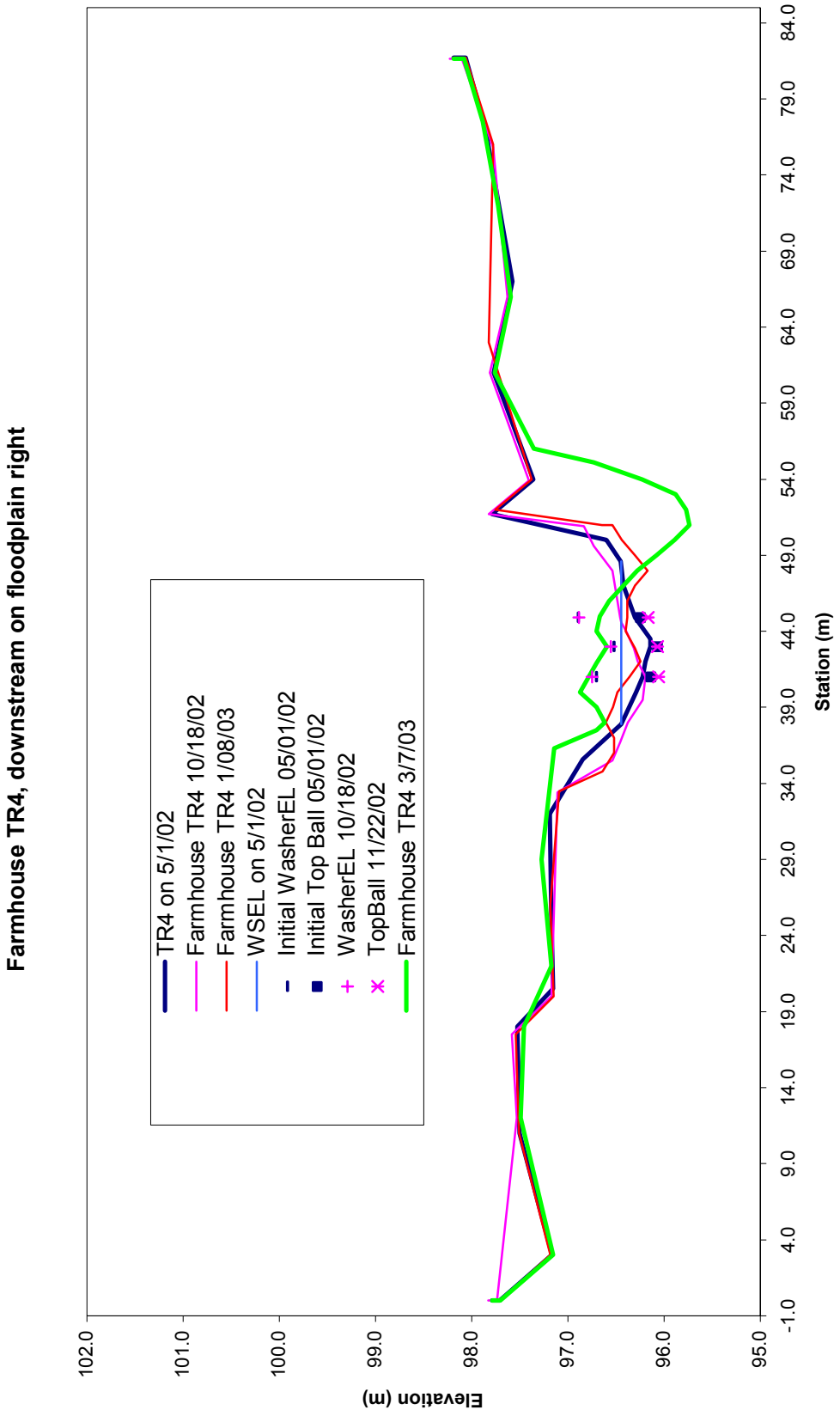
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TR4 on 5/1/02
Farmhouse TR4 10/18/02
Farmhouse TR4 1/08/03
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WasherEL 10/18/02
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Farmhouse TR4 3/7/03
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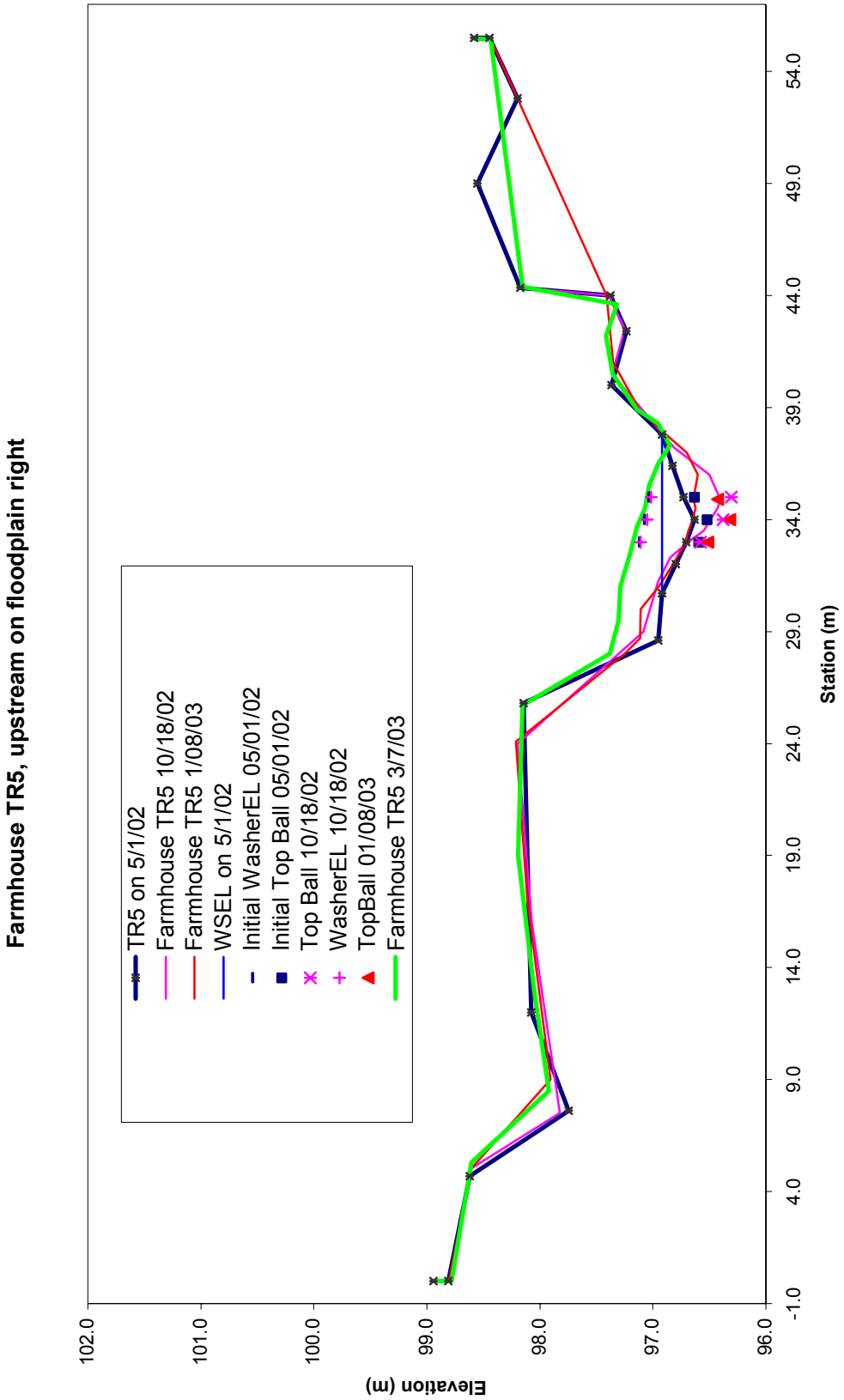
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Farmhouse TR5 1/08/03
WSEL on 5/1/02
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Initial Top Ball 05/01/02
Top Ball 10/18/02
WasherEL 10/18/02
TopBall 01/08/03
Farmhouse TR5 3/7/03
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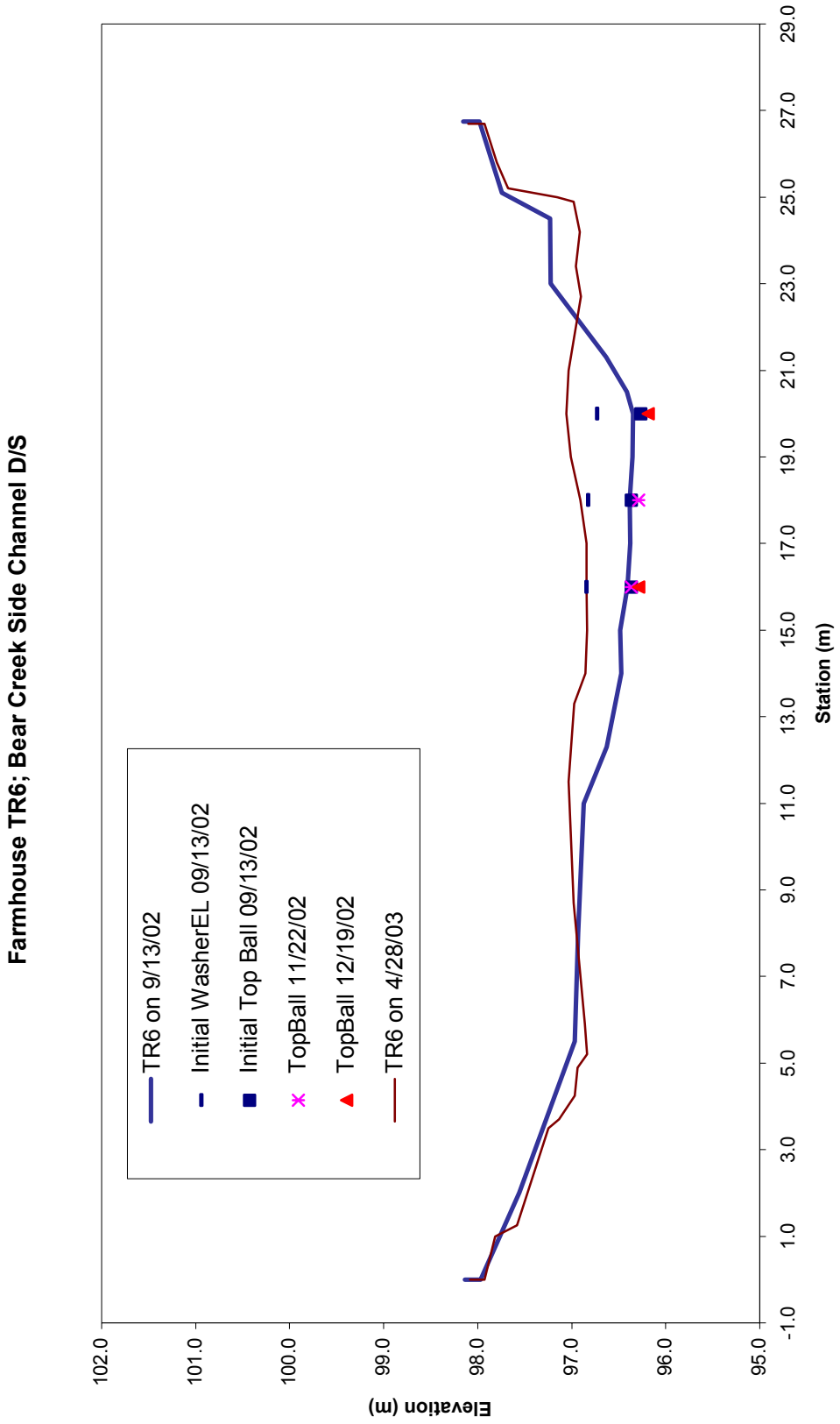
Farmhouse TR6; Bear Creek Side Channel D/S
TR6 on 9/13/02
Initial WasherEL 09/13/02
Initial Top Ball 09/13/02
TopBall 11/22/02
TopBall 12/19/02
TR6 on 4/28/03
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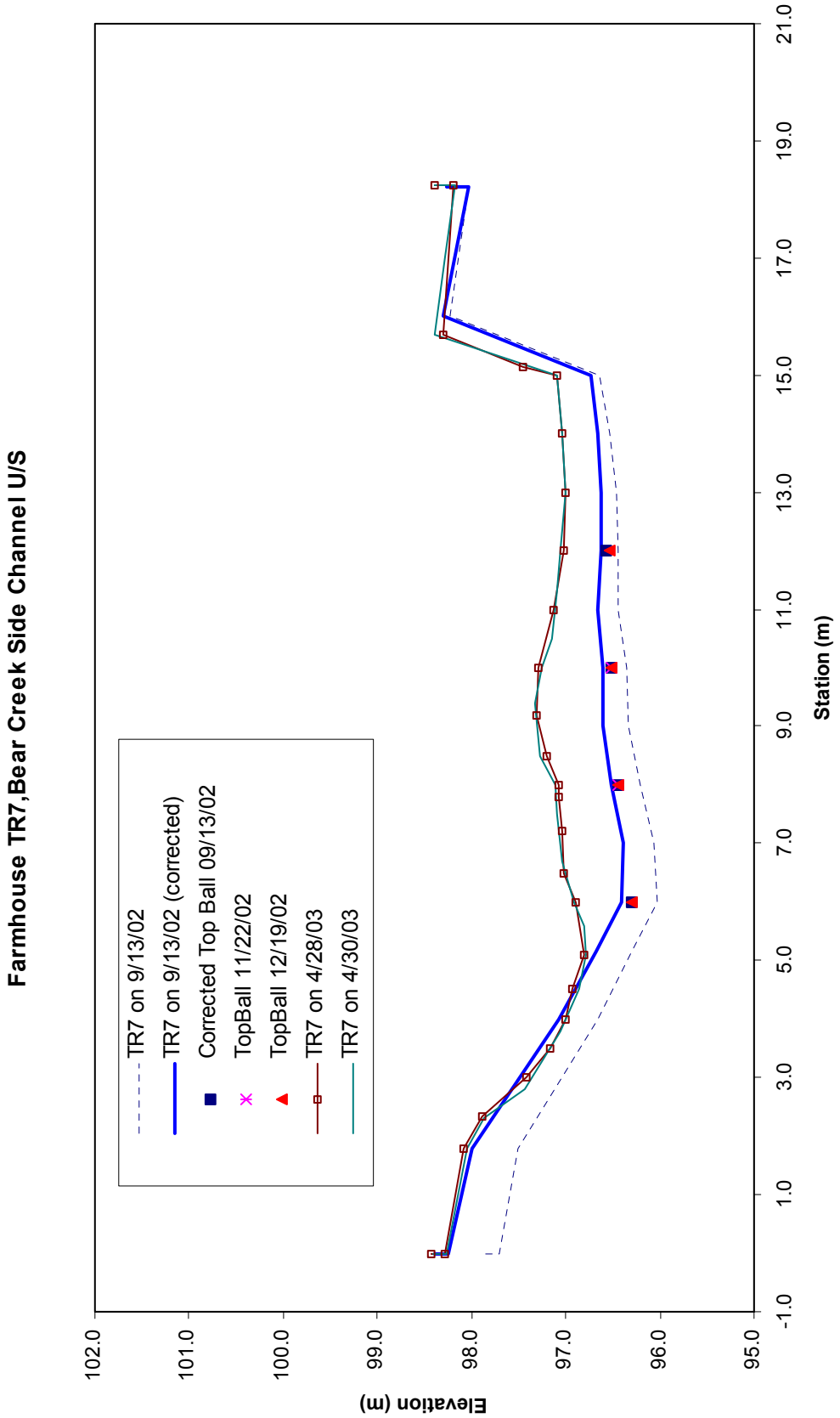
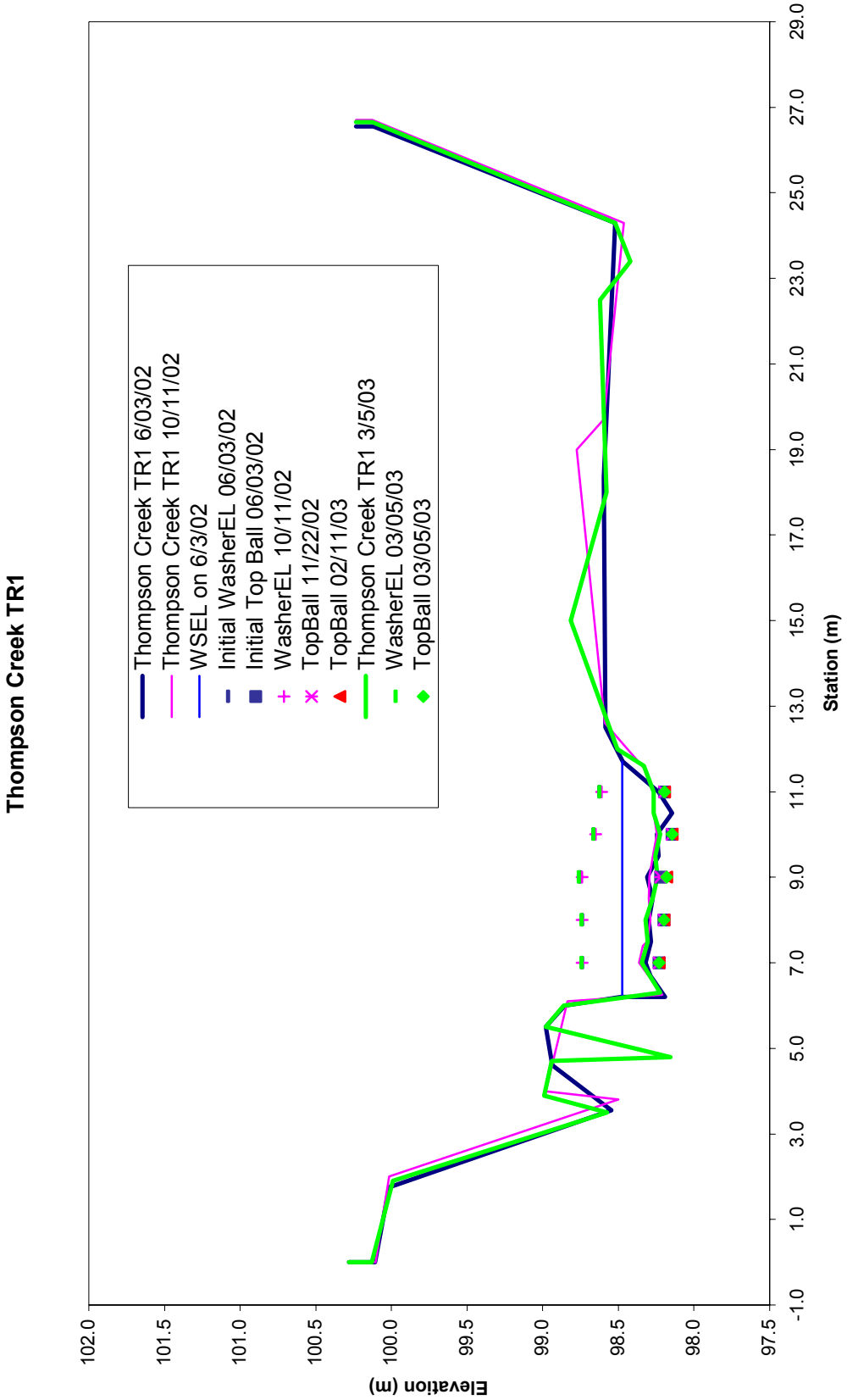
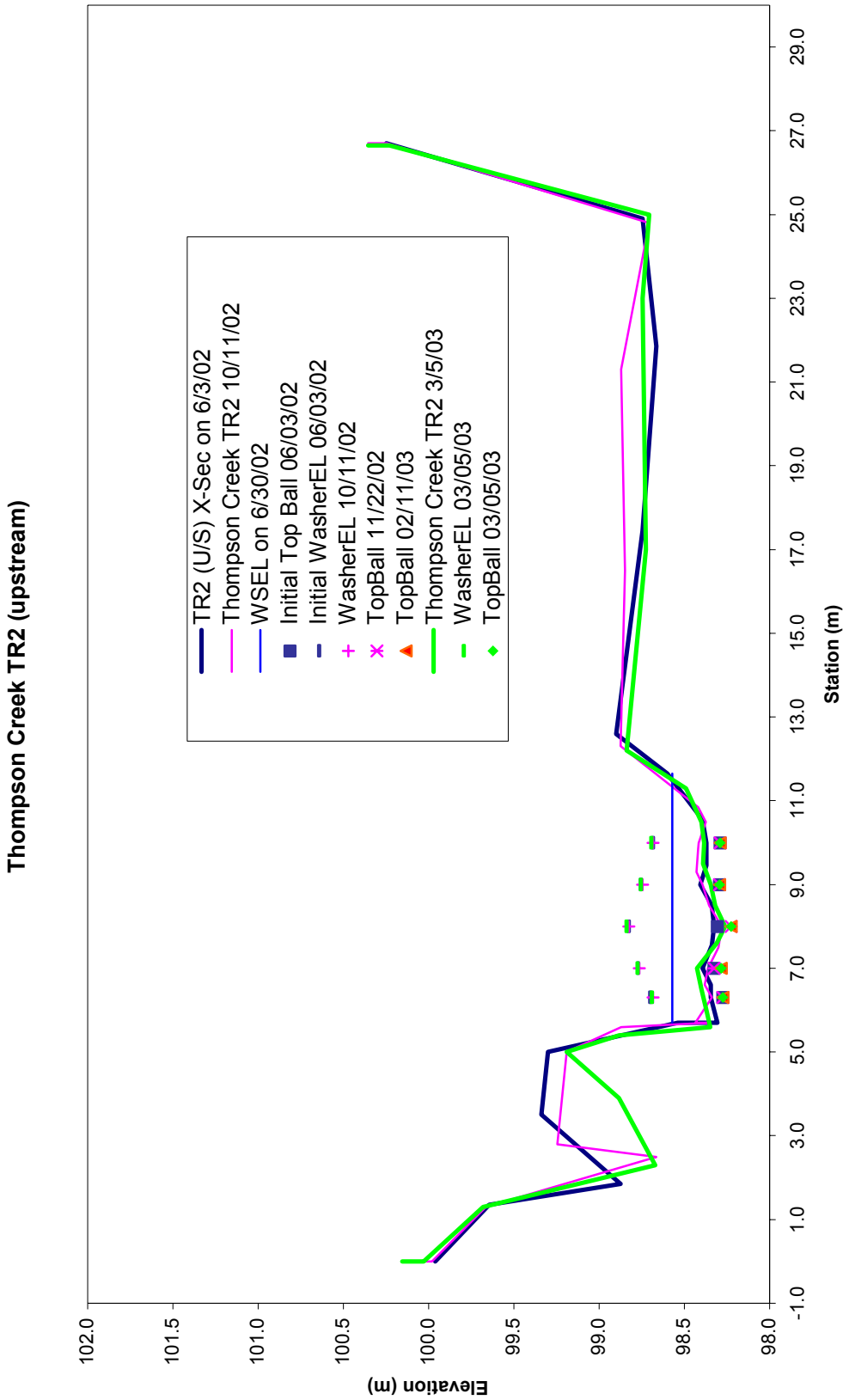
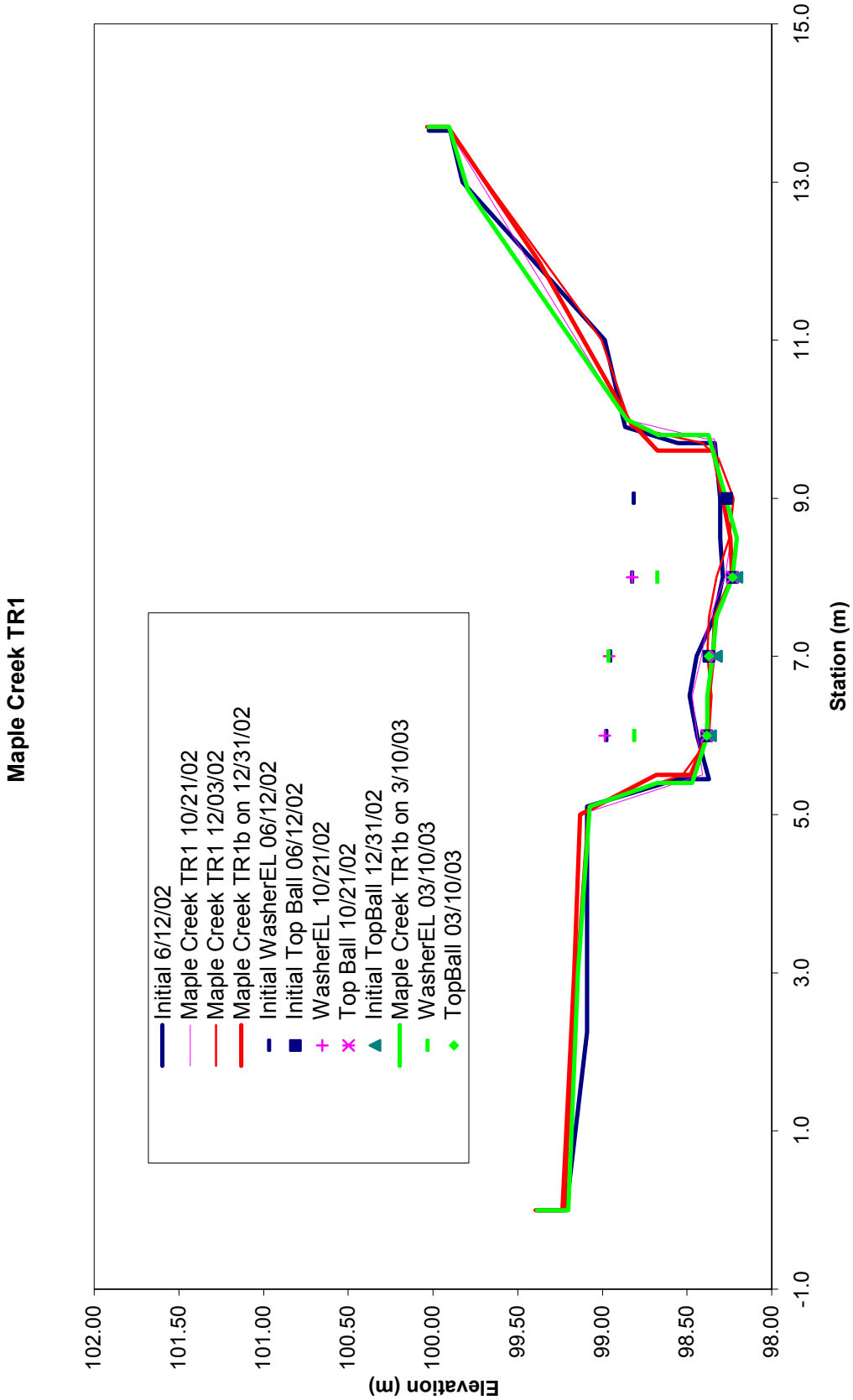
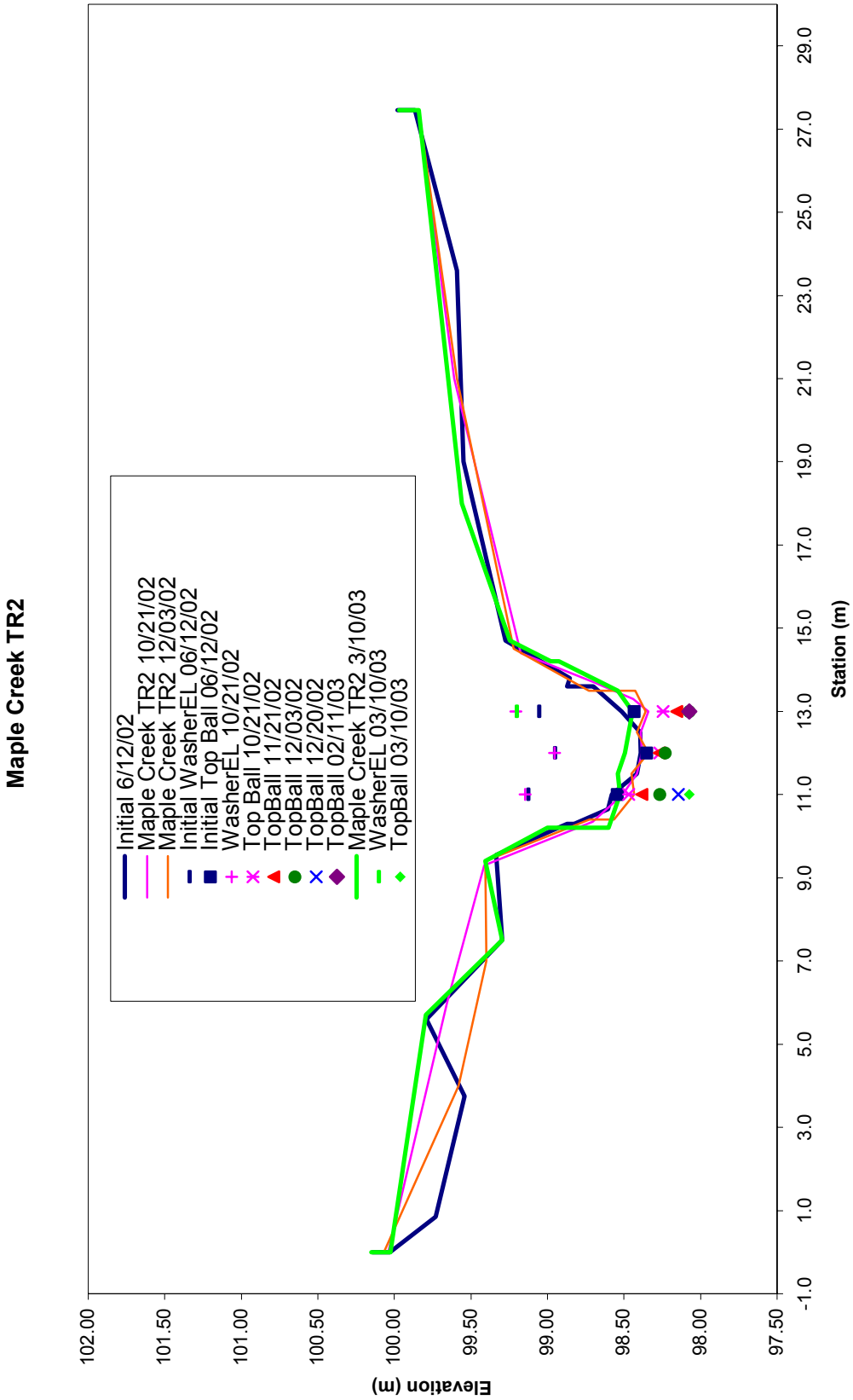

