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Dam Removal Express Assessment Models (DREAM). Part 2: Sample runs/sensitivity tests

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Abstract

This paper presents sample runs of the Dam Removal Express Assessment Models (DREAM) presented in the companion paper, Cui et al. [submitted(c)]: DREAM-1 for simulation of sediment transport following the removal of a dam behind which the reservoir deposit is composed primarily of non-cohesive sand and silt, and DREAM-2 for simulation of sediment transport following the removal of a dam behind which the upper layer of the reservoir deposit is composed primarily of gravel. The primary purposes of the sample runs presented here are to validate some of the assumptions used in the model and to provide guidance as how accurately the field data should be collected. Sample runs indicate that grain size distribution of the reservoir sediment deposit is the most important piece of information needed during the field campaign. Other than the grain size distribution of the reservoir sediment deposit, errors within a reasonable range in other parameters do not result in significant variations in the predicted depositional patterns downstream of the dam, although different magnitudes of sediment deposition may result from such errors. Sample runs also indicate that when the reservoir deposit is composed primarily of gravel, sediment deposition downstream of the dam following dam removal may not propagate far downstream of the dam, and may be limited to isolated reaches where sediment transport capacity is low. Farther downstream sediment deposition becomes progressively smaller due to the attenuation of sediment transport and gravel abrasion. When the reservoir deposit is primarily fine sediment, however, there may be more extensive sediment deposition (both larger area and higher magnitude) downstream of the dam following dam removal. Dredging part of the sediment in advance reduces the downstream impact due to the reduced volume, and the extra distance provided by dredging allows for attenuation of sediment transport. Sample runs with staged dam removal indicate that it provides only limited benefit compared to a one-time removal in case the reservoir deposit is composed primarily of coarse sediment, but may provide significant benefits in case the reservoir deposit is composed primarily of fine sediment. The benefits of a staged removal for the latter case include reduced magnitude and area of deposition as well as reduced suspended sediment concentration downstream of the dam.

1. Introduction

Dam removal has recently been emerged as a major engineering challenge in the U.S. and throughout the world. The key problem in a dam removal project is usually sediment management. In a dam removal project, the sediment deposited in the reservoir during the period of dam operation can be mechanically excavated before the dam removal, or left in place so that the flow erodes and transports it downstream. In general, the expense of dredging the reservoir sediment deposit before removal is very large; more often than not it is orders of magnitude higher than the cost of simply removing the dam and the associated facilities. Thus there are significant economic advantages if the sediment in the reservoir deposit can be left in place for natural erosion in a dam removal project. There are, however, many concerns if the reservoir sediment deposit is left in place before dam removal. For example, sediment eroded from the reservoir will deposit in the reach downstream of the dam, creating the potential for flooding problems and damage to aquatic ecosystems. The excess sediment deposit may burry spawning habitat; the high suspended sediment concentration may kill or stress aquatic species. In addition, the low dissolved oxygen and high nitrogen content of the sediment released from reservoir may reduce or even temporally eliminate invertebrate populations, which are a major food source for fish. Useful reviews on the geomorphic and biological effects following dam removal can be found in the August issue of BioScience, which is dedicated to the subject of dam removal [e.g., Pizzuto, 2002; Stanley and Doyle, 2002]. In order to make a decision as whether the reservoir sediment deposit should be left in place for natural erosion in a dam removal project, the above concerns must be addressed. The first step toward addressing those concerns is to understand the sediment transport characteristics following dam removal.

The companion paper, Cui et al. [submitted(c)], presents the Dam Removal Express Assessment Models (DREAM), which can serve as tools for evaluating sediment transport characteristics at a cross-sectionally and reach-averaged scale in dam removal projects. DREAM-1 is for simulation of sediment transport following the removal of a dam behind which the reservoir deposit is composed primarily of non-cohesive sand and silt, and DREAM-2 is for simulation of sediment transport following the removal of a dam behind which the upper layer of reservoir deposit is composed primarily of gravel. Both models are one-dimensional and apply a combination of the backwater equation and the quasi-normal flow assumption in flow calculations. In calculating flow parameters, channel cross sections are simplified to rectangles of bankfull widths. For sediment continuity calculations, the channel downstream of the dam is assumed to have the same rectangular cross-sections as those for the flow calculation, and the channel cross-sections upstream of the dam are assumed to be trapezoidal, allowing for bank erosion during the period of downcutting. The surface-based bedload equation of Parker [1990a,b] and the bed material load equation of Brownlie [1982] are employed in the models to calculate the transport capacities of gravel and sand, respectively. DREAM-1 simulates the transport of sand over a channel that can be any combination of bedrock, gravel-bedded, and sand-bedded. DREAM-2 simulates the transport of gravel and sand over a channel that can be a combination of bedrock and gravel-bedded. Readers are referred to the companion paper, Cui et al. [submitted(c)], for details.