Farmhouse TR7,Bear Creek Side Channel U/S
TR7 on 9/13/02
TR7 on 9/13/02 (corrected)
Corrected Top Ball 09/13/02
TopBall 11/22/02
TopBall 12/19/02
TR7 on 4/28/03
TR7 on 4/30/03
Elevation (m)
102.0
101.0
100.0
99.0
98.0
97.0
96.0
95.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0
21.0


Thompson Creek TR1
Thompson Creek TR1 6/03/02
Thompson Creek TR1 10/11/02
WSEL on 6/3/02
Initial WasherEL 06/03/02
Initial Top Ball 06/03/02
WasherEL 10/11/02
TopBall 11/22/02
TopBall 02/11/03
Thompson Creek TR1 3/5/03
WasherEL 03/05/03
TopBall 03/05/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0
21.0
23.0
25.0
27.0
29.0


Thompson Creek TR2 (upstream)
TR2 (U/S) X-Sec on 6/3/02
Thompson Creek TR2 10/11/02
WSEL on 6/30/02
Initial Top Ball 06/03/02
Initial WasherEL 06/03/02
WasherEL 10/11/02
TopBall 11/22/02
TopBall 02/11/03
Thompson Creek TR2 3/5/03
WasherEL 03/05/03
TopBall 03/05/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0
21.0
23.0
25.0
27.0
29.0


Maple Creek TR1
Initial 6/12/02
Maple Creek TR1 10/21/02
Maple Creek TR1 12/03/02
Maple Creek TR1b on 12/31/02
Initial WasherEL 06/12/02
Initial Top Ball 06/12/02
WasherEL 10/21/02
Top Ball 10/21/02
Initial TopBall 12/31/02
Maple Creek TR1b on 3/10/03
WasherEL 03/10/03
TopBall 03/10/03
Elevation (m)
102.00
101.50
101.00
100.50
100.00
99.50
99.00
98.50
98.00
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0


Maple Creek TR2
Initial 6/12/02
Maple Creek TR2 10/21/02
Maple Creek TR2 12/03/02
Initial WasherEL 06/12/02
Initial Top Ball 06/12/02
WasherEL 10/21/02
Top Ball 10/21/02
TopBall 11/21/02
TopBall 12/03/02
TopBall 12/20/02
TopBall 02/11/03
Maple Creek TR2 3/10/03
WasherEL 03/10/03
TopBall 03/10/03
Elevation (m)
102.00
101.50
101.00
100.50
100.00
99.50
99.00
98.50
98.00
97.50
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
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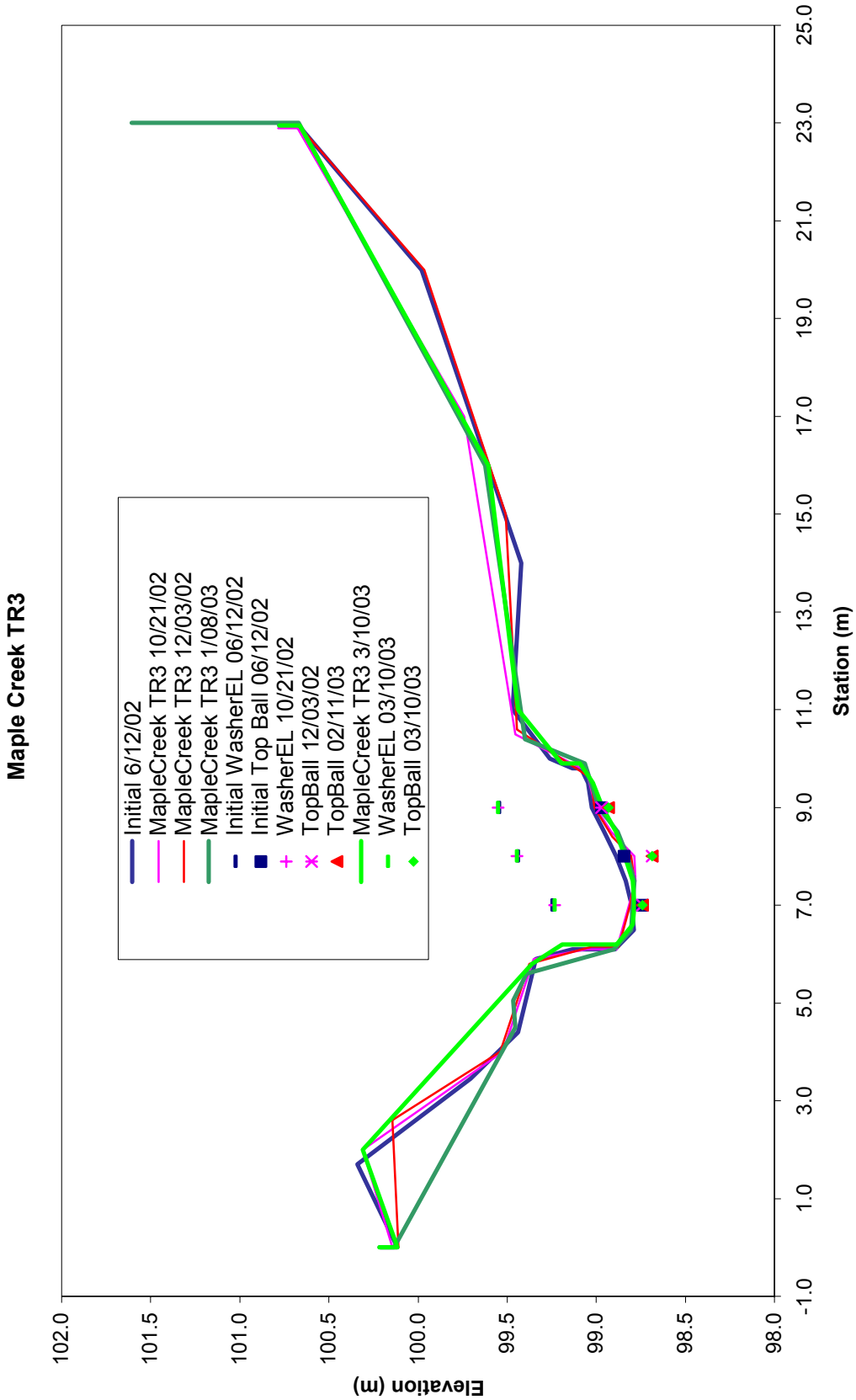
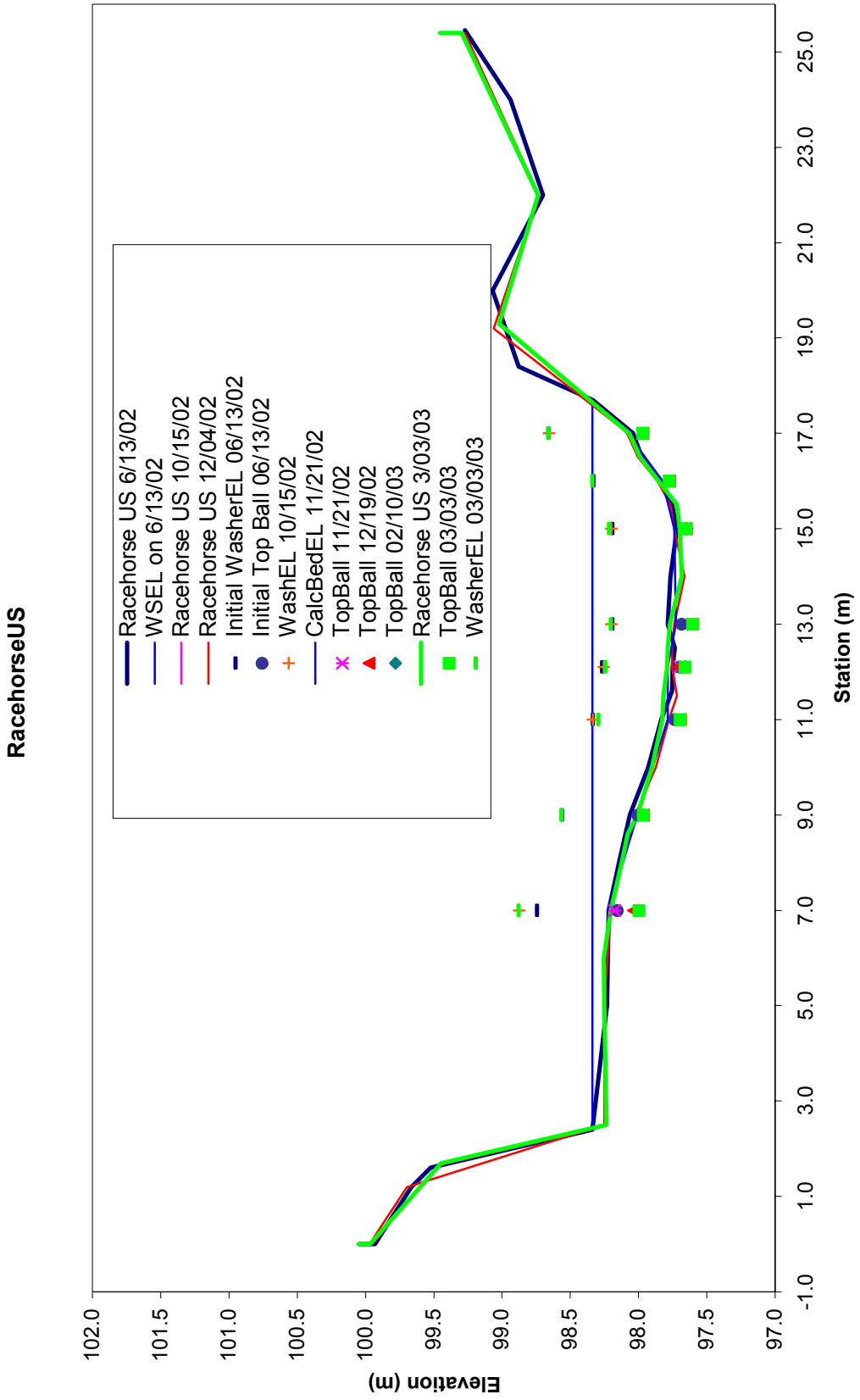
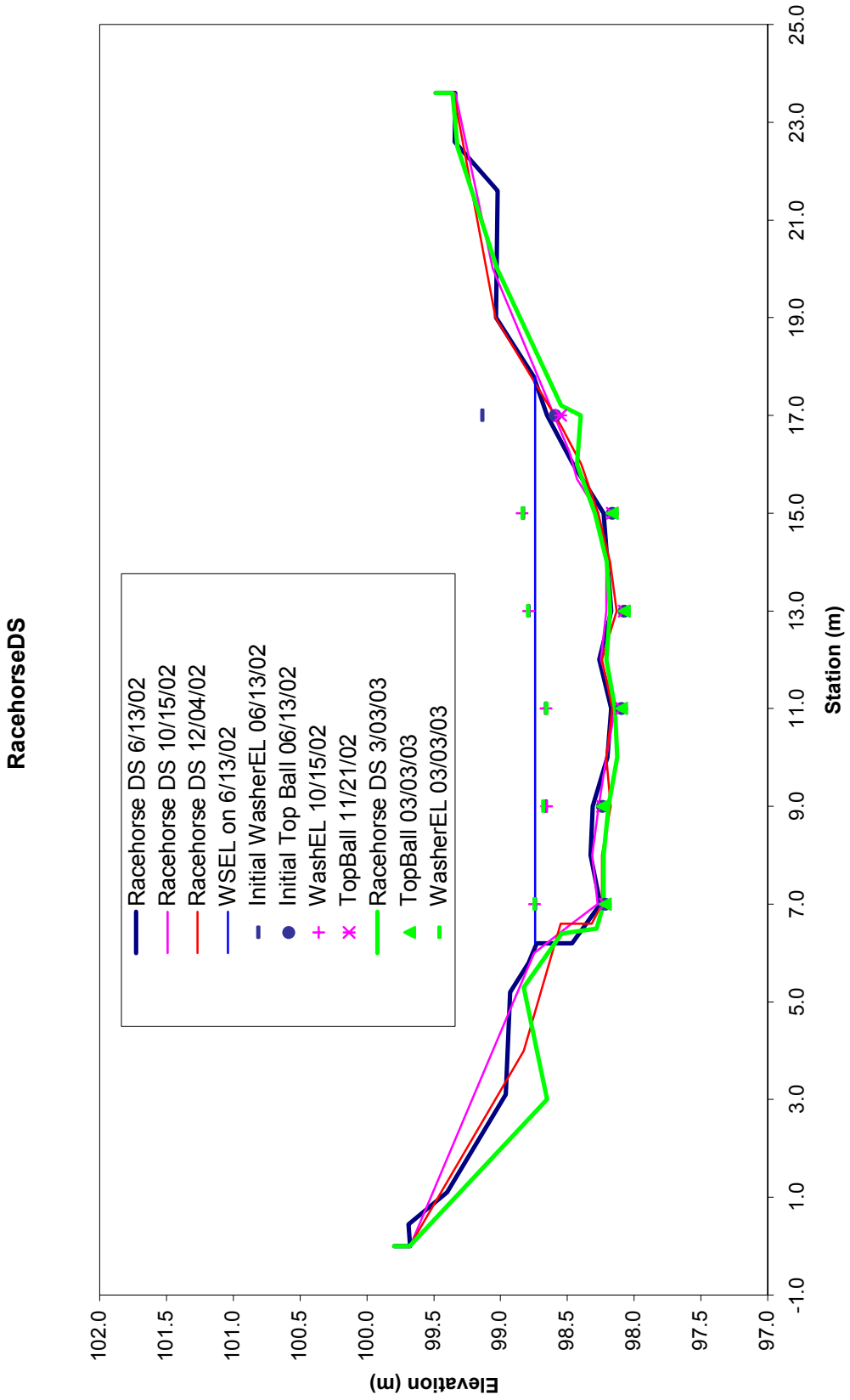
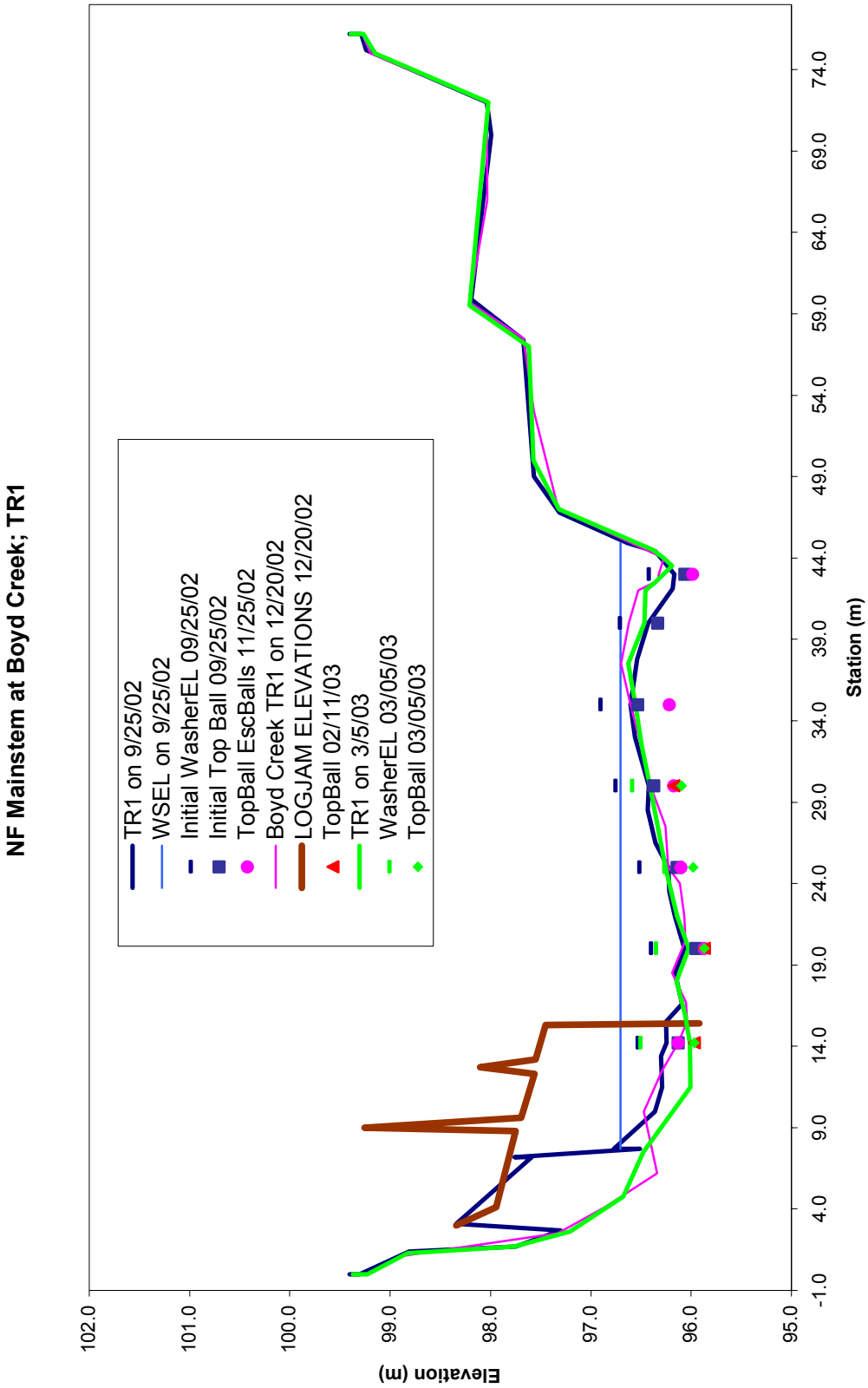
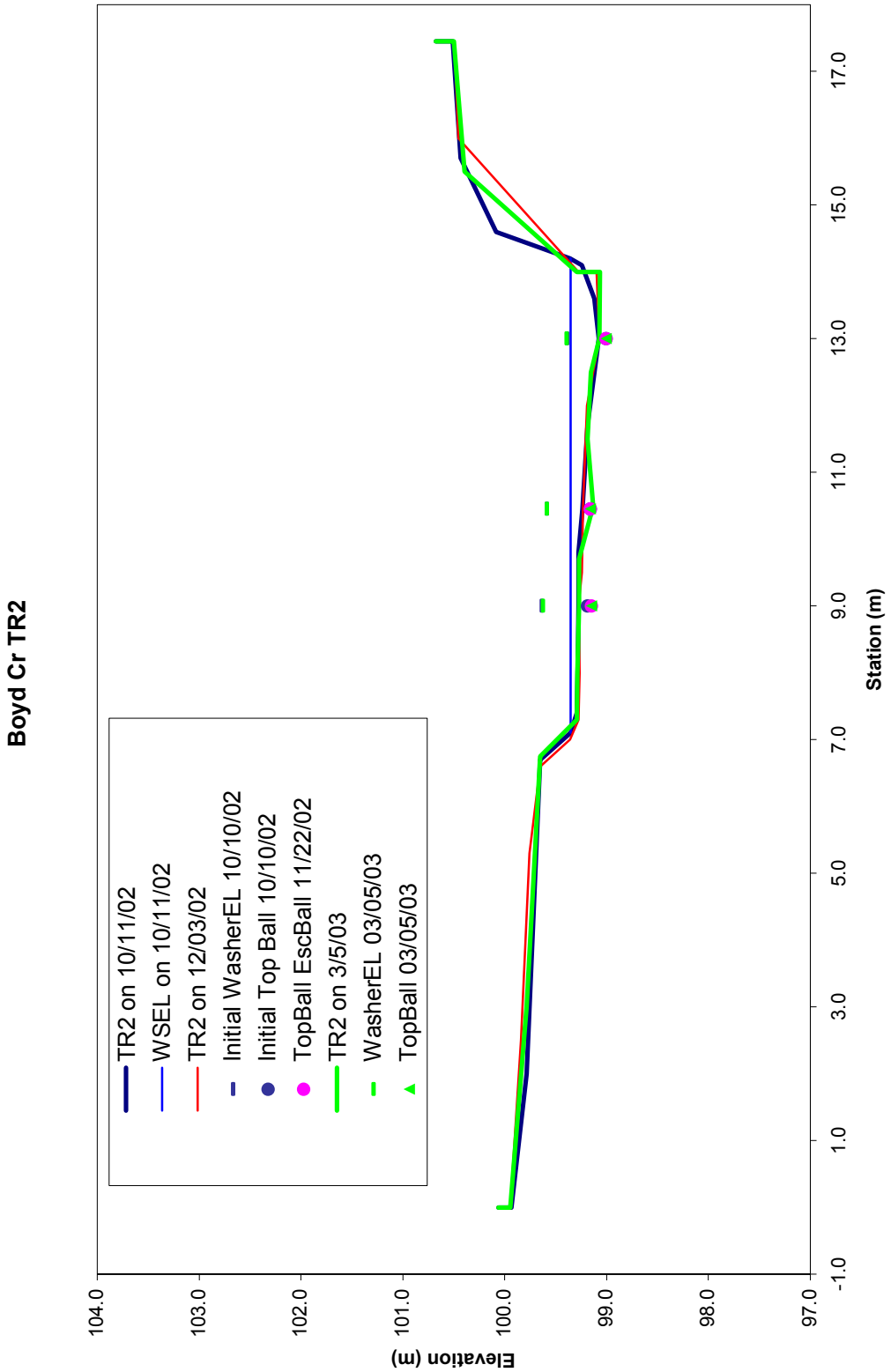
19.0
21.0
23.0
25.0
27.0
29.0

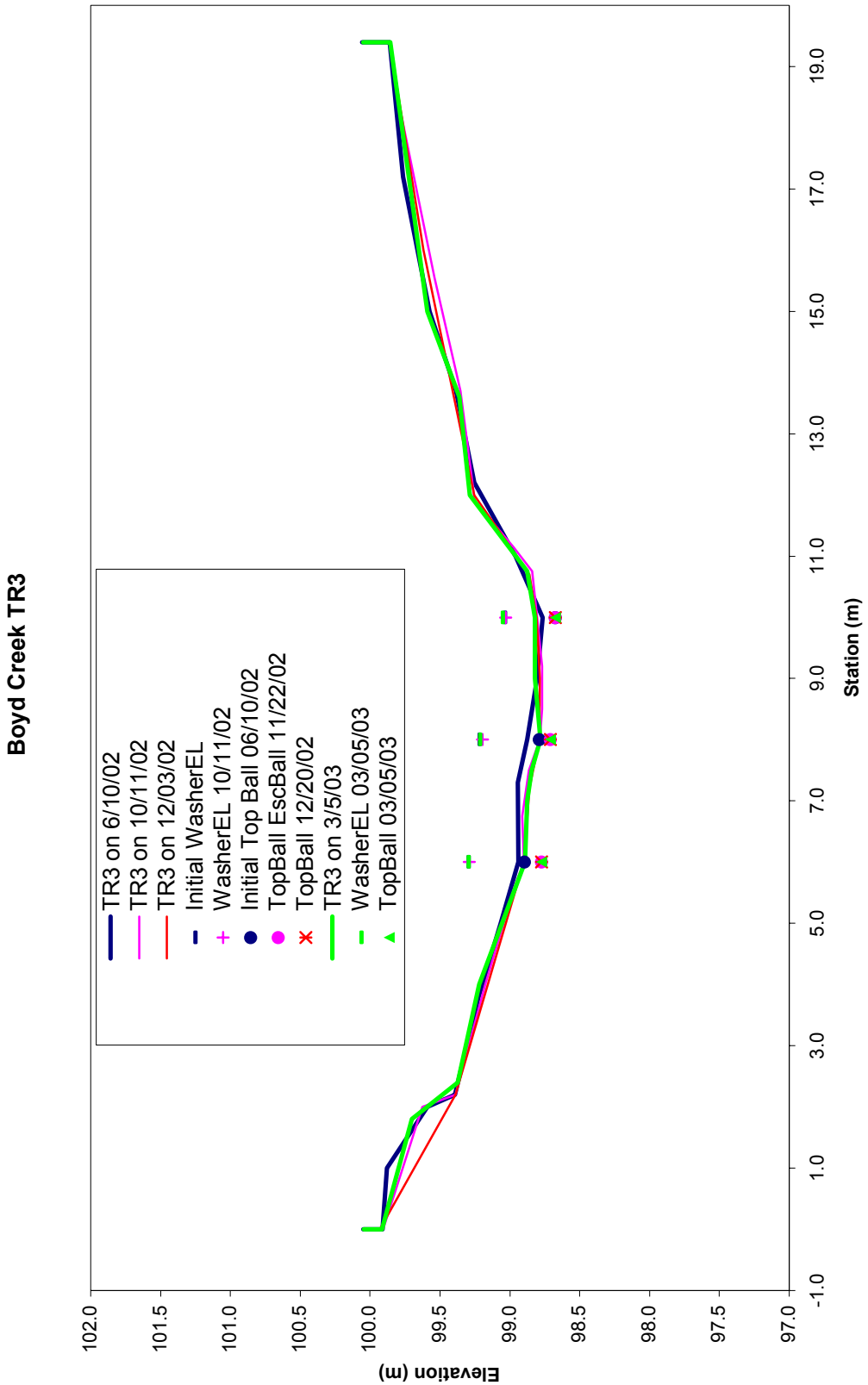

Maple Creek TR3
Initial 6/12/02
MapleCreek TR3 10/21/02
MapleCreek TR3 12/03/02
MapleCreek TR3 1/08/03
Initial WasherEL 06/12/02
Initial Top Ball 06/12/02
WasherEL 10/21/02
TopBall 12/03/02
TopBall 02/11/03
MapleCreek TR3 3/10/03
WasherEL 03/10/03
TopBall 03/10/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0
21.0
23.0
25.0

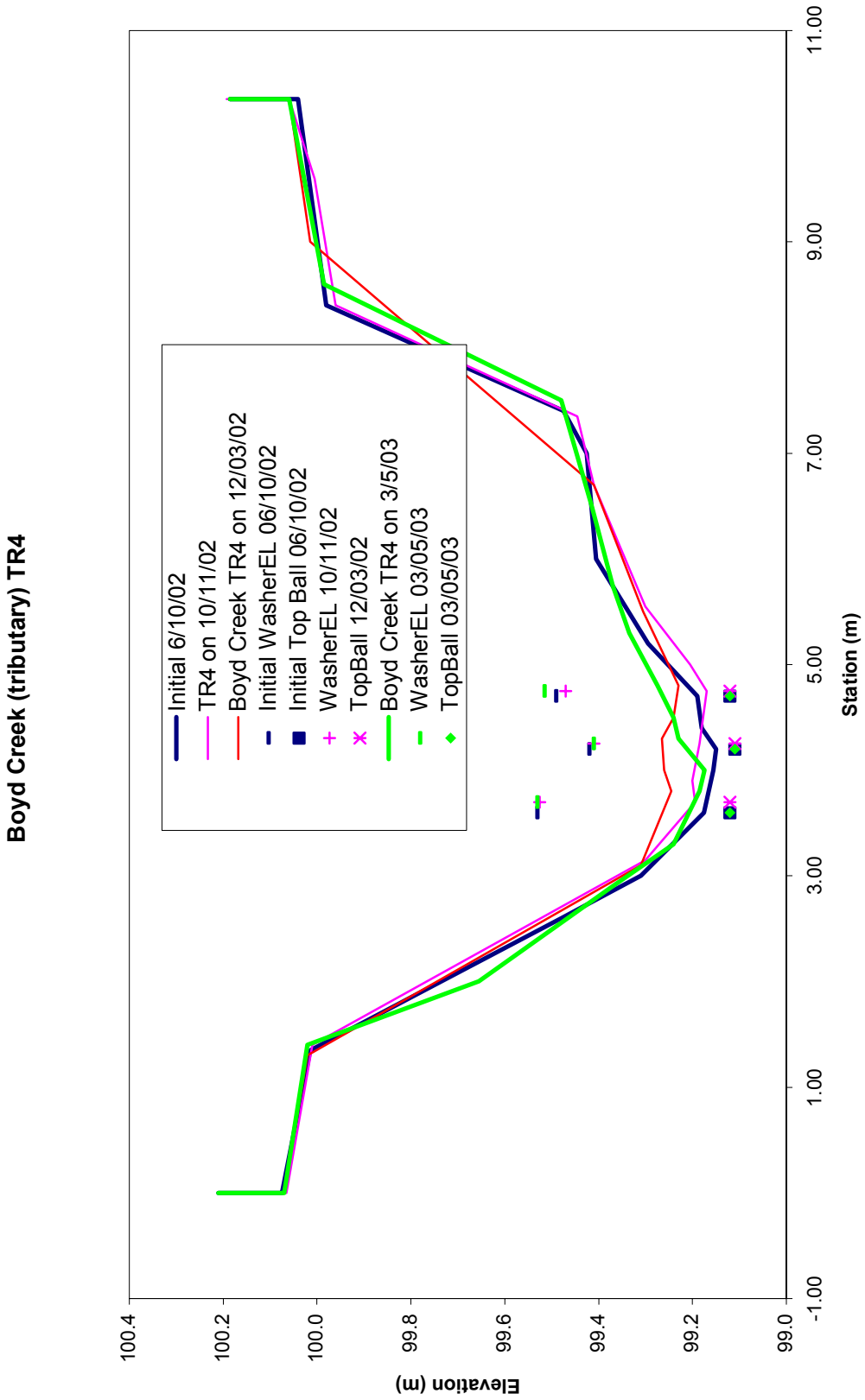

RacehorseUS
Racehorse US 6/13/02
WSEL on 6/13/02
Racehorse US 10/15/02
Racehorse US 12/04/02
Initial WasherEL 06/13/02
Initial Top Ball 06/13/02
WashEL 10/15/02
CalcBedEL 11/21/02
TopBall 11/21/02
TopBall 12/19/02
TopBall 02/10/03
Racehorse US 3/03/03
TopBall 03/03/03
WasherEL 03/03/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0
21.0
23.0
25.0

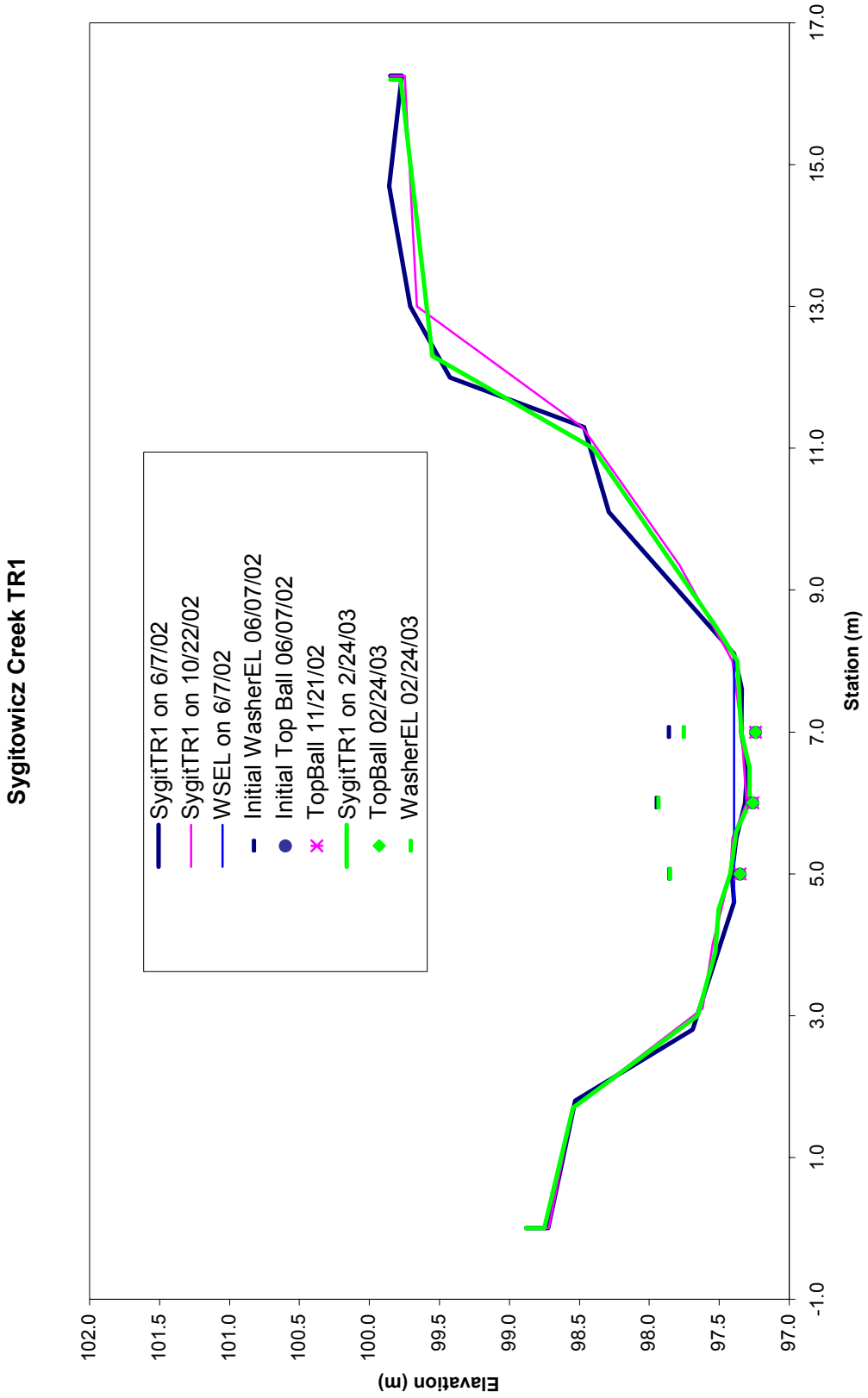

RacehorseDS
Racehorse DS 6/13/02
Racehorse DS 10/15/02
Racehorse DS 12/04/02
WSEL on 6/13/02
Initial WasherEL 06/13/02
Initial Top Ball 06/13/02
WashEL 10/15/02
TopBall 11/21/02
Racehorse DS 3/03/03
TopBall 03/03/03
WasherEL 03/03/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0
21.0
23.0
25.0

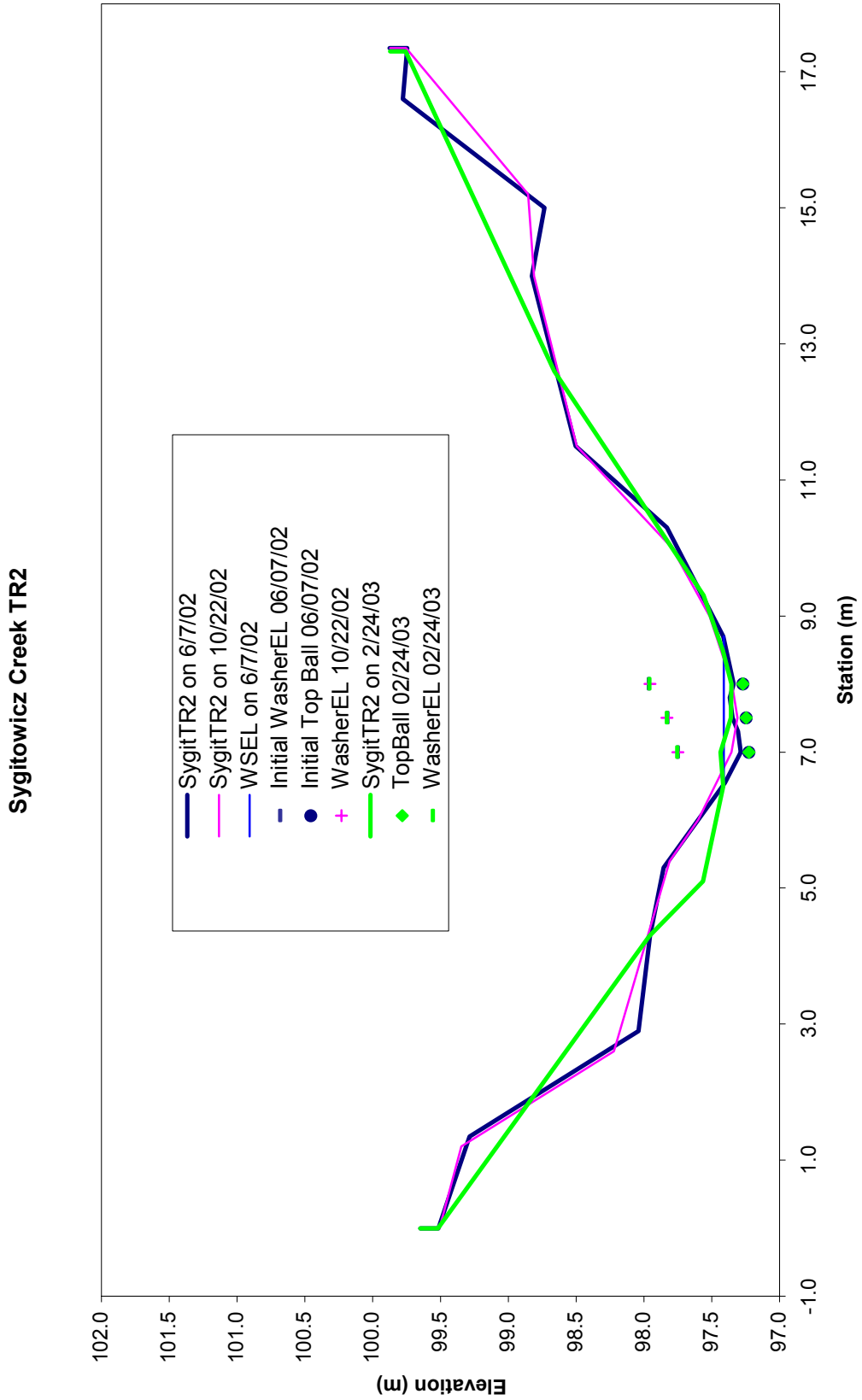

NF Mainstem at Boyd Creek; TR1
TR1 on 9/25/02
WSEL on 9/25/02
Initial WasherEL 09/25/02
Initial Top Ball 09/25/02
TopBall EscBalls 11/25/02
Boyd Creek TR1 on 12/20/02
LOGJAM ELEVATIONS 12/20/02
TopBall 02/11/03
TR1 on 3/5/03
WasherEL 03/05/03
TopBall 03/05/03
Elevation (m)
102.0
101.0
100.0
99.0
98.0
97.0
96.0
95.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0
44.0
49.0
54.0
59.0
64.0
69.0
74.0

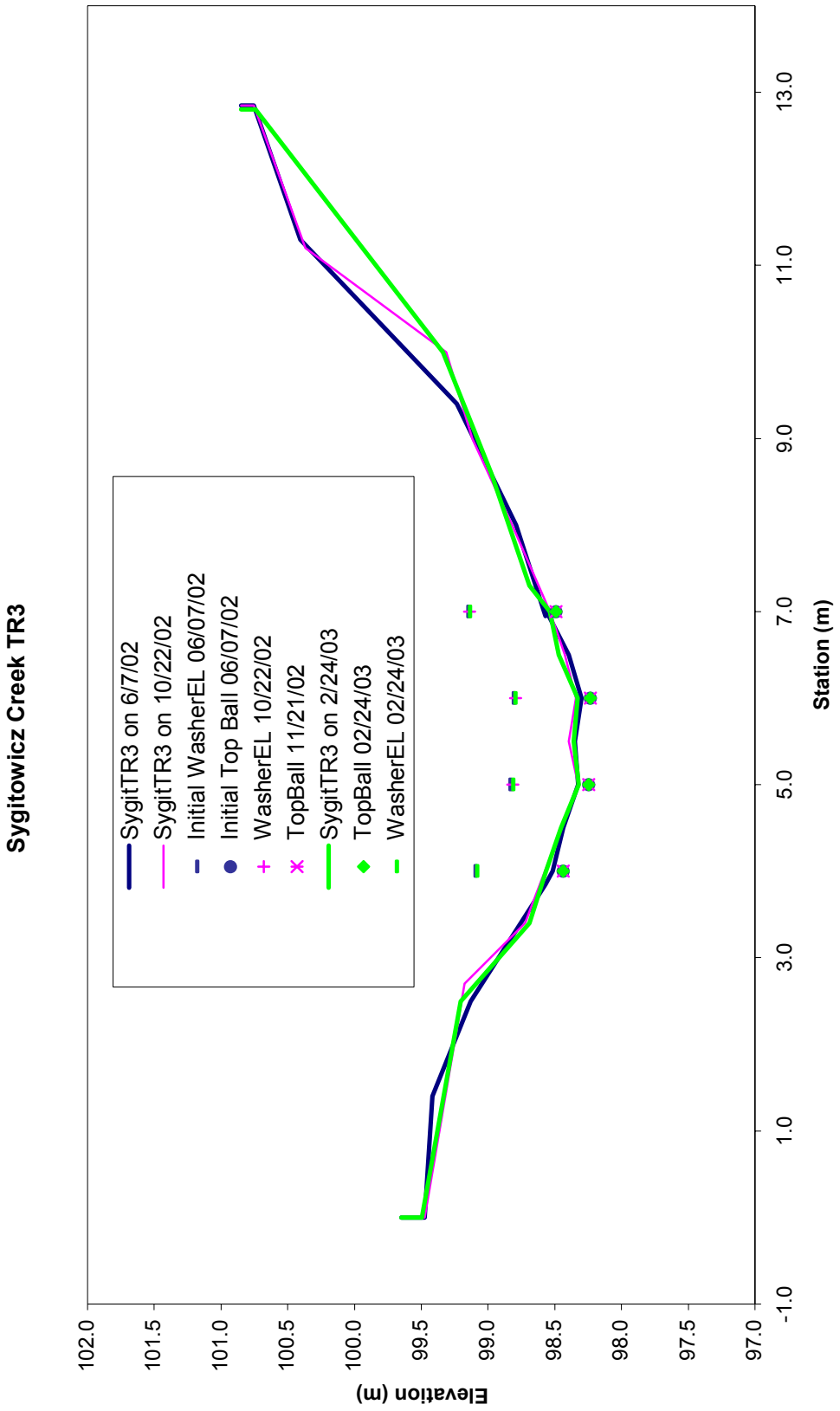

Boyd Cr TR2
TR2 on 10/11/02
WSEL on 10/11/02
TR2 on 12/03/02
Initial WasherEL 10/10/02
Initial Top Ball 10/10/02
TopBall EscBall 11/22/02
TR2 on 3/5/03
WasherEL 03/05/03
TopBall 03/05/03
Elevation (m)
104.0
103.0
102.0
101.0
100.0
99.0
98.0
97.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0

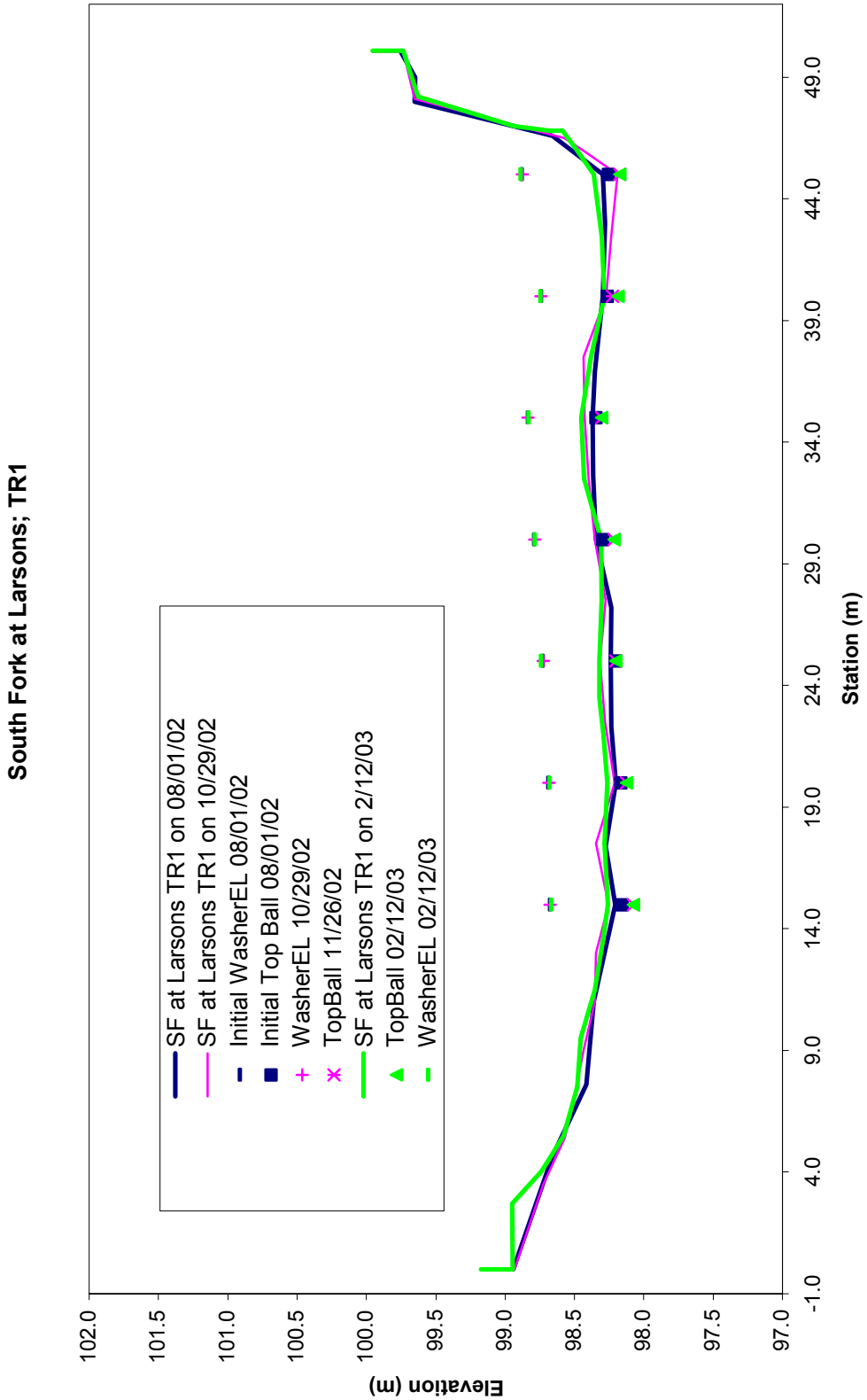

Boyd Creek TR3
TR3 on 6/10/02
TR3 on 10/11/02
TR3 on 12/03/02
Initial WasherEL
WasherEL 10/11/02
Initial Top Ball 06/10/02
TopBall EscBall 11/22/02
TopBall 12/20/02
TR3 on 3/5/03
WasherEL 03/05/03
TopBall 03/05/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0

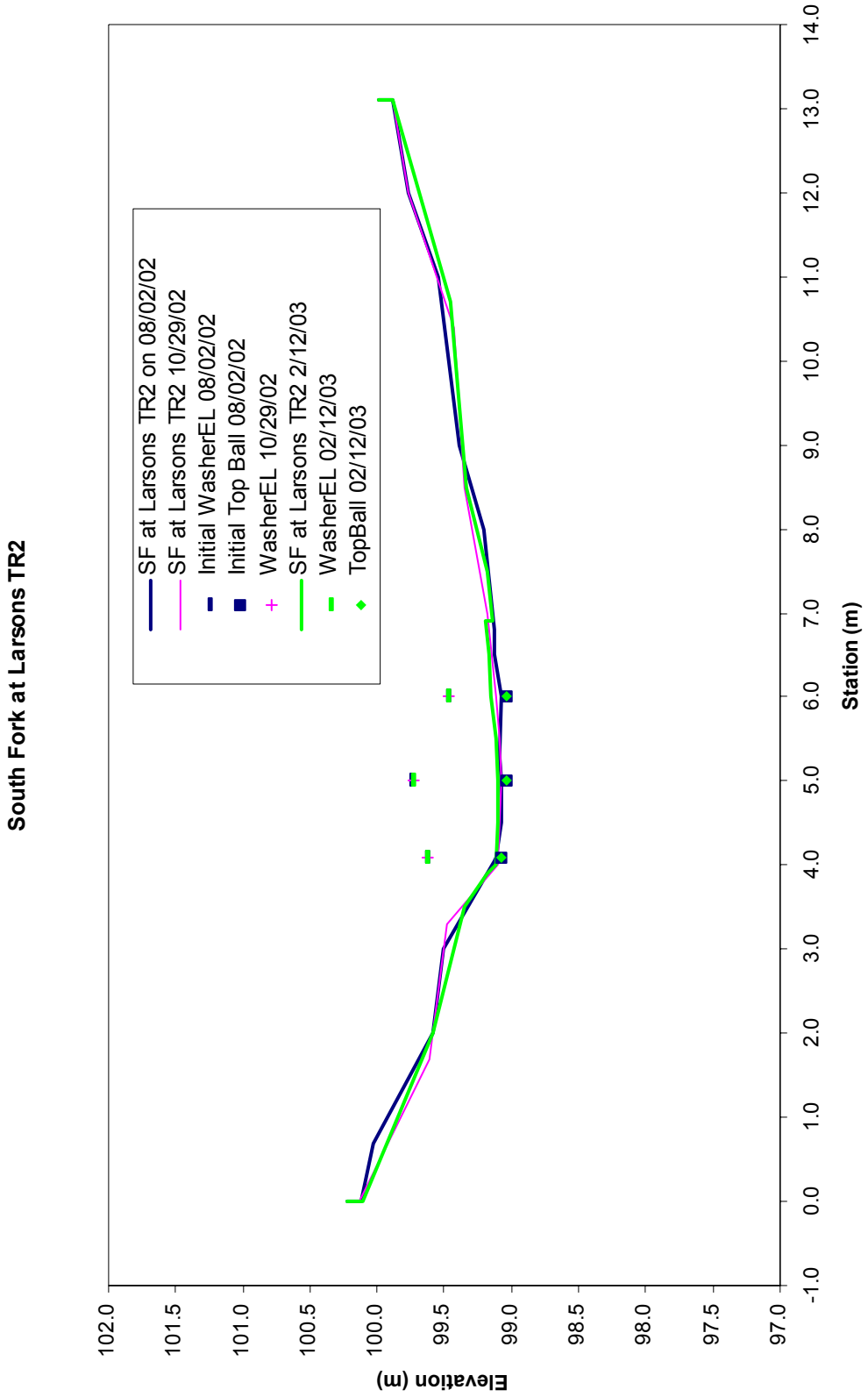

Boyd Creek (tributary) TR4
Initial 6/10/02
TR4 on 10/11/02
Boyd Creek TR4 on 12/03/02
Initial WasherEL 06/10/02
Initial Top Ball 06/10/02
WasherEL 10/11/02
TopBall 12/03/02
Boyd Creek TR4 on 3/5/03
WasherEL 03/05/03
TopBall 03/05/03
Elevation (m)
100.4
100.2
100.0
99.8
99.6
99.4
99.2
99.0
Station (m)
-1.00
1.00
3.00
5.00
7.00
9.00
11.00