This paper provides sample runs of the Dam Removal Express Assessment Models (DREAM) presented in the companion paper, Cui et al. [submitted(c)], to serve as sensitivity tests for some of the key built-in and end-user parameters. The sensitivity tests to the built-in parameters (i.e., those defined by the authors of the models) provide the confidence for the underlying assumptions of those parameters. The sensitivity tests to the end-user parameters (i.e., input parameters by the modeler) provide guidance as how accurately the field data should be collected. That is, the results of the sensitivity tests help answer questions pertaining to the effect of errors in the input data. The sample runs also demonstrate the zeroing process described in the companion paper, by which some of the uncertainties in the input parameters can be reduced. The sample runs are not intended to provide general understanding of the sediment transport characteristics following dam removal, although the sample runs do shed light on certain aspects of such understandings. The general behavior of sediment pulses in mountain rivers, which reproduces the effects of dam removal, was examined experimentally by Lisle et al.

[1997, 2001], and Cui et al. [submitted(a)], and numerically in the generic model of Cui and Parker [submitted] and Cui et al. [submitted(b)].

Most of the sample runs are for DREAM-2, the more complicated of the two models, and only three of the 14 sample runs (Runs 6b, 6c and 11b) are applications of DREAM-1. The parameters in DREAM-1 can be viewed as a subset of those of DREAM-2, and thus, the sensitivity of the model to variation in most of them can be inferred from the sample runs of DREAM-2.

2. Zeroing Process

A brief discussion of the "zeroing process" is provided in the companion paper, Cui et al. [submitted(c)]. The zeroing process consists of a series of model runs under an appropriately chosen reference condition, during which certain input parameters are adjusted in order for the river to achieve a "quasi-equilibrium" state before the dam removal simulation. The process is based on the fact that a) the numerical model is a simplification of a complicated process, and b) field data for model input, particularly estimates of sediment supply, often have relatively large errors. As a result, the input of the raw data to the model will normally result in zones of spurious aggradation and degradation over reaches where it had been observed to change only slowly in the years prior to dam removal. Here quasi-equilibrium is used in a loose sense, corresponding to this slow morphodynamic change.

Here zeroing is applied to the zone of the study reach downstream of the dam. Sediment is supplied to this reach as if no dam were present. The reference state is the longitudinal profile of this zone immediately before dam removal. (The ideal reference state is the longitudinal profile before dam installation, but this information is often not available.) The longitudinal profile and other parameters are adjusted until an acceptable quasi-equilibrium state is realized.

The underlining assumption of the zeroing process is that the sediment transport equations used in the models can accurately calculate sediment transport capacities, even though it is understood that all sediment transport equations may potentially contain relatively large errors, as seen in the DREAM-1 validation in the companion paper, Cui et al. [submitted(c)]. As a result of the above assumption, it is realized that correct input to the model under the reference condition should be able to reproduce the quasi-equilibrium condition prior to dam construction. Modelers may adjust somewhat several of these input parameters, which are difficult to collect in the field and may have very large potential errors, in order to achieve quasi-equilibrium. Input parameters in this category include the sediment supply and the gravel abrasion coefficient. For example, the model will produce extensive spurious aggradation if the sediment supply to the model is too high, and adjusting sediment supply to appropriate values will minimize such spurious aggradation. Similarly a gravel abrasion rate that is too high or too low will result in abnormalities in the reference condition, e.g., aggradation in the upper reaches and degradation in the lower reaches in case of a high abrasion coefficient, and degradation in the upper reaches and aggradation in the lower reaches in case the abrasion coefficient is too low. By adjusting certain input parameters such as sediment supply and the gravel abrasion coefficient, the model should be able to produce a "quasi-equilibrium," "post-zero-process" longitudinal profile that is very close to the existing longitudinal profile downstream of the dam, and experiences only the expected minor aggradation or degradation over time prior to dam removal. This post-zero-process longitudinal profile is used as the initial longitudinal profile downstream of the dam in the dam removal simulation. Because the initial profile is in a quasi-equilibrium state, changes in bed elevation and other parameters following dam removal can be interpreted as the direct results of dam removal rather than spurious predictions of the model that are independent of dam removal.

It should be noted in advance that the reference quasi-equilibrium so produced is a dynamic system that also experiences minor aggradation and degradation at different reaches over different hydrologic conditions, although the long-term average aggradation and degradation is not beyond what is expected in a natural stream not subject to extreme. This realization is helpful in interpreting the predictions for the river after dam removal. Instead of examining the absolute aggradation and degradation, for example, it is of more value to examine bed level change and sediment transport rates relative to those of the reference state before dam removal. Examples of the zeroing processes can be found in the sample runs presented in this paper.

3. Parameters in DREAM-2

Table 1 lists the major parameters for a DREAM-2 simulation. The listed parameters include most of the end-user parameters (e.g., discharge record, sediment supply, abrasion coefficient for gravel), some of the built-in parameters (e.g., active layer thickness), and certain parameters that are calculated with similarity assumptions between different reaches (e.g., active channel geometry in the reach upstream of the dam subsequent to dam removal). Some of the listed parameters can be expected to be modified during the zeroing process, and thus, their sensitivities to model results are either not testable or are already set by the results of the zeroing process (e.g. downstream channel gradient). In addition to the test of end-user and built-in parameters, two sample runs are performed to demonstrate the cases of dredging (Run 10) and staged removal (Runs 11a and 11b). Overall 14 sample runs (Runs 1 to 5, 6a, 6b, 6c, 7 to 10, 11a and 11b) are performed and presented below.