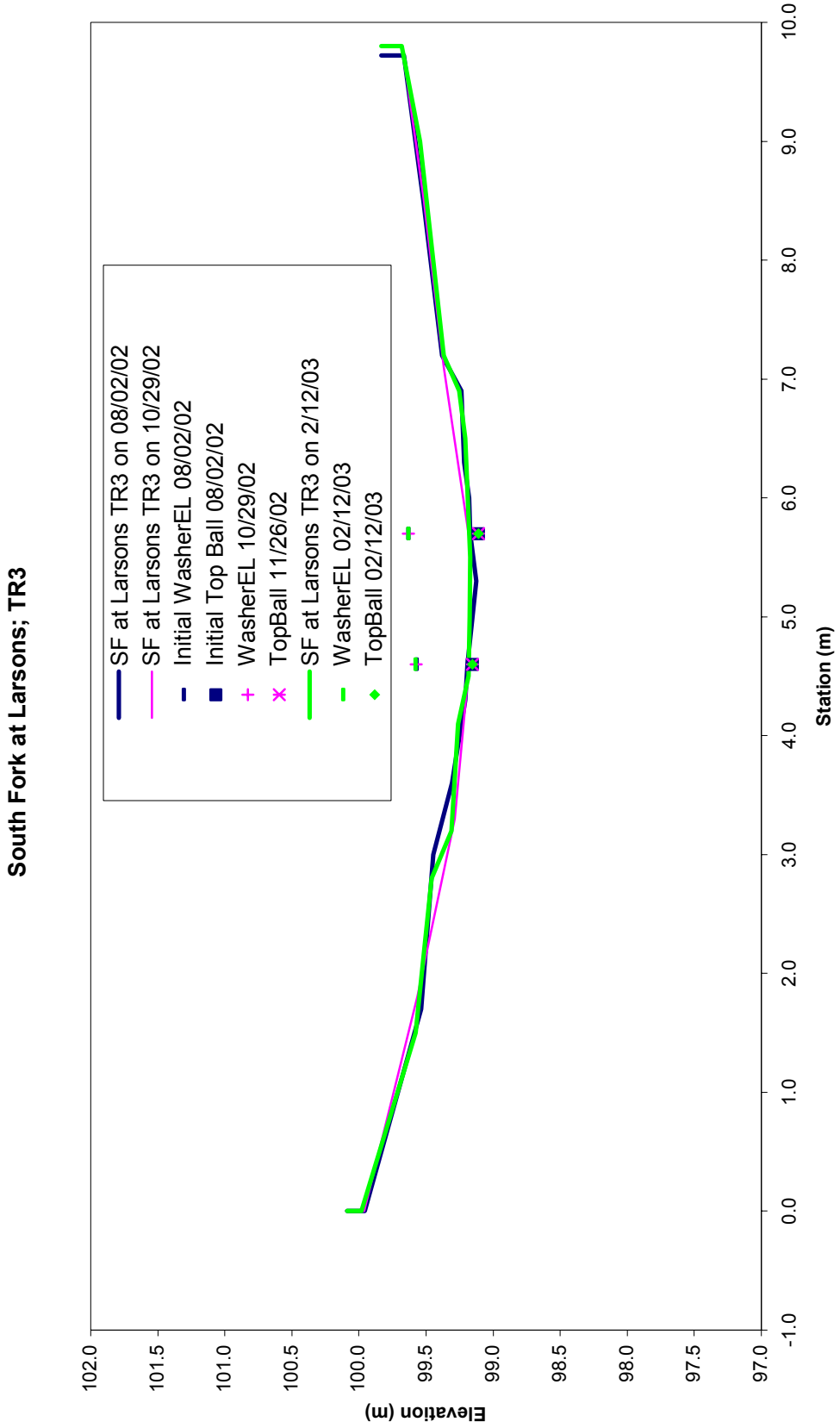

Sygitowicz Creek TR1
SygitTR1 on 6/7/02
SygitTR1 on 10/22/02
WSEL on 6/7/02
Initial WasherEL 06/07/02
Initial Top Ball 06/07/02
TopBall 11/21/02
SygitTR1 on 2/24/03
TopBall 02/24/03
WasherEL 02/24/03
Elavation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0

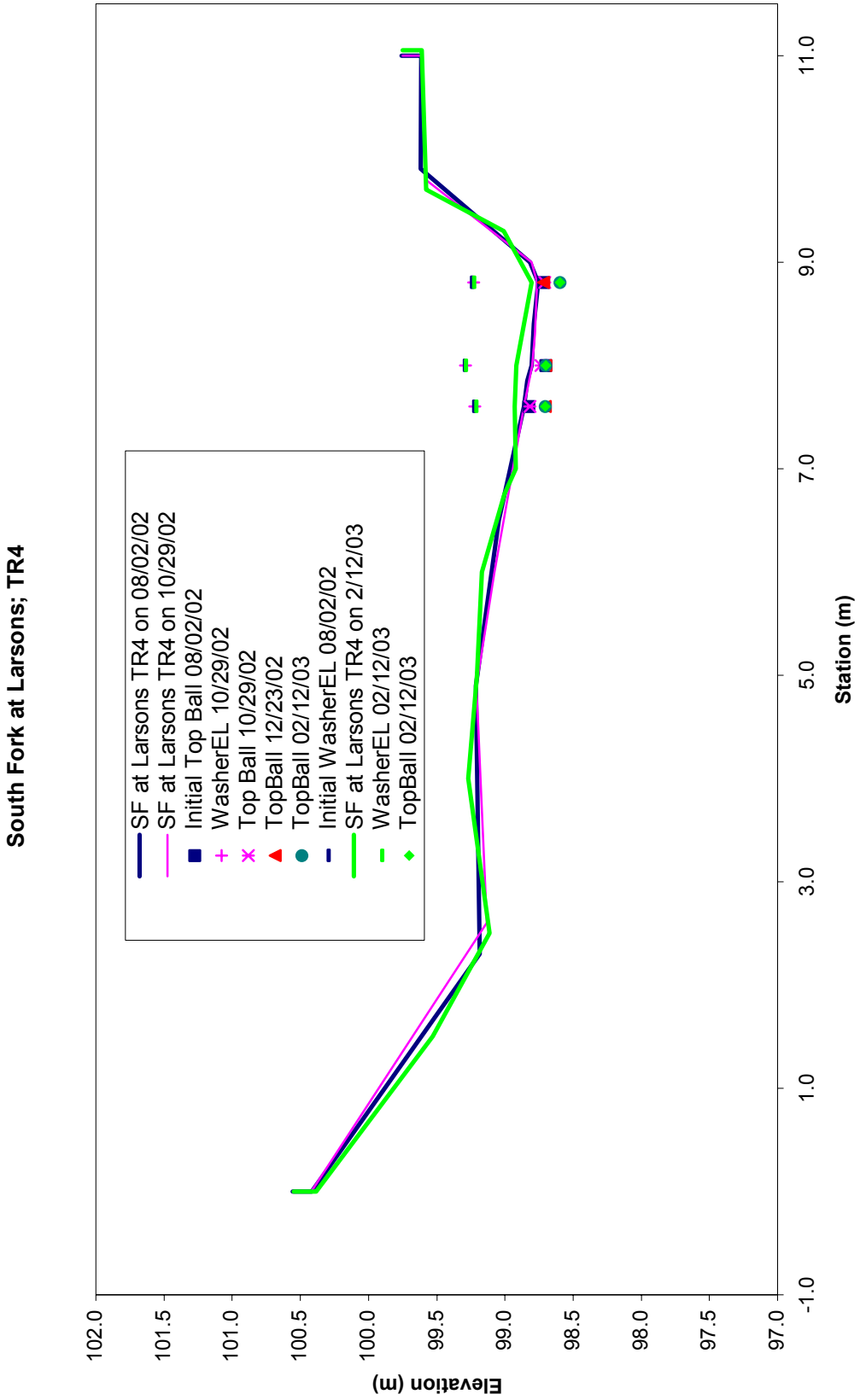

Sygitowicz Creek TR2
SygitTR2 on 6/7/02
SygitTR2 on 10/22/02
WSEL on 6/7/02
Initial WasherEL 06/07/02
Initial Top Ball 06/07/02
WasherEL 10/22/02
SygitTR2 on 2/24/03
TopBall 02/24/03
WasherEL 02/24/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0

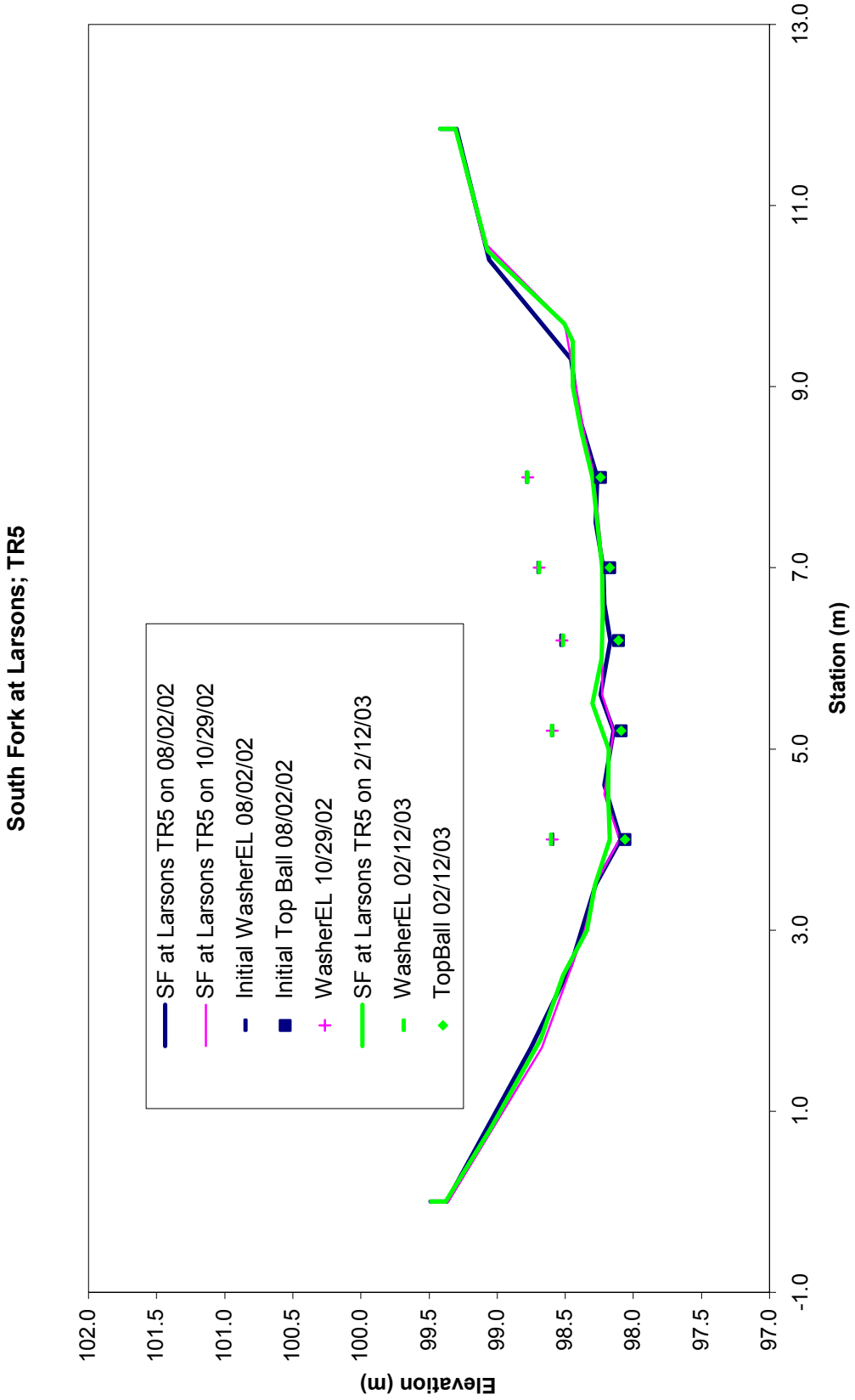

Sygitowicz Creek TR3
SygitTR3 on 6/7/02
SygitTR3 on 10/22/02
Initial WasherEL 06/07/02
Initial Top Ball 06/07/02
WasherEL 10/22/02
TopBall 11/21/02
SygitTR3 on 2/24/03
TopBall 02/24/03
WasherEL 02/24/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0

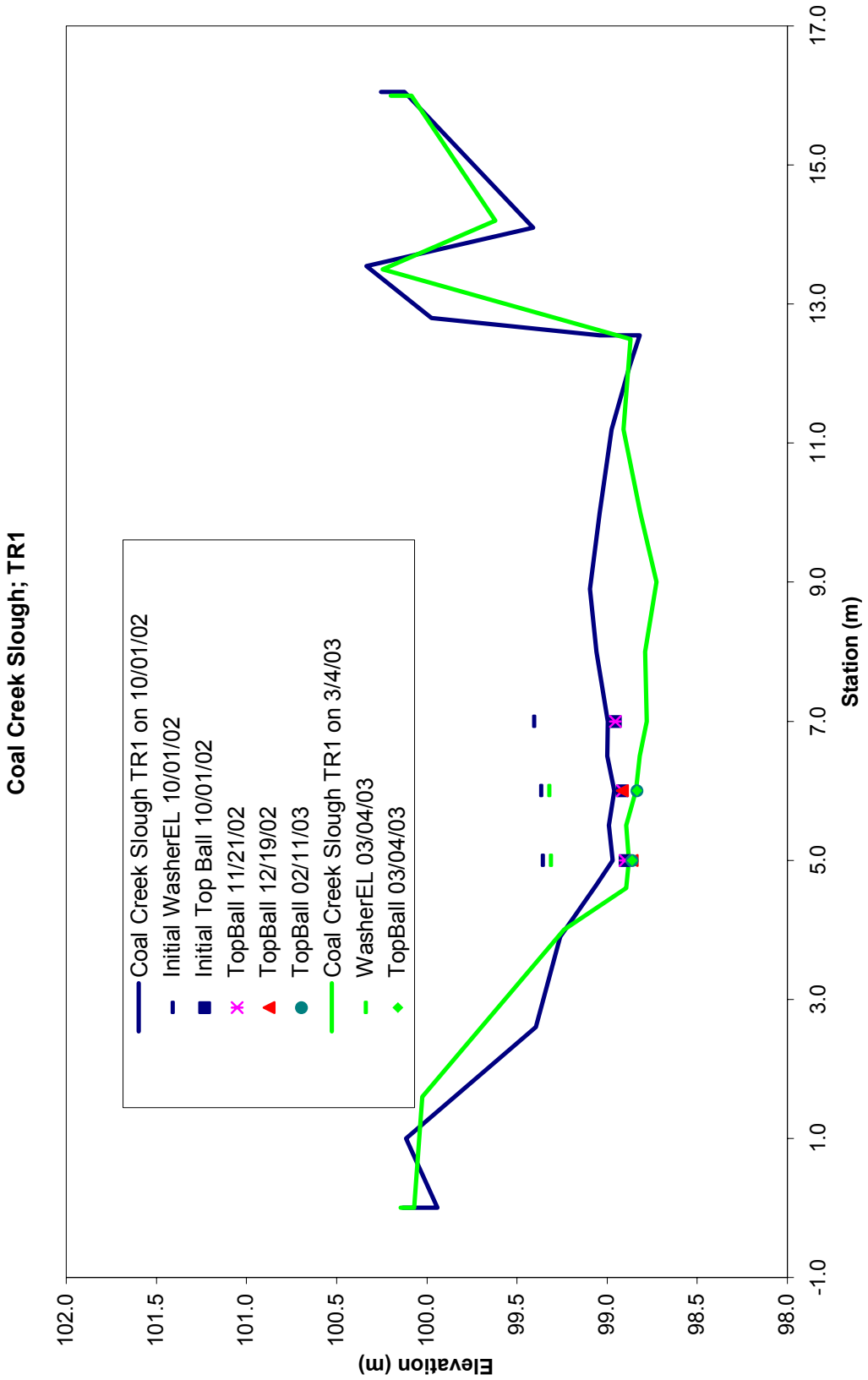

South Fork at Larsons; TR1
SF at Larsons TR1 on 08/01/02
SF at Larsons TR1 on 10/29/02
Initial WasherEL 08/01/02
Initial Top Ball 08/01/02
WasherEL 10/29/02
TopBall 11/26/02
SF at Larsons TR1 on 2/12/03
TopBall 02/12/03
WasherEL 02/12/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0
44.0
49.0

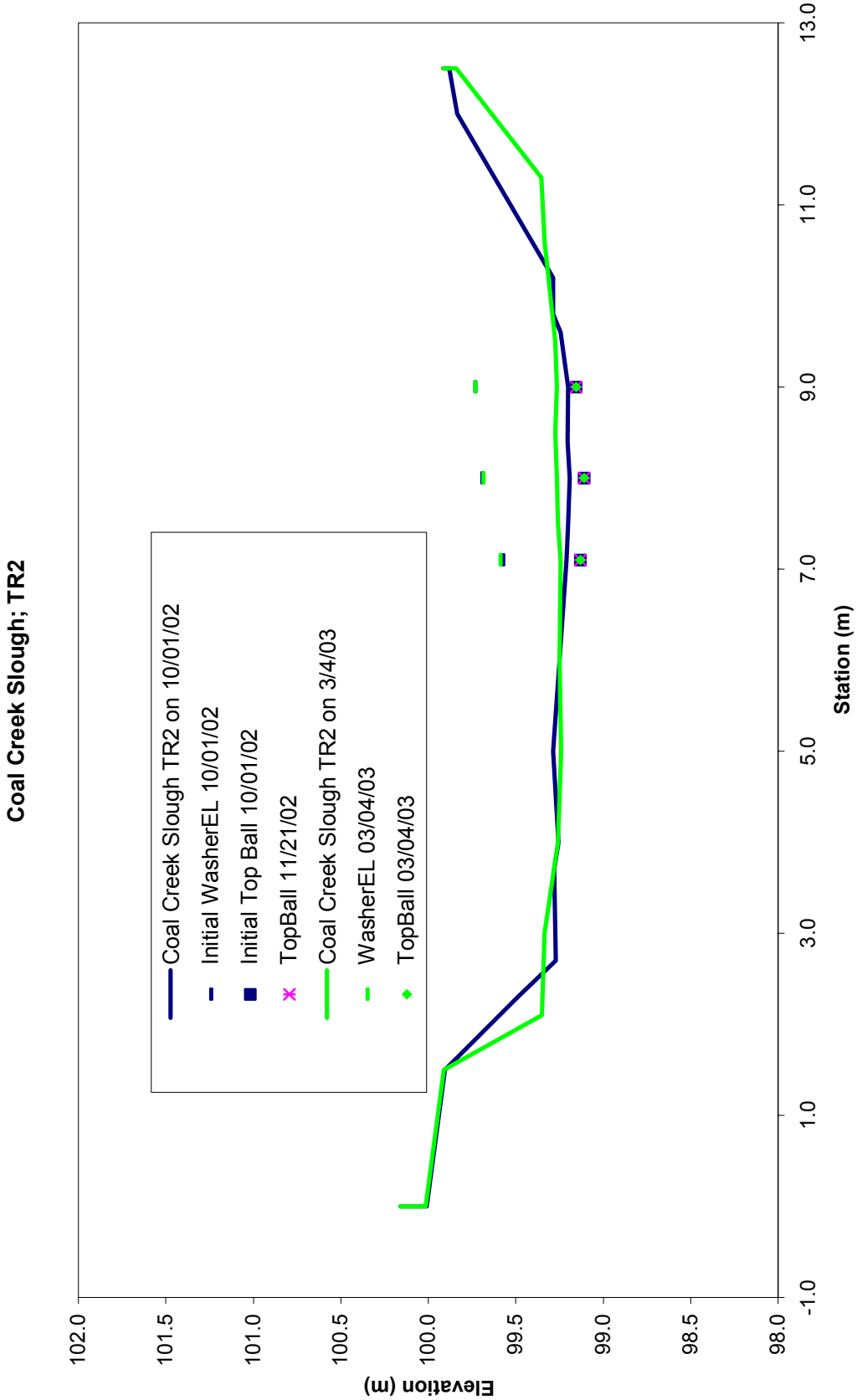

South Fork at Larsons TR2
SF at Larsons TR2 on 08/02/02
SF at Larsons TR2 10/29/02
Initial WasherEL 08/02/02
Initial Top Ball 08/02/02
WasherEL 10/29/02
SF at Larsons TR2 2/12/03
WasherEL 02/12/03
TopBall 02/12/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0

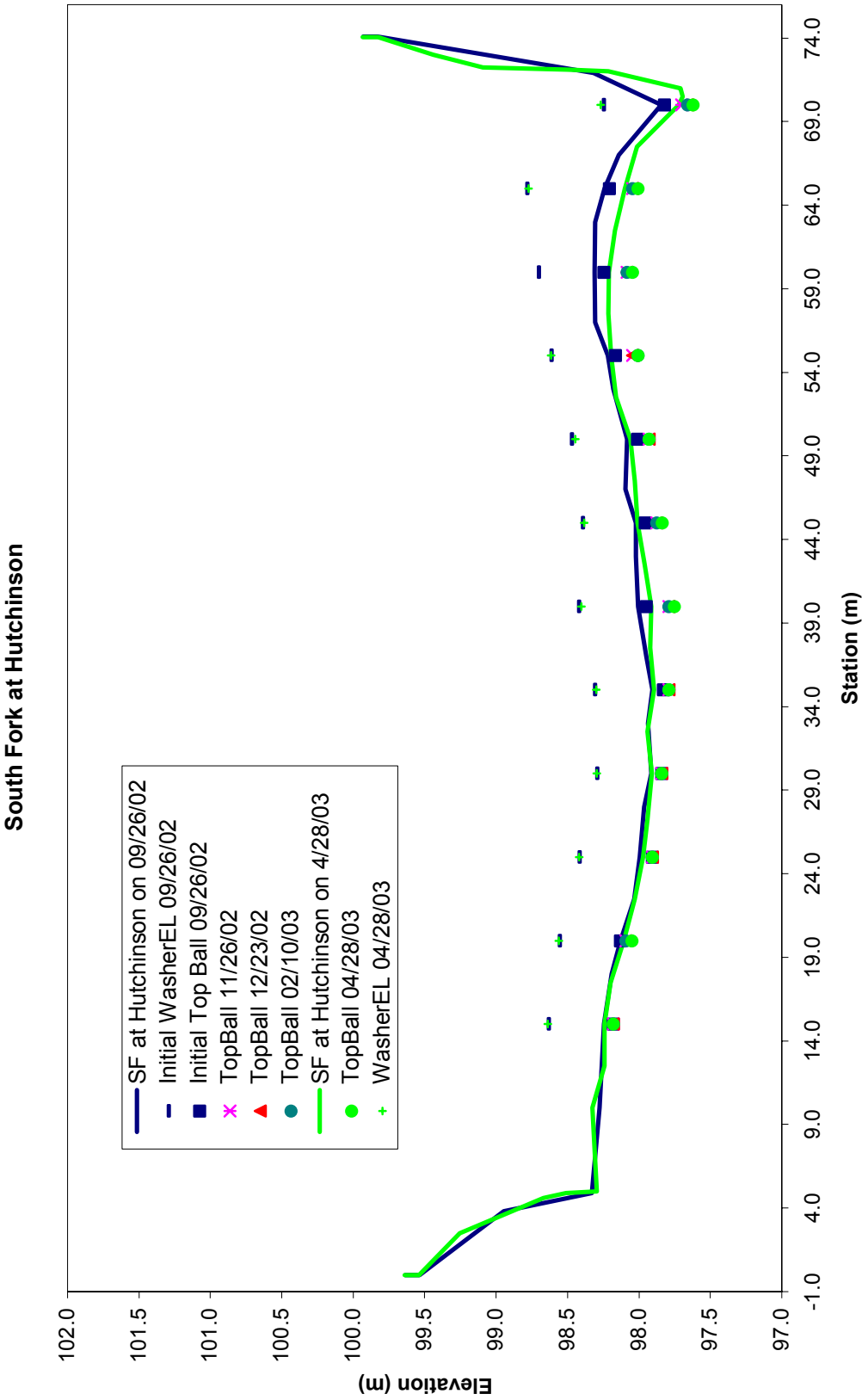

South Fork at Larsons; TR3
SF at Larsons TR3 on 08/02/02
SF at Larsons TR3 on 10/29/02
Initial WasherEL 08/02/02
Initial Top Ball 08/02/02
WasherEL 10/29/02
TopBall 11/26/02
SF at Larsons TR3 on 2/12/03
WasherEL 02/12/03
TopBall 02/12/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

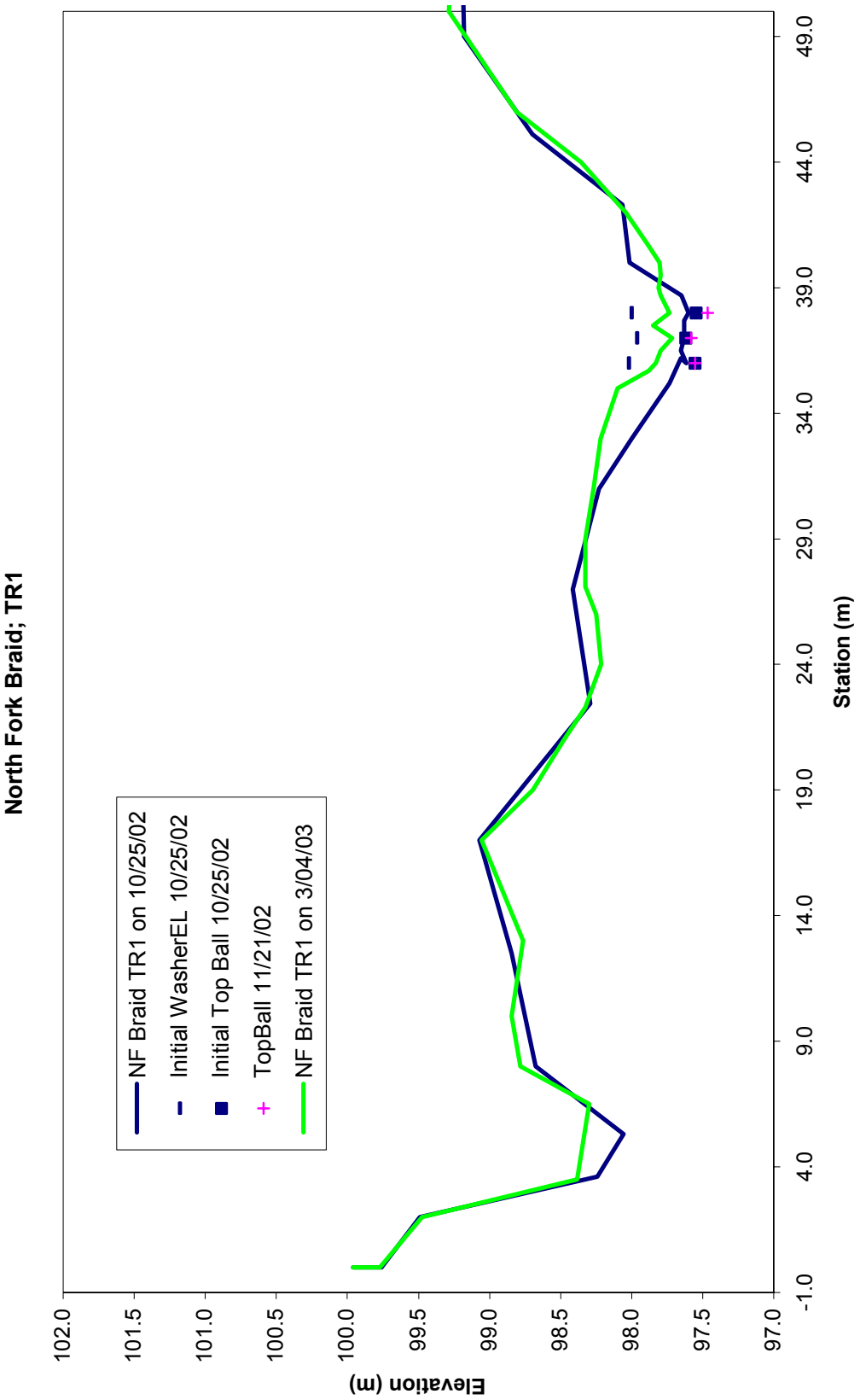

South Fork at Larsons; TR4
SF at Larsons TR4 on 08/02/02
SF at Larsons TR4 on 10/29/02
Initial Top Ball 08/02/02
WasherEL 10/29/02
Top Ball 10/29/02
TopBall 12/23/02
TopBall 02/12/03
Initial WasherEL 08/02/02
SF at Larsons TR4 on 2/12/03
WasherEL 02/12/03
TopBall 02/12/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0

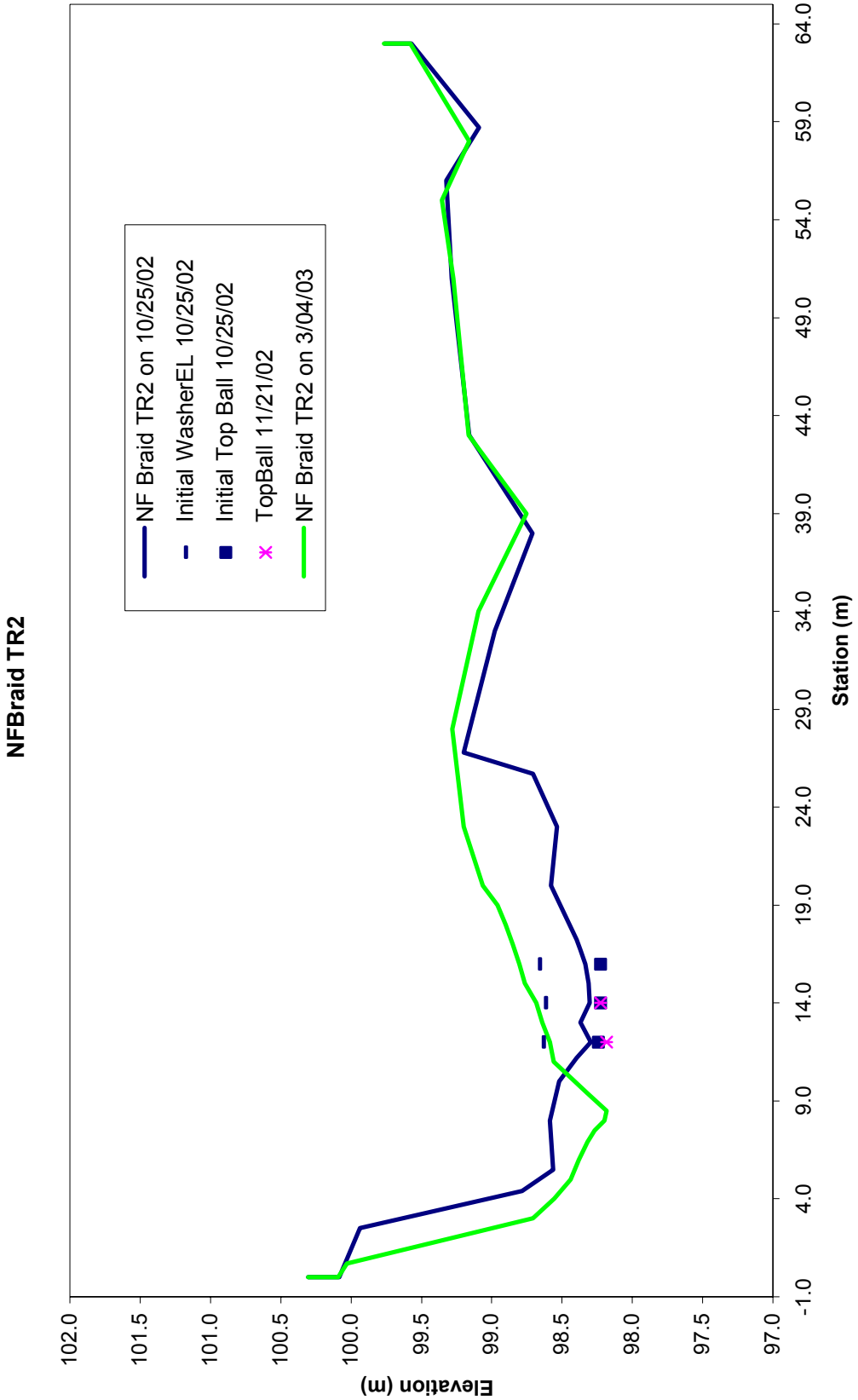

South Fork at Larsons; TR5
SF at Larsons TR5 on 08/02/02
SF at Larsons TR5 on 10/29/02
Initial WasherEL 08/02/02
Initial Top Ball 08/02/02
WasherEL 10/29/02
SF at Larsons TR5 on 2/12/03
WasherEL 02/12/03
TopBall 02/12/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0

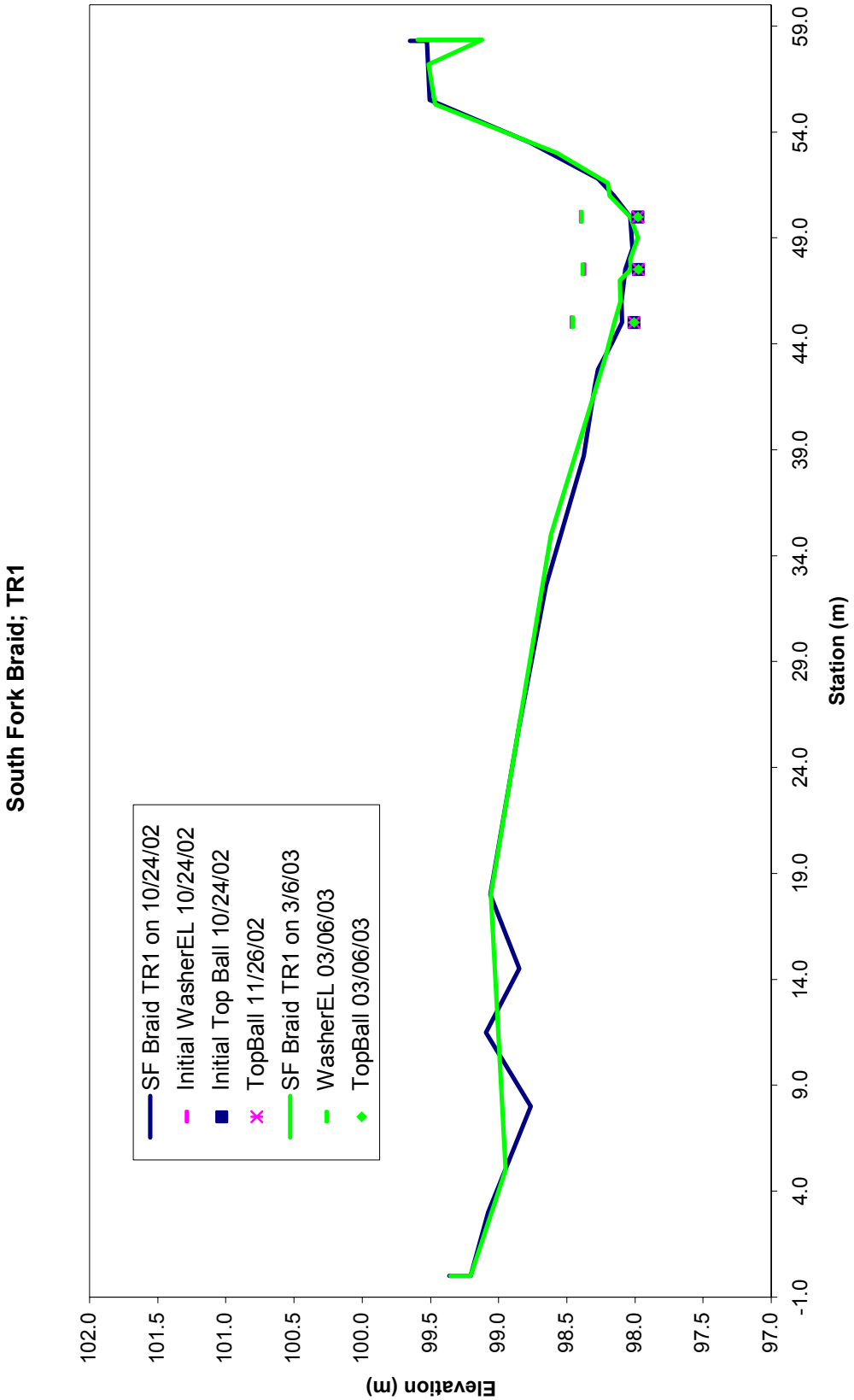

Coal Creek Slough; TR1
Coal Creek Slough TR1 on 10/01/02
Initial WasherEL 10/01/02
Initial Top Ball 10/01/02
TopBall 11/21/02
TopBall 12/19/02
TopBall 02/11/03
Coal Creek Slough TR1 on 3/4/03
WasherEL 03/04/03
TopBall 03/04/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0

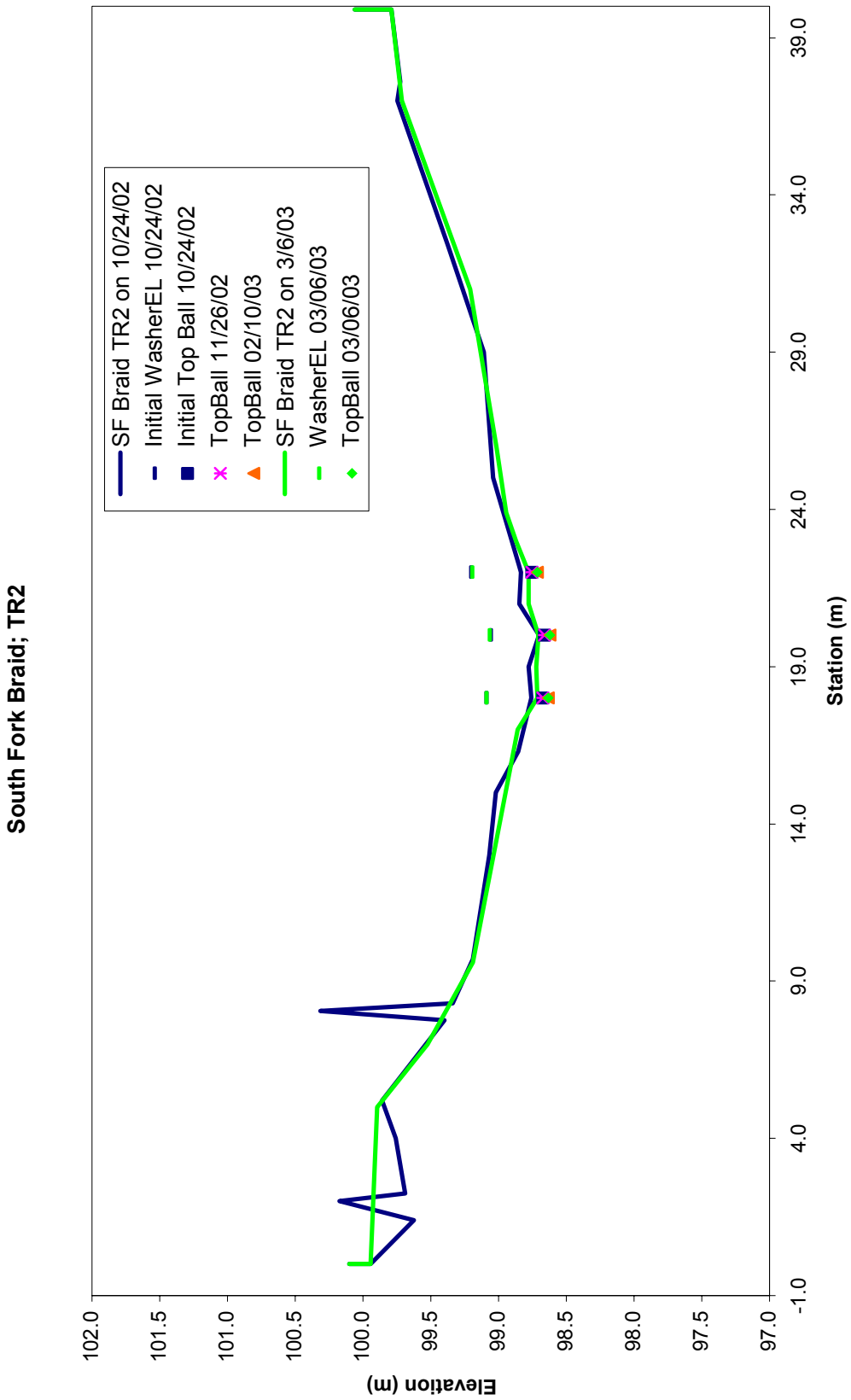

Coal Creek Slough; TR2
Coal Creek Slough TR2 on 10/01/02
Initial WasherEL 10/01/02
Initial Top Ball 10/01/02
TopBall 11/21/02
Coal Creek Slough TR2 on 3/4/03
WasherEL 03/04/03
TopBall 03/04/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
Station (m)
-1.0
1.0
3.0
5.0
7.0
9.0
11.0
13.0

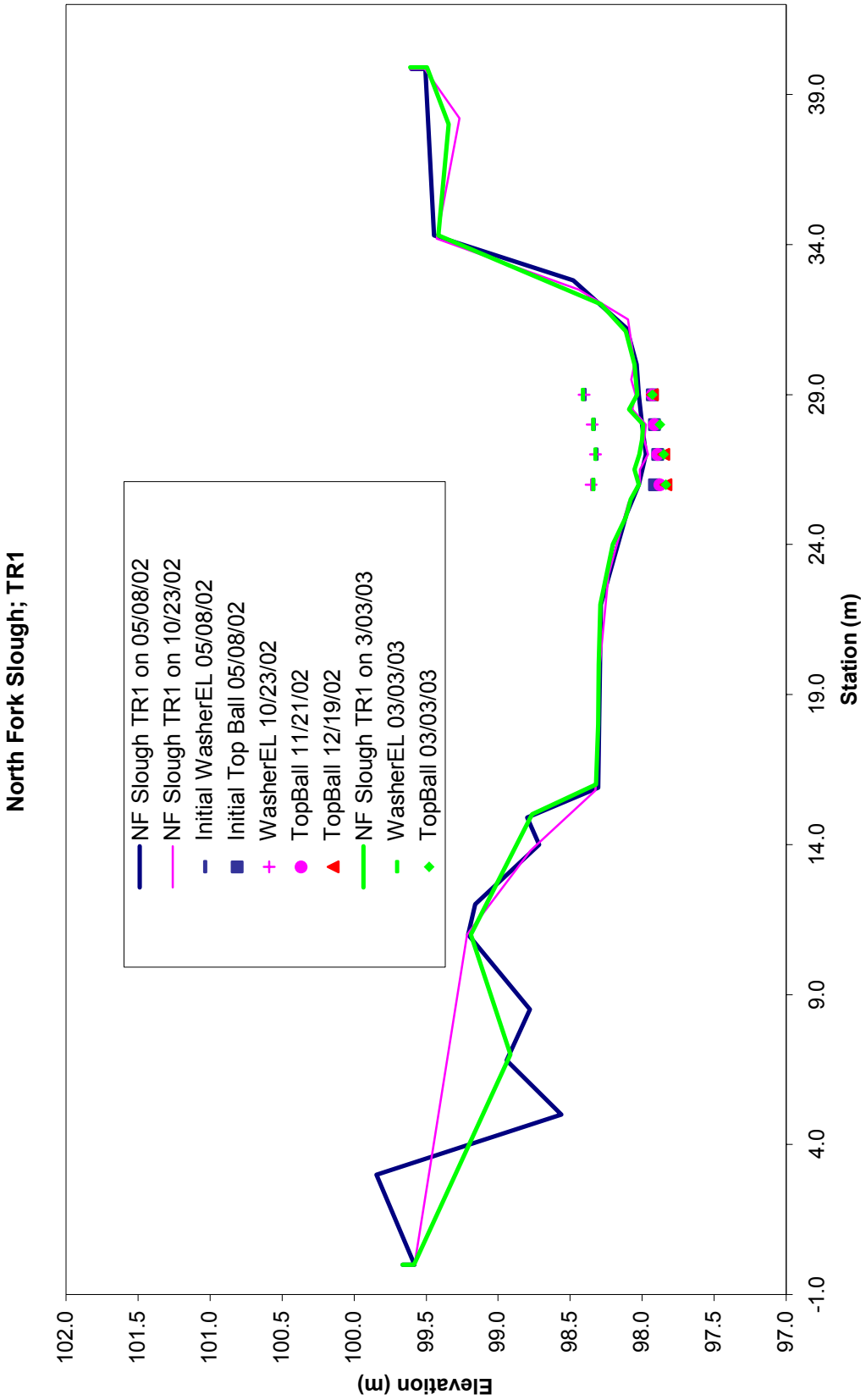

South Fork at Hutchinson
SF at Hutchinson on 09/26/02
Initial WasherEL 09/26/02
Initial Top Ball 09/26/02
TopBall 11/26/02
TopBall 12/23/02
TopBall 02/10/03
SF at Hutchinson on 4/28/03
TopBall 04/28/03
WasherEL 04/28/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0
44.0
49.0
54.0
59.0
64.0
69.0
74.0

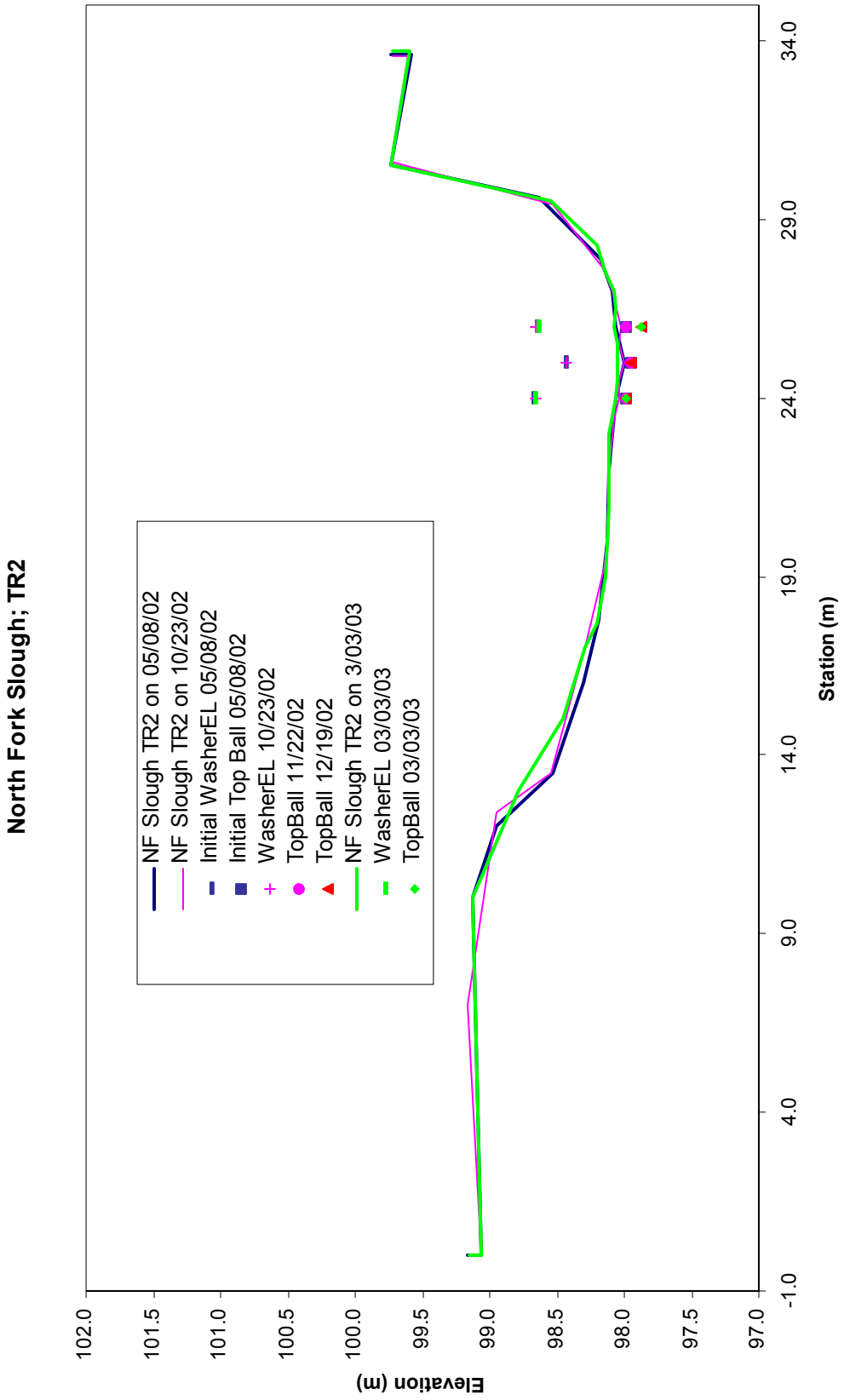

North Fork Braid; TR1
NF Braid TR1 on 10/25/02
Initial WasherEL 10/25/02
Initial Top Ball 10/25/02
TopBall 11/21/02
NF Braid TR1 on 3/04/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0
44.0
49.0

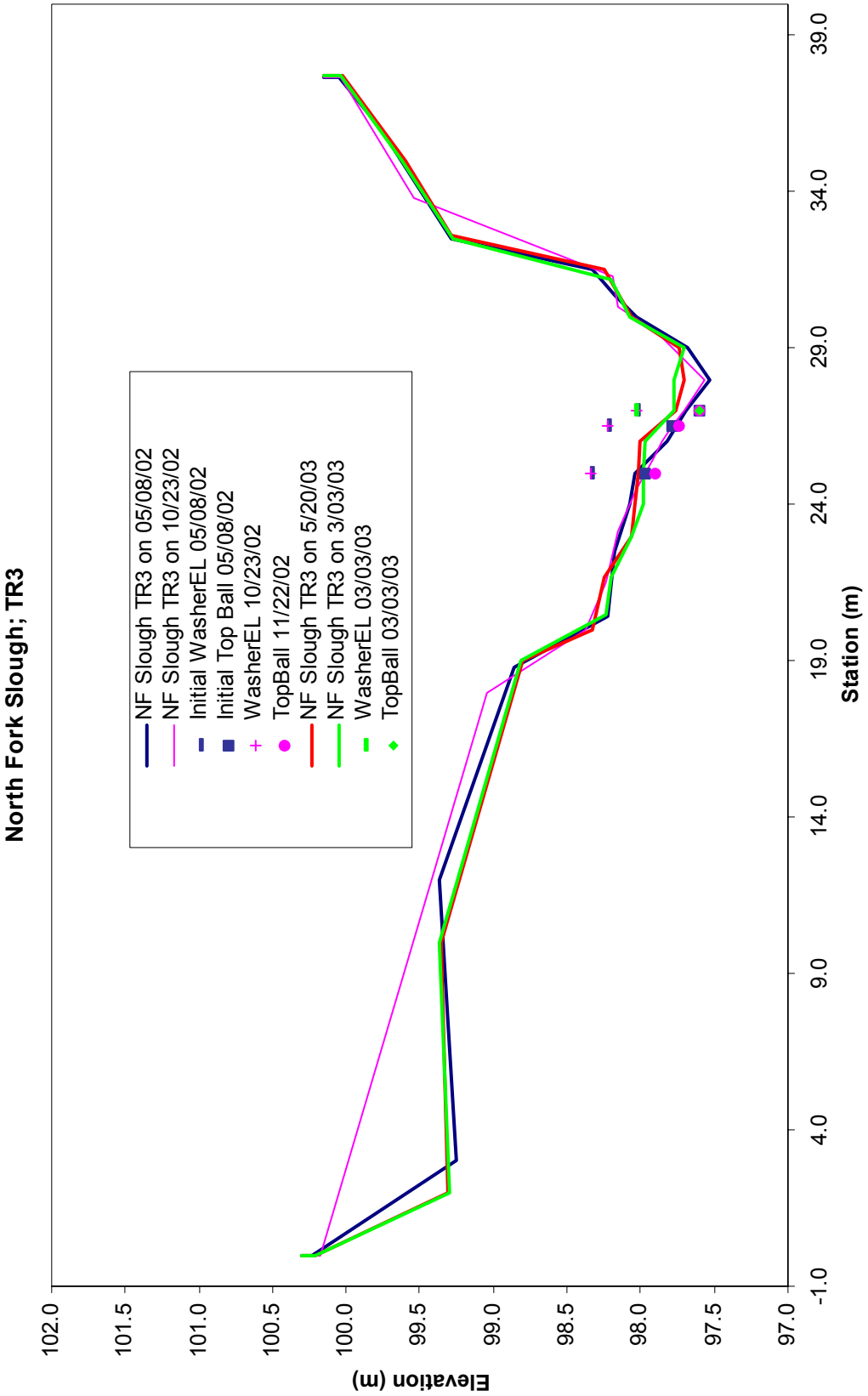

NFBraid TR2
NF Braid TR2 on 10/25/02
Initial WasherEL 10/25/02
Initial Top Ball 10/25/02
TopBall 11/21/02
NF Braid TR2 on 3/04/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0
44.0
49.0
54.0
59.0
64.0

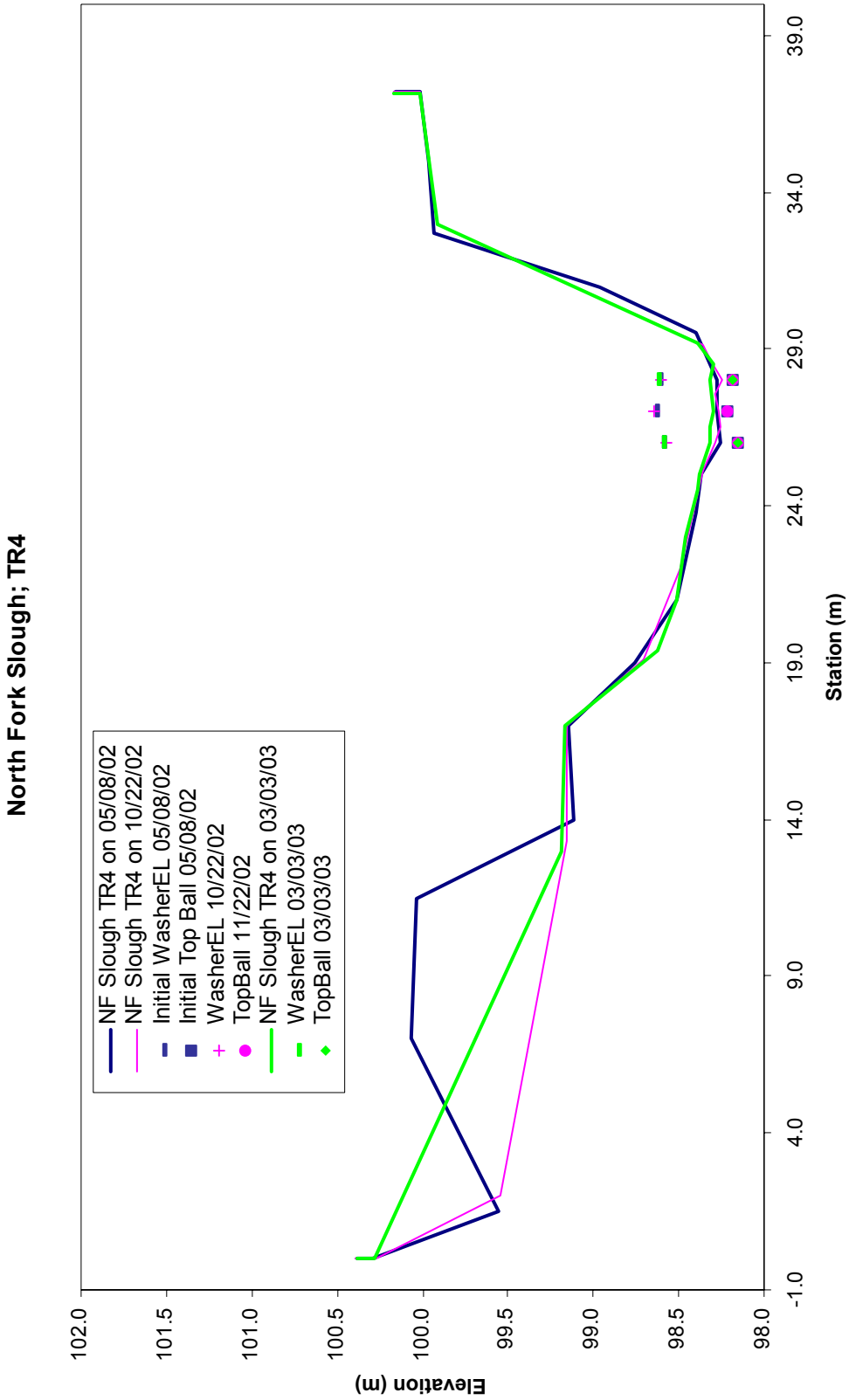

South Fork Braid; TR1
SF Braid TR1 on 10/24/02
Initial WasherEL 10/24/02
Initial Top Ball 10/24/02
TopBall 11/26/02
SF Braid TR1 on 3/6/03
WasherEL 03/06/03
TopBall 03/06/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0
44.0
49.0
54.0
59.0

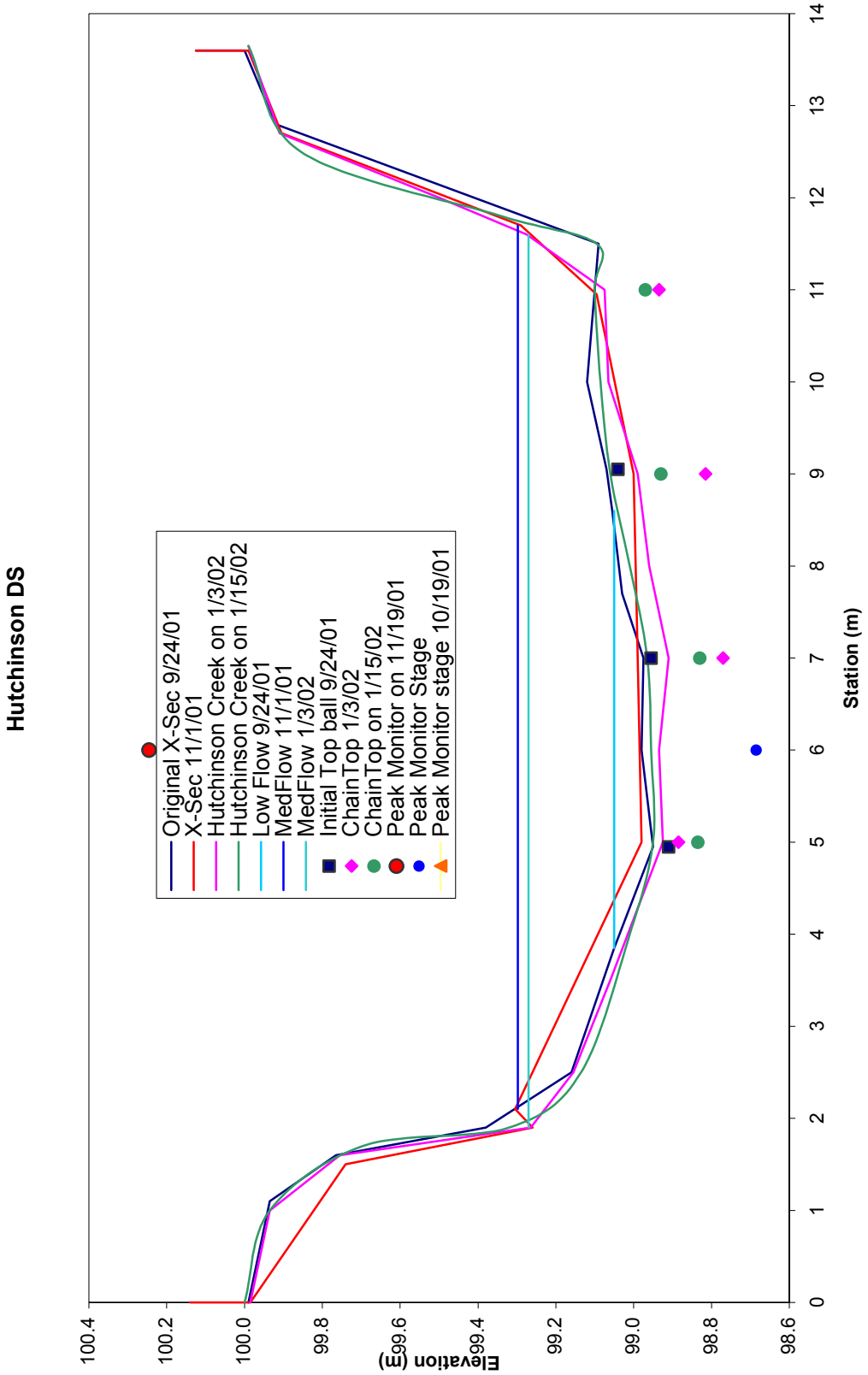

South Fork Braid; TR2
SF Braid TR2 on 10/24/02
Initial WasherEL 10/24/02
Initial Top Ball 10/24/02
TopBall 11/26/02
TopBall 02/10/03
SF Braid TR2 on 3/6/03
WasherEL 03/06/03
TopBall 03/06/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0

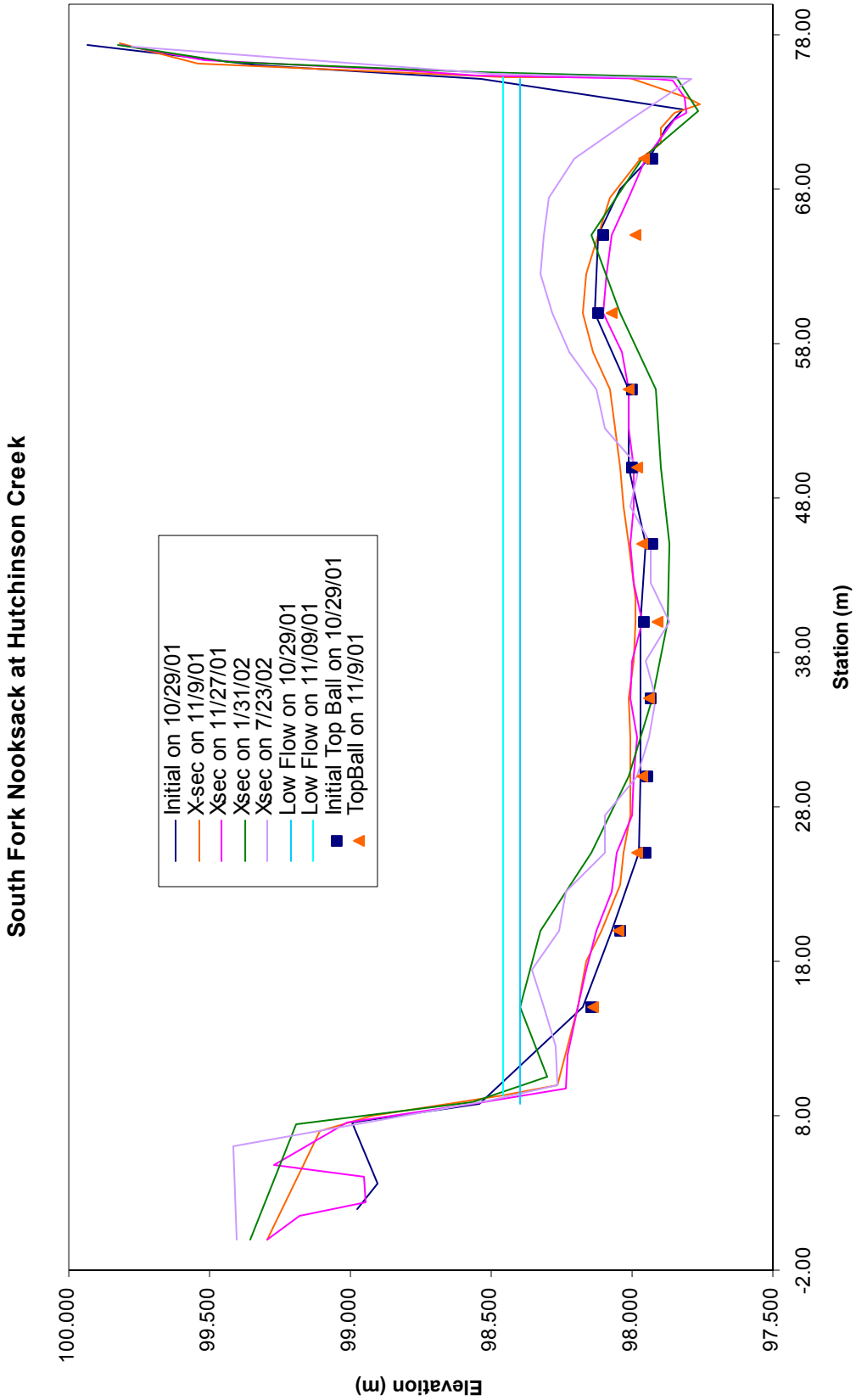

North Fork Slough; TR1
NF Slough TR1 on 05/08/02
NF Slough TR1 on 10/23/02
Initial WasherEL 05/08/02
Initial Top Ball 05/08/02
WasherEL 10/23/02
TopBall 11/21/02
TopBall 12/19/02
NF Slough TR1 on 3/03/03
WasherEL 03/03/03
TopBall 03/03/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0
Station (m)

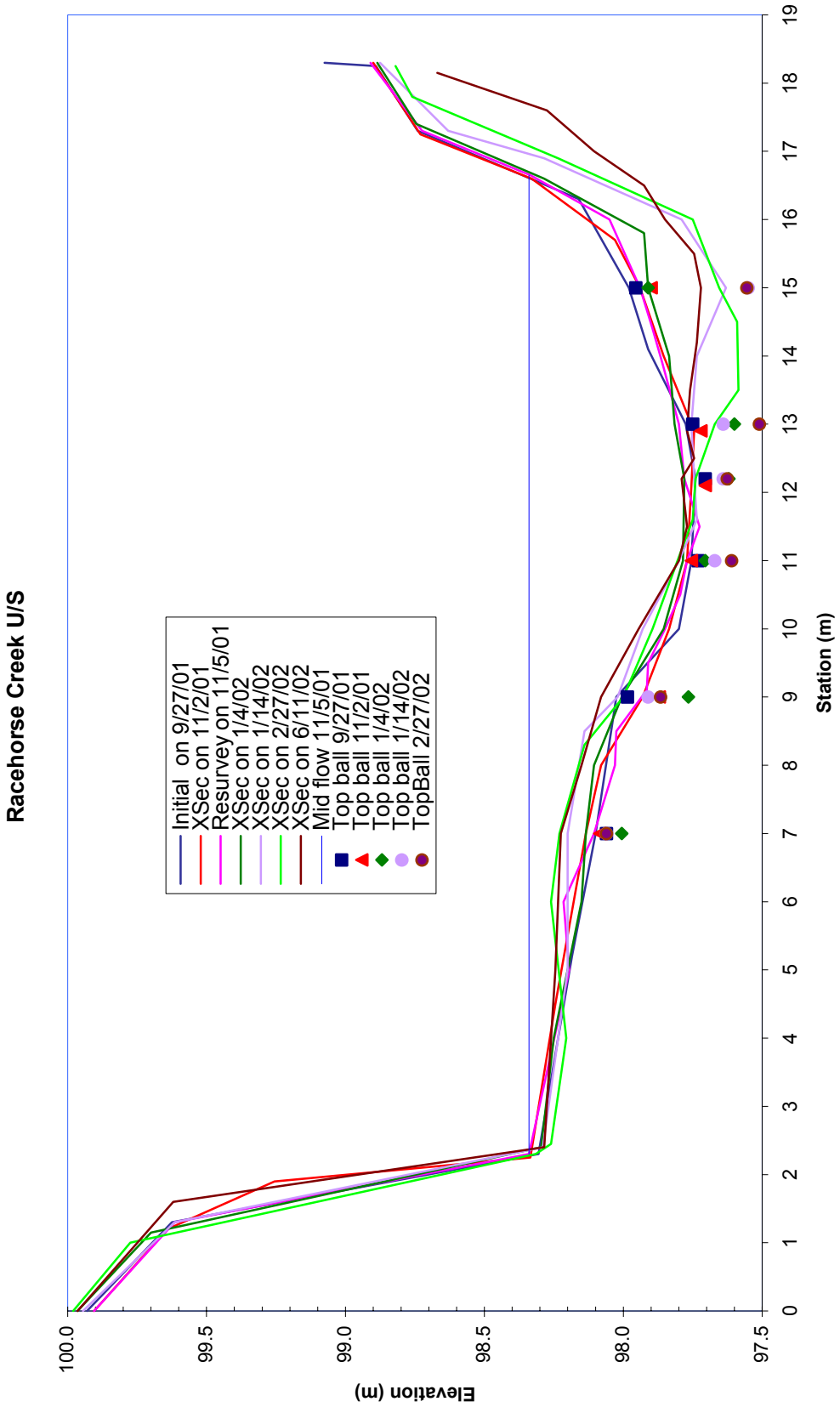

North Fork Slough; TR2
NF Slough TR2 on 05/08/02
NF Slough TR2 on 10/23/02
Initial WasherEL 05/08/02
Initial Top Ball 05/08/02
WasherEL 10/23/02
TopBall 11/22/02
TopBall 12/19/02
NF Slough TR2 on 3/03/03
WasherEL 03/03/03
TopBall 03/03/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0

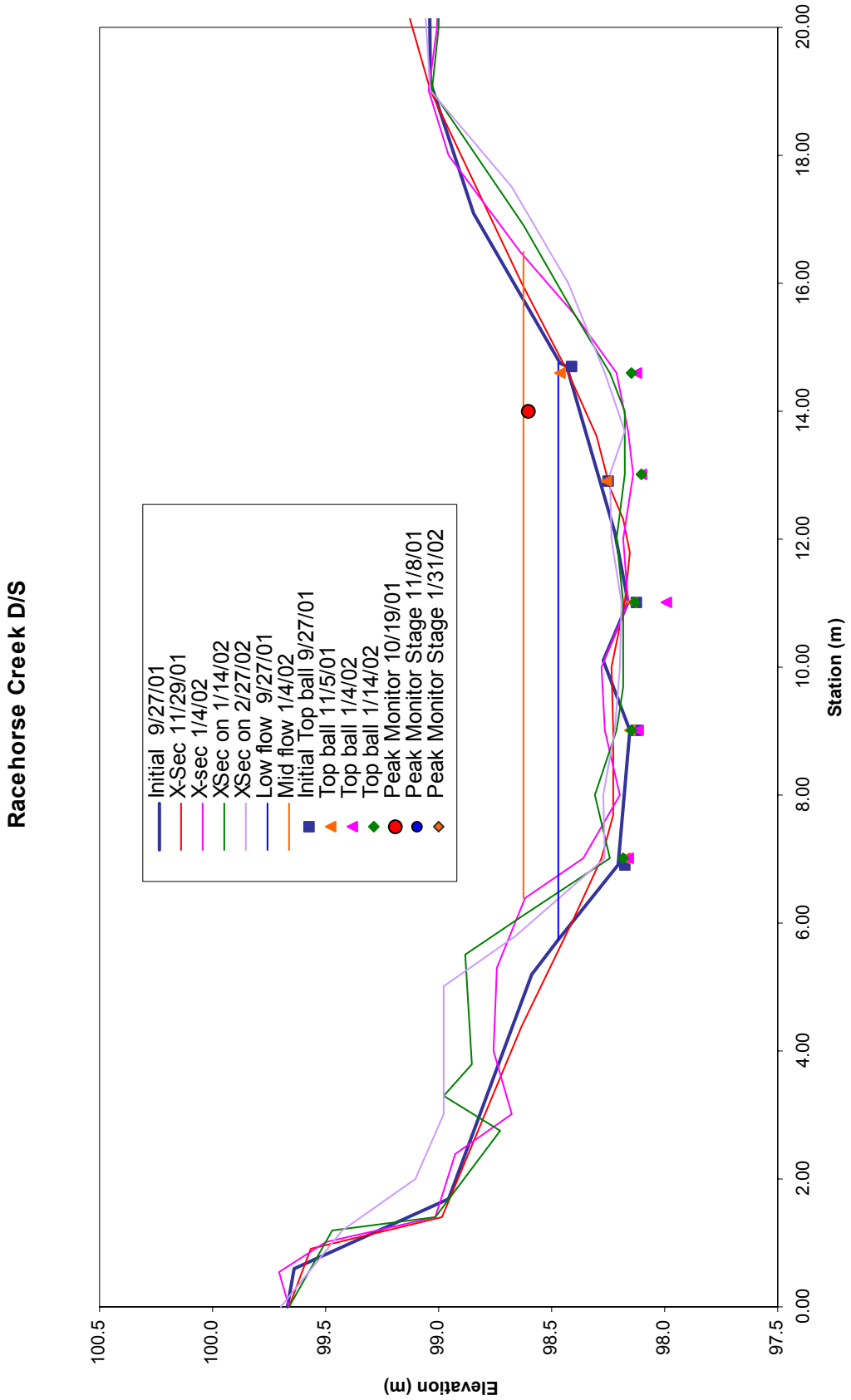

North Fork Slough; TR3
NF Slough TR3 on 05/08/02
NF Slough TR3 on 10/23/02
Initial WasherEL 05/08/02
Initial Top Ball 05/08/02
WasherEL 10/23/02
TopBall 11/22/02
NF Slough TR3 on 5/20/03
NF Slough TR3 on 3/03/03
WasherEL 03/03/03
TopBall 03/03/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0

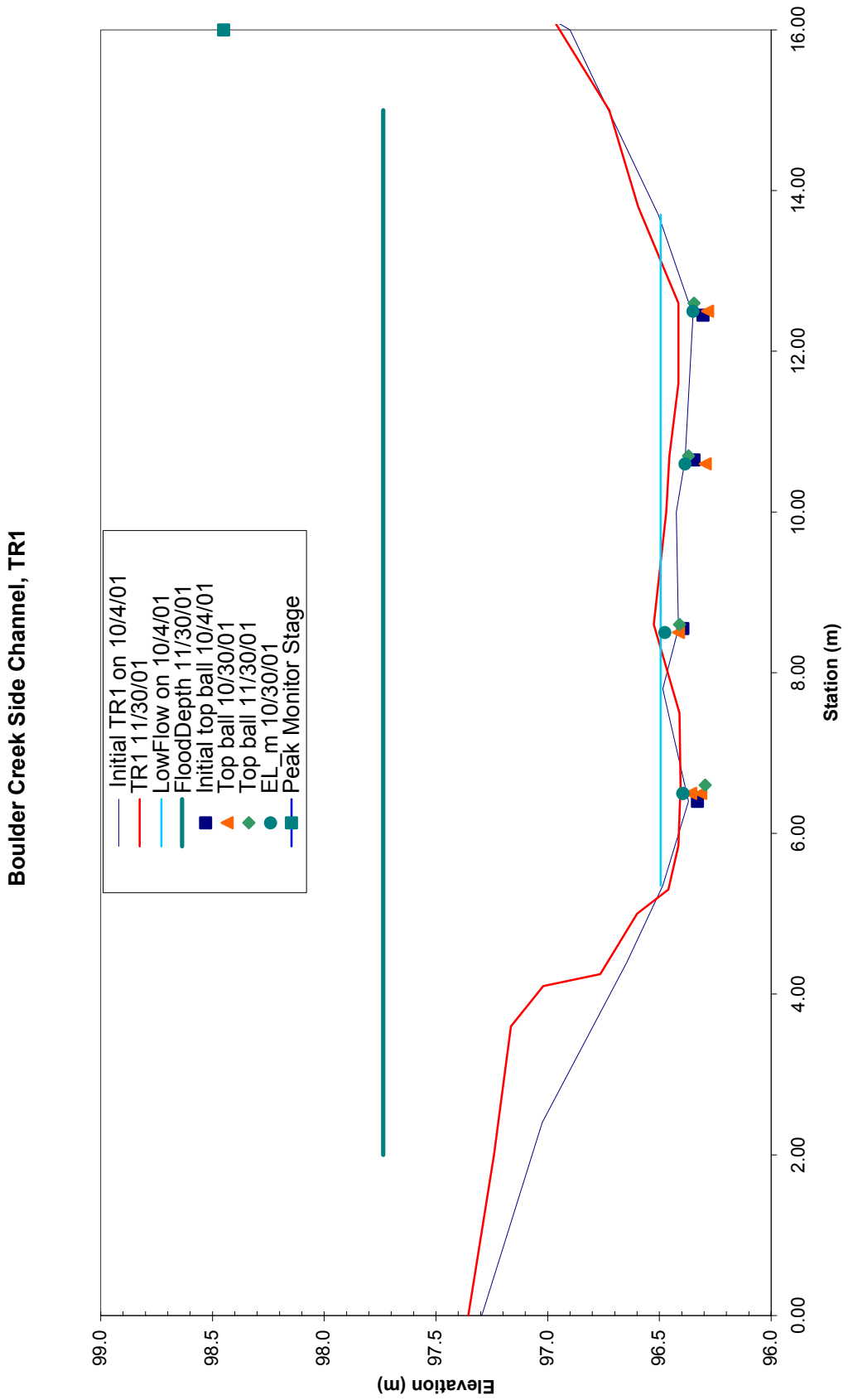

North Fork Slough; TR4
NF Slough TR4 on 05/08/02
NF Slough TR4 on 10/22/02
Initial WasherEL 05/08/02
Initial Top Ball 05/08/02
WasherEL 10/22/02
TopBall 11/22/02
NF Slough TR4 on 03/03/03
WasherEL 03/03/03
TopBall 03/03/03
Elevation (m)
102.0
101.5
101.0
100.5
100.0
99.5
99.0
98.5
98.0
Station (m)
-1.0
4.0
9.0
14.0
19.0
24.0
29.0
34.0
39.0

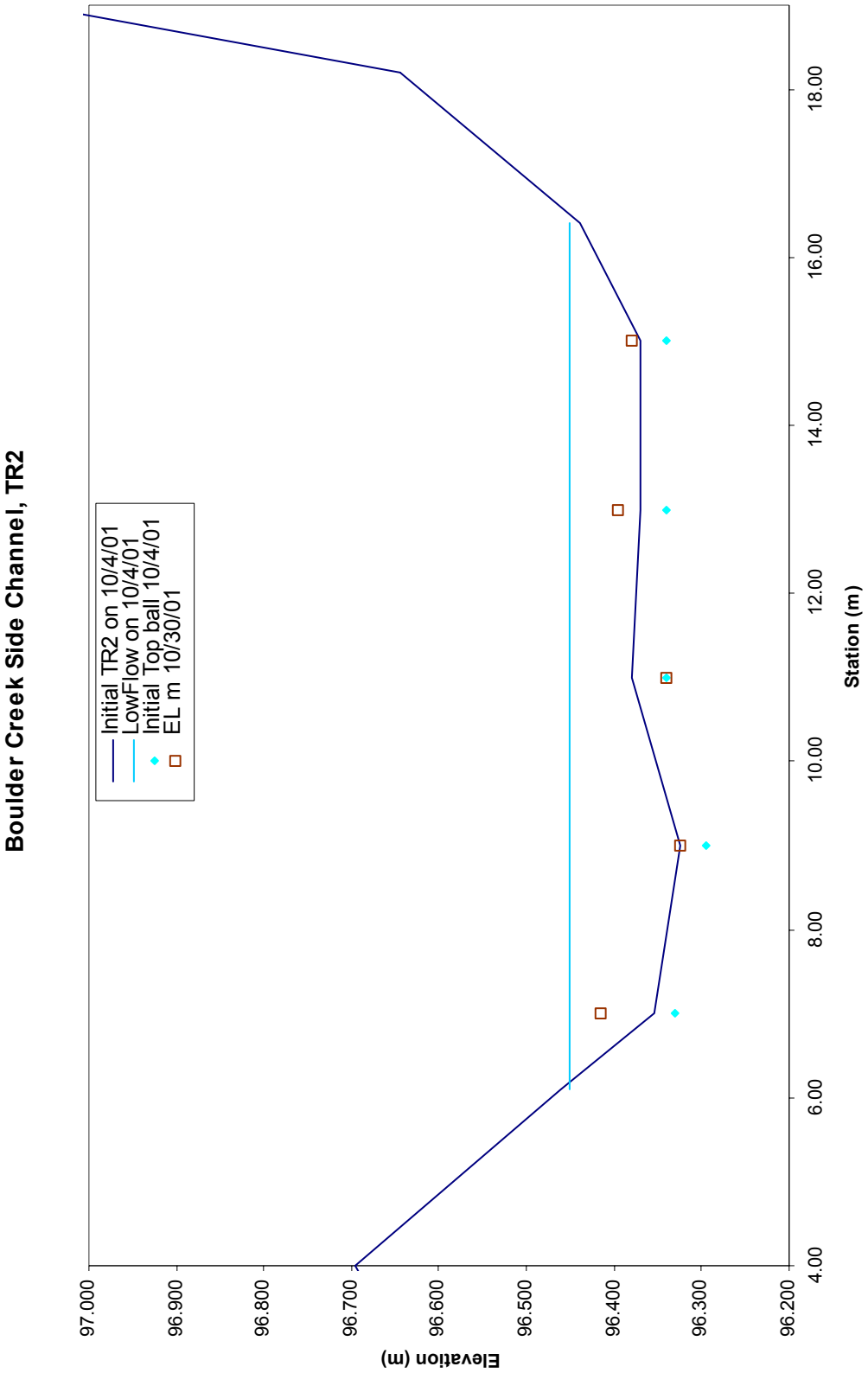

Hutchinson DS
Original X-Sec 9/24/01
X-Sec 11/1/01
Hutchinson Creek on 1/3/02
Hutchinson Creek on 1/15/02
Low Flow 9/24/01
MedFlow 11/1/01
MedFlow 1/3/02
Initial Top ball 9/24/01
ChainTop 1/3/02
ChainTop on 1/15/02
Peak Monitor on 11/19/01
Peak Monitor Stage
Peak Monitor stage 10/19/01
Elevation (m)
100.4
100.2
100.0
99.8
99.6
99.4
99.2
99.0
98.8
98.6
Station (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

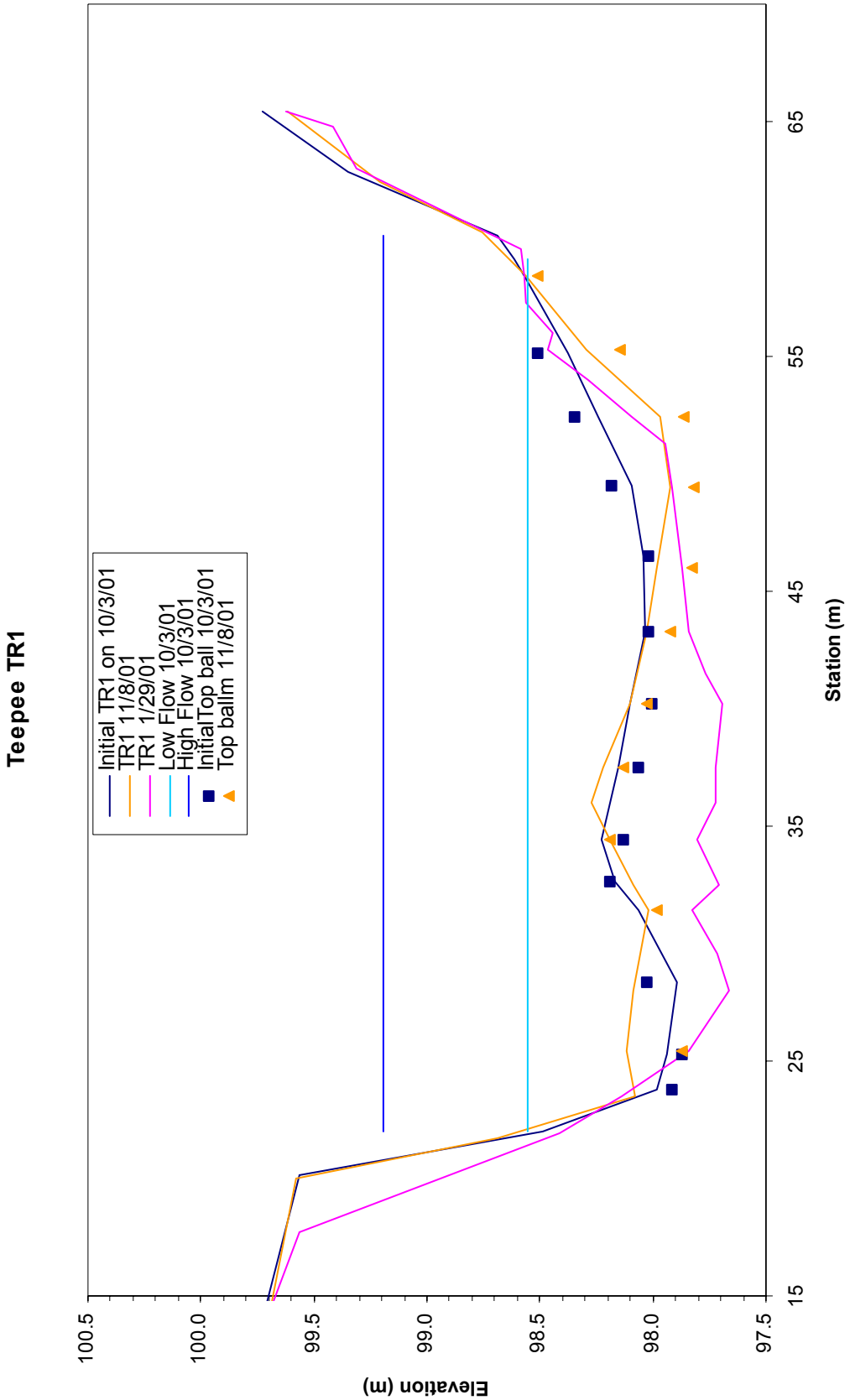

South Fork Nooksack at Hutchinson Creek
Initial on 10/29/01
X-sec on 11/9/01
Xsec on 11/27/01
Xsec on 1/31/02
Xsec on 7/23/02
Low Flow on 10/29/01
Low Flow on 11/09/01
Initial Top Ball on 10/29/01
TopBall on 11/9/01
Elevation (m)
100.000
99.500
99.000
98.500
98.000
97.500
Station (m)
-2.00
8.00
18.00
28.00
38.00
48.00
58.00
68.00
78.00

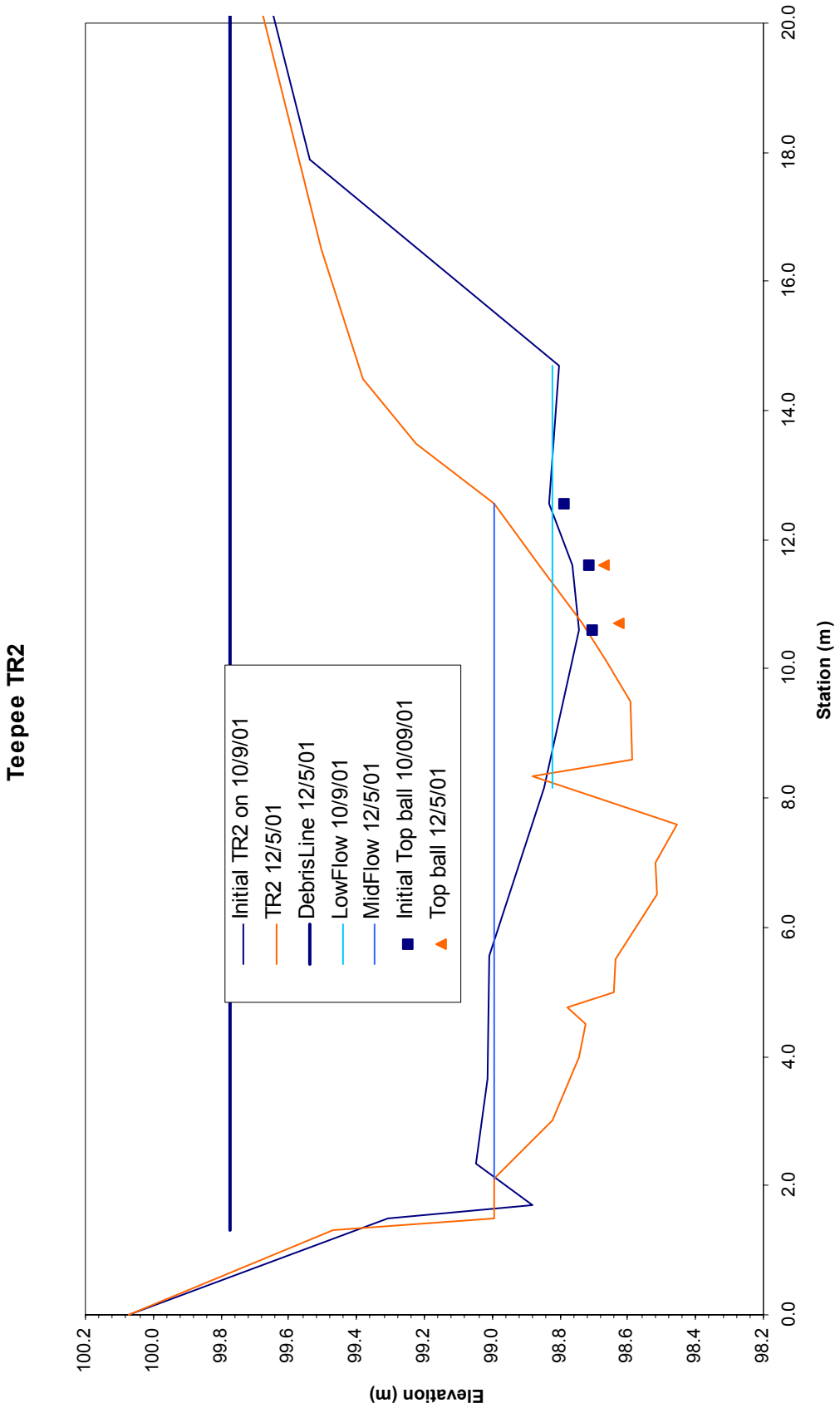

Racehorse Creek U/S
Initial on 9/27/01
XSec on 11/2/01
Resurvey on 11/5/01
XSec on 1/4/02
XSec on 1/14/02
XSec on 2/27/02
XSec on 6/11/02
Mid flow 11/5/01
Top ball 9/27/01
Top ball 11/2/01
Top ball 1/4/02
Top ball 1/14/02
TopBall 2/27/02
Elevation (m)
100.0
99.5
99.0
98.5
98.0
97.5
Station (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

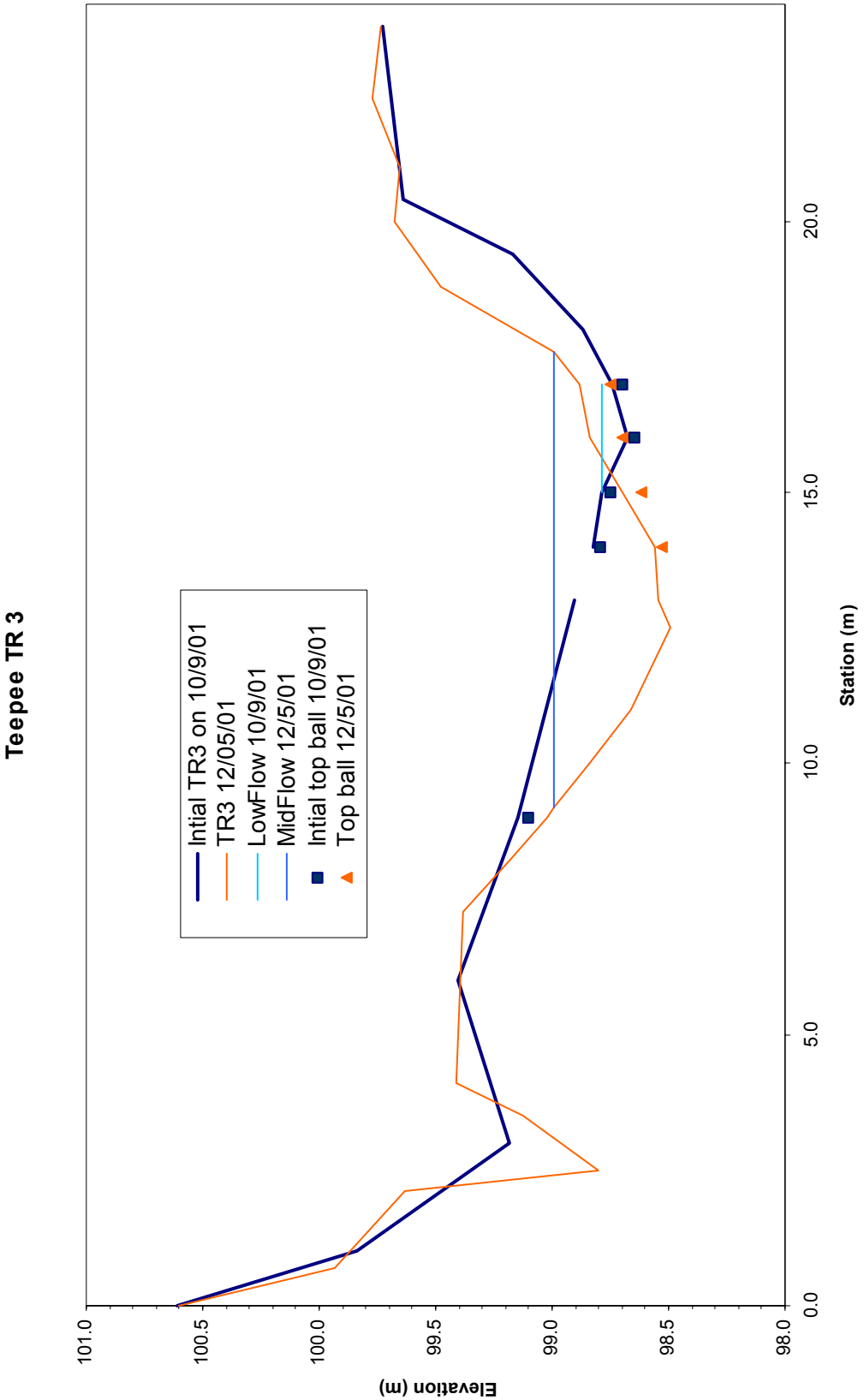

Racehorse Creek D/S
Initial 9/27/01
X-Sec 11/29/01
X-sec 1/4/02
XSec on 1/14/02
XSec on 2/27/02
Low flow 9/27/01
Mid flow 1/4/02
Initial Top ball 9/27/01
Top ball 11/5/01
Top ball 1/4/02
Top ball 1/14/02
Peak Monitor 10/19/01
Peak Monitor Stage 11/8/01
Peak Monitor Stage 1/31/02
Elevation (m)
100.5
100.0
99.5
99.0
98.5
98.0
97.5
Station (m)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00

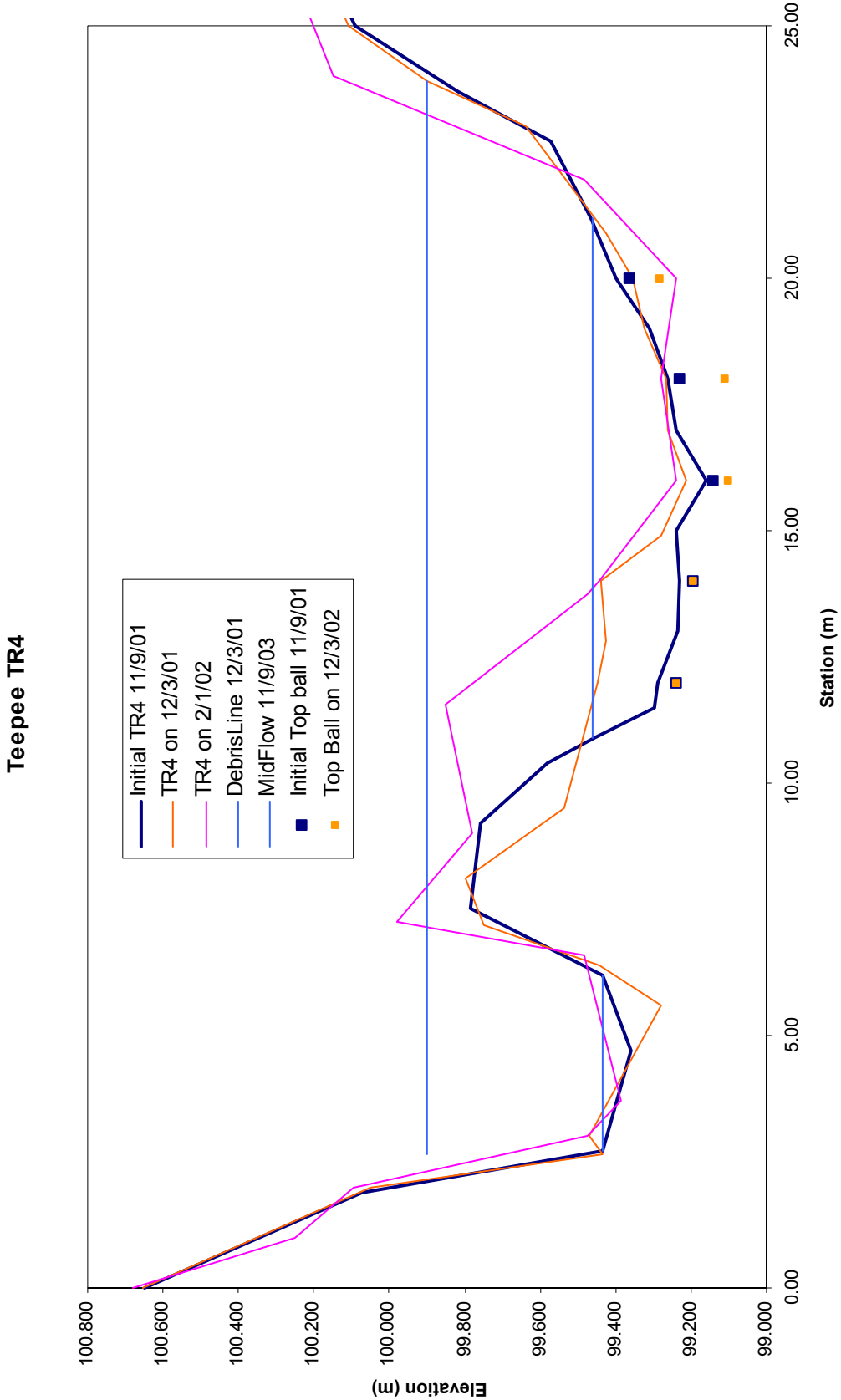

Boulder Creek Side Channel, TR1
Initial TR1 on 10/4/01
TR1 11/30/01
LowFlow on 10/4/01
FloodDepth 11/30/01
Initial top ball 10/4/01
Top ball 10/30/01
Top ball 11/30/01
EL_m 10/30/01
Peak Monitor Stage
Elevation (m)
99.0
98.5
98.0
97.5
97.0
96.5
96.0
Station (m)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00

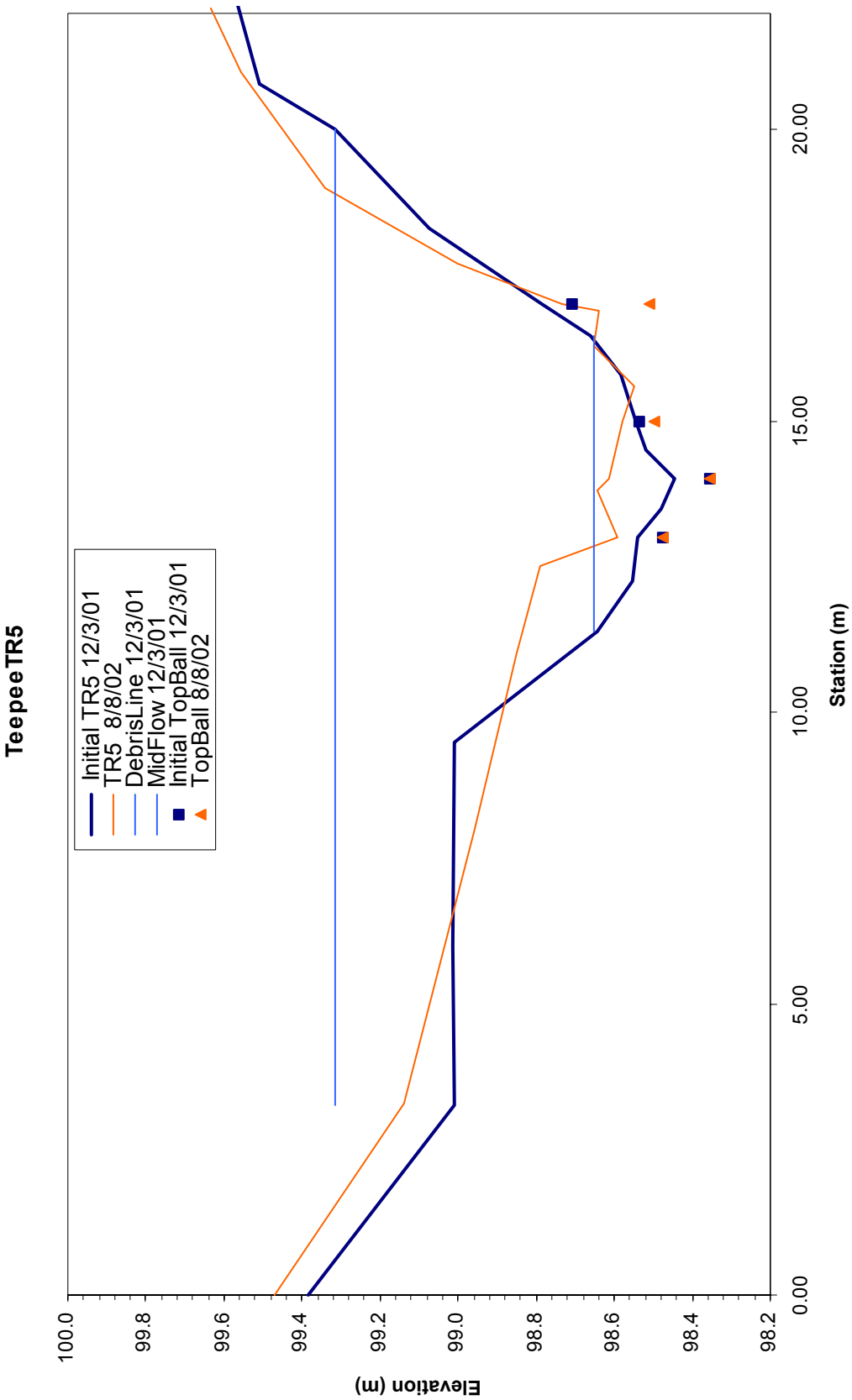

Boulder Creek Side Channel, TR2
Initial TR2 on 10/4/01
LowFlow on 10/4/01
Initial Top ball 10/4/01
EL m 10/30/01
Elevation (m)
97.000
96.900
96.800
96.700
96.600
96.500
96.400
96.300
96.200
Station (m)
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00

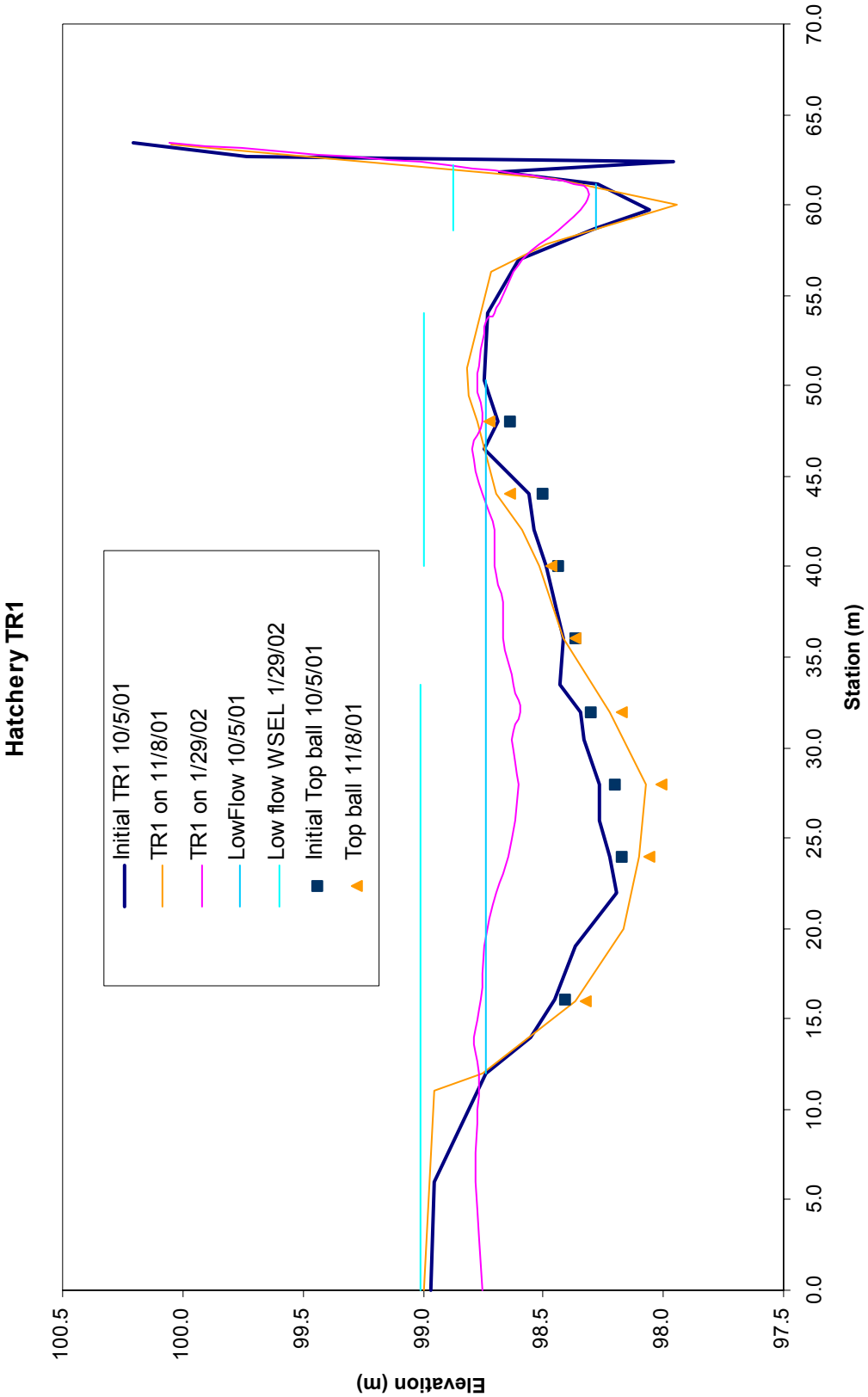

Teepee TR1
Initial TR1 on 10/3/01
TR1 11/8/01
TR1 1/29/01
Low Flow 10/3/01
High Flow 10/3/01
InitialTop ball 10/3/01
Top ballm 11/8/01
Elevation (m)
100.5
100.0
99.5
99.0
98.5
98.0
97.5
Station (m)
15
25
35
45
55
65

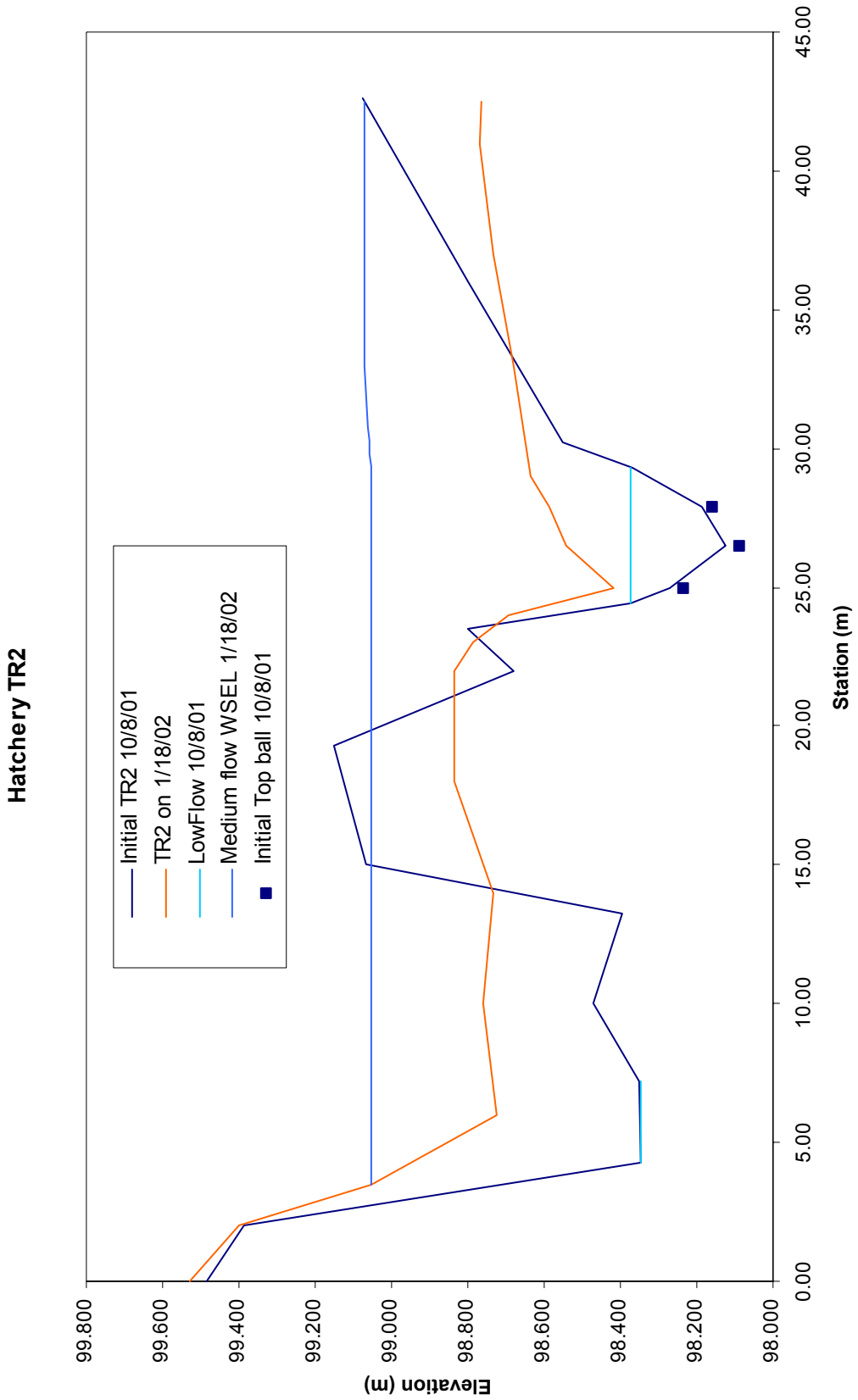

Teepee TR2
Initial TR2 on 10/9/01
TR2 12/5/01
DebrisLine 12/5/01
LowFlow 10/9/01
MidFlow 12/5/01
Initial Top ball 10/09/01
Top ball 12/5/01
Elevation (m)
100.2
100.0
99.8
99.6
99.4
99.2
99.0
98.8
98.6
98.4
98.2
Station (m)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0

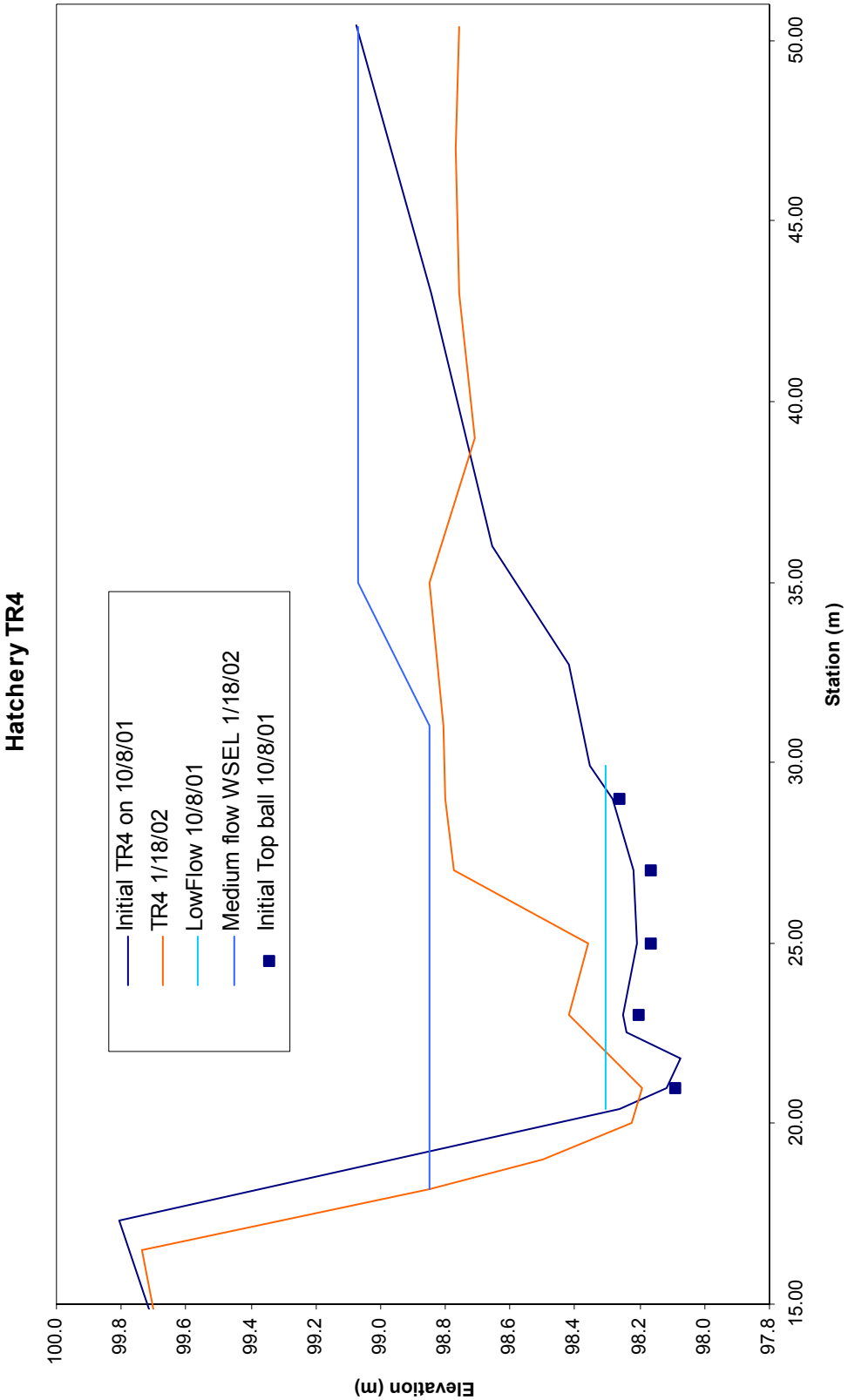

Teepee TR 3
Intial TR3 on 10/9/01
TR3 12/05/01
LowFlow 10/9/01
MidFlow 12/5/01
Intial top ball 10/9/01
Top ball 12/5/01
Elevation (m)
101.0
100.5
100.0
99.5
99.0
98.5
98.0
Station (m)
0.0
5.0
10.0
15.0
20.0


Teepee TR4
Initial TR4 11/9/01
TR4 on 12/3/01
TR4 on 2/1/02
DebrisLine 12/3/01
MidFlow 11/9/03
Initial Top ball 11/9/01
Top Ball on 12/3/02
Elevation (m)
100.800
100.600
100.400
100.200
100.000
99.800
99.600
99.400
99.200
99.000
Station (m)
0.00
5.00
10.00
15.00
20.00
25.00


Teepee TR5
Initial TR5 12/3/01
TR5 8/8/02
DebrisLine 12/3/01
MidFlow 12/3/01
Initial TopBall 12/3/01
TopBall 8/8/02
Elevation (m)
100.0
99.8
99.6
99.4
99.2
99.0
98.8
98.6
98.4
98.2
0.00
5.00
10.00
15.00
20.00
Station (m)


Hatchery TR1
Initial TR1 10/5/01
TR1 on 11/8/01
TR1 on 1/29/02
LowFlow 10/5/01
Low flow WSEL 1/29/02
Initial Top ball 10/5/01
Top ball 11/8/01
Elevation (m)
100.5
100.0
99.5
99.0
98.5
98.0
97.5
Station (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0


Hatchery TR2
Initial TR2 10/8/01
TR2 on 1/18/02
LowFlow 10/8/01
Medium flow WSEL 1/18/02
Initial Top ball 10/8/01
Elevation (m)
99.800
99.600
99.400
99.200
99.000
98.800
98.600
98.400
98.200
98.000
Station (m)
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00


Hatchery TR4
Initial TR4 on 10/8/01
TR4 1/18/02
LowFlow 10/8/01
Medium flow WSEL 1/18/02
Initial Top ball 10/8/01
Elevation (m)
100.0
99.8
99.6
99.4
99.2
99.0
98.8
98.6
98.4
98.2
98.0
97.8
Station (m)
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00

Appendix B. Spawning gravel characteristics, 1982-2002.

Transect	Year	Area_k	Elev_m	P085	D84	D75	D50	D25	D16	Dg	Fredle Index (Fi)
N1 NFBerryTea	2001			0.11	70.21	51.49	20.93	6.18	3.00	14.52	5.03
N2 BoydCr	2001	282.95	368	0.13	57.20	42.48	16.17	3.97	1.75	10.00	3.06
N3 BoydMain	2001	282.96	363	0.10	94.36	72.41	31.99	11.53	5.55	22.88	9.13
N4 NFCamp85	2001	271.96	377	0.10	99.29	78.72	41.07	14.65	4.68	21.56	9.30
N5 Gallop	2001	6.39	267	0.13	77.77	52.27	12.29	2.17	1.06	9.08	1.85
N6 NFBaptistCamp	2001	516.76	188	0.18	39.10	27.10	8.55	1.55	0.59	4.79	1.14
N7 NFMapleGlen	2001	591.83	143	0.08	64.41	54.98	35.44	15.47	7.70	22.27	11.81
N8 NFCarolsCafe	2001	1,015.94	74	0.22	32.27	21.64	7.53	1.12	0.39	3.53	0.80
N9 NFMosquitoBr	2001	745.13	89	0.13	46.71	32.29	11.25	2.13	1.04	6.95	1.79
S1 SFNewBr	2001	220.52	138	0.09	48.97	38.53	16.79	4.52	2.02	9.93	3.40
S10 SFAqueduct	2001	341.56	96	0.16	80.06	52.45	12.76	1.99	0.87	8.36	1.63
S11 SFElkFlats	2001	176.26	197	0.14	48.76	36.42	12.20	2.19	1.02	7.04	1.73
S2 LarsonsDS	2001	189.10	154	0.21	62.24	47.41	17.70	1.70	0.23	3.75	0.71
S3 Larsons	2001	189.10	154	0.23	43.10	28.54	6.51	1.02	0.30	3.62	0.68
S4 LarsonsUS	2001	189.10	154	0.09	59.51	41.71	16.71	5.63	3.07	13.51	4.96
S5 SFatSkookum	2001	267.18	114	0.14	50.39	33.02	10.25	1.88	0.96	6.97	1.66
S6 SFatGasPipe	2001	388.96	88	0.19	40.61	28.76	10.35	1.77	0.41	4.07	1.01
S7 HomesteadUS	2001	416.39	79	0.20	51.74	37.93	11.65	1.66	0.22	3.38	0.71
S8 HomesteadDS	2001	420.65	79	0.15	52.26	41.09	16.46	2.51	1.01	7.28	1.80
S9 PotterDS	2002	473.18	68	0.19	42.75	28.72	9.78	1.23	0.50	4.65	0.96
BoydTR1	2002	282.96	363	0.13	58.00	48.30	29.05	6.49	1.15	8.17	2.99
BoydTR2	2002	282.95	368	0.05	117.21	86.79	27.42	7.20	2.78	18.04	5.20
BoydTR3	2002	282.95	368	0.06	72.19	56.68	28.95	9.82	4.92	18.84	7.84
BoydTR4	2002	282.95	368	0.05	105.22	72.92	20.52	5.04	2.74	16.98	4.46
CoalTR1	2002	12.43	112	0.14	71.36	47.84	11.15	1.80	0.95	8.22	1.59
CoalTR2	2002	12.43	112	0.11	84.13	49.51	11.53	2.49	1.28	10.38	2.33
FarmhouseTR2	2002	602.03	130	0.12	112.27	81.13	13.23	2.08	1.09	11.06	1.77
FarmhouseTR3	2002	602.03	130	0.14	70.67	45.68	10.68	1.46	0.95	8.21	1.47
FarmhouseTR4	2002	602.03	130	0.13	66.31	52.50	27.45	3.16	1.07	8.44	2.07
FarmhouseTR5	2002	602.03	130	0.09	114.51	83.68	28.65	5.68	1.82	14.45	3.76

Transect	Year	Area_k	Elev_m	P085	D84	D75	D50	D25	D16	Dg	Fredle Index (Fi)
FarmhouseTR6	2002	602.03	130	0.14	53.89	39.41	11.28	1.37	0.92	7.06	1.32
HutchDSb	2002	43.61	94	0.15	61.67	45.46	17.46	3.65	1.08	8.17	2.32
HutchUSTR1	2002	43.48	97	0.12	43.39	26.62	10.67	2.95	1.33	7.59	2.53
HutchUSTR2	2002	43.48	97	0.10	100.71	69.07	26.14	6.10	2.20	14.88	4.42
HutchUSTR3	2002	43.48	97	0.16	29.59	22.88	13.65	6.03	0.80	4.88	2.51
SFLarsonsTR1	2002	189.10	154	0.06	121.47	91.76	22.34	3.80	2.13	16.10	3.28
SFLarsonsTR2	2002	189.10	154	0.15	49.99	37.00	13.70	1.62	0.93	6.82	1.43
SFLarsonsTR3	2002	189.10	154	0.12	100.16	67.63	21.22	2.41	1.10	10.52	1.99
SFLarsonsTR4	2002	189.10	154	0.13	75.60	50.21	11.53	2.05	1.06	8.97	1.81
SFLarsonsTR5	2002	189.10	154	0.14	111.16	79.88	32.18	5.41	1.18	11.47	2.98
MapleTR1	2002	31.02	154	0.13	21.28	16.81	8.47	1.78	1.02	4.66	1.52
MapleTR2	2002	31.02	154	0.03	42.76	28.53	16.21	9.58	6.55	16.74	9.70
MapleTR3	2002	31.02	154	0.09	39.09	27.10	12.87	3.70	1.84	8.49	3.14
NFBraidTR1	2002	603.33	119	0.05	83.55	62.17	31.86	8.42	3.38	16.80	6.18
NFBraidTR2	2002	603.33	119	0.09	100.61	69.91	30.97	8.71	3.35	18.34	6.47
NFSloughTR1	2002	0.92	96	0.20	86.91	61.64	27.84	2.99	0.34	5.45	1.20
NFSloughTR2	2002	0.92	96	0.21	98.31	64.56	17.52	2.33	0.43	6.47	1.23
NFSloughTR3	2002	0.92	96	0.18	86.87	57.09	18.71	3.04	0.70	7.81	1.80
NFSloughTR4	2002	0.92	96	0.10	111.08	79.80	27.19	4.35	1.39	12.43	2.90
RacehorseDSb	2002	29.30	118	0.10	99.36	69.83	34.84	11.98	5.60	23.58	9.77
RacehorseDS2	2002	29.30	118	0.13	52.75	40.75	16.18	3.06	1.24	8.08	2.21
RacehorseUSb	2002	29.30	118	0.15	80.14	53.93	15.83	2.44	0.98	8.86	1.88
RacehorseUS2	2002	29.30	118	0.14	57.29	42.94	13.96	2.55	1.03	7.69	1.87
SFBraidTR1	2002	282.95	370	0.15	70.92	48.05	14.47	1.55	0.91	8.02	1.44
SFBraidTR2	2002	282.95	370	0.09	110.28	78.89	18.51	2.84	1.45	12.66	2.40
SouthForkb	2002	12.43	112	0.10	62.28	42.62	12.28	2.22	1.26	8.86	2.02
SygitowiczTR1	2002	5.27	73	0.17	109.46	77.99	23.33	2.41	0.64	8.36	1.47
SygitowiczTR2	2002	5.27	73	0.20	42.73	24.86	6.46	1.17	0.42	4.25	0.92
SygitowiczTR3	2002	5.27	73	0.20	107.24	75.53	19.69	1.49	0.42	6.71	0.94
ThompsonTR1	2002	12.76	344	0.08	62.46	45.54	16.62	3.84	1.89	10.88	3.16
ThompsonTR2	1982	12.76	344	0.05	65.72	51.71	26.58	5.12	3.00	14.04	4.42
1982 BERTRAND CR	1982	13.62	27	0.19	27.12	19.53	8.09	1.40	0.66	4.24	1.13

Transect	Year	Area_k	Elev_m	P085	D84	D75	D50	D25	D16	Dg	Fredle Index (Fi)
1982 BOULDER CREEK	1982	20.21	188	0.13	39.57	25.10	7.33	2.08	1.10	6.59	1.90
1982 BOYD CREEK	1982	282.95	368	0.08	49.25	38.31	15.98	4.70	2.19	10.39	3.64
1982 CANYON CREEK	1982	79.31	257	0.08	77.47	52.36	15.25	3.45	1.92	12.21	3.13
1982 DEADHORSE CR	1982	16.49	399	0.11	47.47	34.80	11.11	2.43	1.26	7.73	2.04
1982 EDFRO CREEK	1982	6.23	129	0.20	37.64	25.16	8.20	1.40	0.55	4.55	1.07
1982 GALLUP CREEK	1982	6.39	267	0.11	59.49	45.34	17.36	3.73	1.76	10.24	2.94
1982 HEDRICK CREEK	1982	5.24	255	0.06	59.58	43.71	17.04	5.52	2.92	13.20	4.69
1982 HUTCHINSON CR	1982	43.48	97	0.12	31.17	21.25	8.64	2.26	1.18	6.06	1.98
1982 MAPLE CREEK	1982	31.02	154	0.11	53.00	40.14	15.65	4.23	1.88	9.98	3.24
1982 PORTER CREEK	1982	11.37	147	0.11	65.96	47.86	16.50	3.81	1.84	11.02	3.11
1982 RACEHORSE CR	1982	29.30	118	0.12	51.98	41.67	19.04	4.40	1.54	8.96	2.91
1982 S.F. AT LARSON	1982	189.10	154	0.11	75.65	51.07	14.57	2.78	1.36	10.15	2.37
1982 SKOOKUM CREE	1982	58.70	121	0.13	60.82	39.62	12.47	3.00	1.27	8.77	2.41
1982 SQUALICUM CR	1982	59.40	4	0.11	51.48	38.91	14.54	3.41	1.50	8.79	2.60
1982 THOMPSON CR	1983	12.76	344	0.06	60.00	44.15	16.48	4.78	2.70	12.73	4.19
1983 ANDERSON CR	1983	18.43	0	0.29	44.61	26.47	7.46	0.60	0.28	3.54	0.53
1983 BELL CREEK	1983	0.00	92	0.12	67.86	45.66	12.24	2.52	1.21	9.08	2.13
1983 BOYD CREEK	1983	282.95	368	0.07	49.19	36.98	13.92	4.25	2.37	10.80	3.66
1983 CANYON CREEK	1983	79.31	257	0.08	68.55	45.82	13.26	3.28	1.81	11.13	2.98
1983 CORNELL CREEK	1983	13.65	257	0.17	52.71	37.17	11.59	2.07	0.80	6.48	1.53
1983 DEER CREEK	1983	2.03	247	0.26	32.77	20.97	6.43	0.82	0.54	4.19	0.83
1983 EDFRO CREEK	1983	6.23	129	0.12	48.17	33.82	11.45	2.57	1.24	7.72	2.13
1983 FISHTRAP CREEK	1983	15.64	28	0.17	38.12	25.83	10.62	2.15	0.80	5.53	1.60
1983 MAPLE CREEK	1983	31.02	154	0.07	40.63	28.35	10.09	3.06	1.79	8.52	2.80
1983 NORTH FORK	1983	276.56	373	0.14	46.09	32.35	10.64	2.10	0.98	6.72	1.71
1983 RACEHORSE CR	1983	29.30	118	0.20	48.14	32.49	9.62	1.36	0.66	5.65	1.15
1983 S.F. AT LARSON	1983	189.10	154	0.11	54.40	38.17	13.62	3.70	1.53	9.13	2.84
1983 SKOOKUM CREE	1984	58.70	121	0.09	70.48	51.48	19.36	4.56	1.93	11.67	3.47
1984 ANDERSON CR	1984	18.43	0	0.15	47.31	34.62	12.27	2.38	0.95	6.71	1.76
1984 BOYD CREEK	1984	282.95	368	0.05	66.45	49.01	19.93	7.02	3.68	15.63	5.91
1984 CANYON CREEK	1984	79.31	257	0.10	42.62	27.37	8.57	2.22	1.28	7.38	2.10
1984 CORNELL CREEK	1984	13.65	257	0.08	52.80	40.30	14.56	3.71	1.93	10.09	3.06

Transect	Year	Area_k	Elev_m	P085	D84	D75	D50	D25	D16	Dg	Fredle Index (Fi)
1984 DEER CREEK	1984	2.03	247	0.20	44.91	33.16	12.52	2.01	0.63	5.33	1.31
1984 HOWARD CREEK	1984	19.92	0	0.15	46.40	31.82	9.87	1.91	0.91	6.50	1.59
1984 HUTCHINSON CR	1984	43.48	97	0.12	35.97	24.09	9.56	2.56	1.21	6.60	2.15
1984 KAMM DITCH	1984			0.25	22.14	15.40	5.35	0.81	0.22	2.19	0.50
1984 MAPLE CREEK	1984	31.02	154	0.07	53.88	40.21	14.90	4.04	2.13	10.71	3.40
1984 RACEHORSE CR	1984	29.30	118	0.20	41.53	27.36	7.91	1.25	0.63	5.12	1.09
1984 S.F. AT LARSON	1984	189.10	154	0.11	59.78	42.93	13.90	2.80	1.39	9.10	2.33
1984 SKOOKUM CREE	1984	58.70	121	0.07	68.69	52.08	21.84	4.24	2.09	11.99	3.42
1984 TENMILE CREEK	1984			0.25	33.37	19.93	5.13	0.87	0.45	3.86	0.81
1984 THOMPSON CR	1984	12.76	344	0.06	62.02	48.35	22.46	6.10	2.82	13.23	4.70
1984 WHATCOM CR	1985			0.09	56.64	44.02	18.33	3.96	1.81	10.14	3.04
1985 ANDERSON CR	1985	18.43	0	0.19	47.82	34.19	10.09	1.39	0.70	5.79	1.17
1985 BOULDER CR	1985	20.21	188	0.12	48.10	34.71	9.80	2.07	1.13	7.39	1.80
1985 BOYD CREEK	1985	282.95	368	0.06	56.50	45.79	24.54	7.25	3.23	13.51	5.38
1985 CANYON CREEK	1985	79.31	257	0.06	55.39	33.91	13.26	4.62	2.24	11.14	4.11
1985 CORNELL CR	1985	13.65	257	0.08	57.91	42.89	13.86	3.40	1.95	10.63	2.99
1985 EDFRO CREEK	1985	6.23	129	0.13	69.84	49.35	15.12	2.36	1.08	8.69	1.90
1985 RACEHORSE CR	1985	29.30	118	0.18	44.45	30.16	9.67	1.58	0.68	5.52	1.26
1985 S.F. LARSON BR	1985	189.10	154	0.13	47.74	34.36	11.20	2.61	1.16	7.45	2.05
1985 S.F. SKOOKUM	1985	267.18	114	0.13	46.93	33.12	10.15	1.93	1.02	6.92	1.67
1985 THOMPSON CR	1986	12.76	344	0.11	54.76	39.38	12.65	2.87	1.41	8.78	2.37
1986 S.F. AT ACME	1986	396.87	86	0.10	76.06	55.49	20.64	3.03	1.35	10.14	2.37
1986 S.F. AT LARSON	1986	189.10	154	0.13	53.55	39.49	12.61	2.46	1.10	7.67	1.91
1986 S.F. SKOOKUM	1987	267.18	114	0.11	76.51	56.33	18.68	2.53	1.22	9.67	2.05
1987 S.F. AT STRAND	1987	424.91	78	0.14	40.41	27.52	9.91	2.22	1.05	6.52	1.85
1987 SILVER CR	1987			0.22	48.93	35.44	13.01	1.48	0.32	3.97	0.81
1987 SILVER CR	1987			0.32	29.22	18.13	4.41	0.49	0.16	2.14	0.35