4. Sample Runs

The Prototype River and Assumed Reservoir Deposit: Sample runs were conducted for a hypothetical dam removal. In order to make the data realistic, however, input data for the sample runs are loosely connected to the proposed removal of the Marmot Dam on the Sandy River, Oregon. This site is selected because the data are readily available to the authors from a consulting project [Stillwater Sciences, 2000] (see also Cui and Wilcox [in press]). In particular, the channel geometry and discharge record are taken directly from the Sandy River, and the dam to be removed is assumed to be located at the same location as the current Marmot Dam, as shown in Figure 1. To demonstrate that the model is capable of handling large dams, the dam is assumed to be 30 m high as compared to the 14 m height of the Marmot Dam. Assuming an average width of sediment deposit of 50.5 m, which is the estimated averaged width of the reservoir deposit behind Marmot Dam [Cui and Wilcox, in press], the estimated sediment deposit in the reservoir is about 4,800,000 m^3 compared to the estimated 750,000 m^3 in the Marmot Reservoir. The reach of interest in the river is approximately 58 km, from about 10 km upstream of the dam to its confluence to the Columbia River. Reach-averaged channel gradient ranges between approximately 0.01 at the upstream reaches to approximately 0.0001 at the downstream reach, as shown in Figure 1. Channel width for the base run (Run 1), measured from high-quality aerial photograph and in the field, ranges between 24 m and 168 m, as shown in Figure 2. Figure 2 indicates that the river runs through a narrow gorge between about 4 km and 10 km downstream of the dam with a bankfull channel width of approximately 30 m. There are several tributaries to the river, most of which are very small compared to the main stem Sandy River. The only major tributary to the river is Bull Run River, which joins Sandy River approximately 21 km downstream of the dam, as shown in Figure 1. Interested readers can find a detailed reach-by-reach description of the Sandy River in Cui and Wilcox [in press].

The reservoir deposit is assumed to be composed of two units (layers) for the base run (Run 1); a coarser unit for the upper layer deposit and a finer unit for the lower layer deposit as shown in Figure 3. For simplicity, the grain size distribution for each unit is assumed to be uniformly distributed in space. The upper layer (coarser unit) is composed primarily of gravel with a small fraction of sand and silt, and the lower layer (finer unit) is composed primarily of sand and small fractions of gravel and silt, as shown in Figure 3. The width of the reservoir deposit is assumed to be 120 m at the surface of the deposit.

Daily average discharge record at two USGS stations were used for the sample runs: the USGS Sandy River near Marmot gauge (station no. 1413700) is applied to the reach upstream of the Bull Run River confluence, and the USGS Sandy River below Bull Run River gauge (station no. 14142500) is applied to the reach downstream of the Bull Run River confluence. Discharges and sediment supply from other small tributaries are neglected. The sample runs are performed for an arbitrary 10-year period for all the runs except for Runs 6b, 6c, and 11b, in which reservoir deposit is assumed to be composed of entirely sand. Runs 6b, 6c and 11b are simulated for 208 weeks, or approximately 4 years because of the very rapid transport of the finer reservoir deposit. The same 10 years selected for the Marmot Dam removal simulation in Stillwater Sciences [2000] and Cui and Wilcox [in press] are used for the base run (Run 1) of the sensitivity test, as shown in Table 2. The first year of the 10-year series was selected by Stillwater Sciences [2000] and Cui and Wilcox [in press] based on the average condition for both the annual peak flow and annual runoff, i.e., the exceedance probabilities for both the peak flow and annual runoff were close to 50% in that year. The rest of the years in the 10-year series were selected randomly from the available record. The hydrograph for the first year of simulation (water year 1991) in the base run (Run 1) is shown in Figure 4.

Sediment Supply: Grain size distributions for the gravel (> 2mm) and sand supply (62.5 microns – 2 mm) upstream of the dam are assumed to be the same as the gravel and sand portions of the cumulative grain size distribution of the reservoir deposit, as shown in Figure 5. The volumetric abrasion coefficient (i.e., the fraction of volume lost to abrasion for transport of a unit distance) is assumed to be 0.02 km^{-1} for the base run (Run 1), so that 2% of the gravel volume is lost to sand and silt for every kilometer transported. Due to the presence of large reservoirs in Bull Run River, gravel supply from Bull Run River is minimal and is completely ignored in the simulation. The assumed sediment supply rates for the base run (Run 1) are given in Table 3. They were selected as part of the zeroing process.

Run 1: Base Run

The purpose of the base run is to define the condition to which the other sample runs are compared. Based on the hydrologic record given in Table 2, the gravel and sand grain size distributions in the sediment supply given in Figure 5 and the sediment supply rates given in Table 3, zeroing was performed to adjust channel longitudinal profile, as discussed briefly in the companion paper, Cui et al. [submitted(c)], and earlier in this paper. The longitudinal profile after the zeroing process is given in Figure 6a, along with the longitudinal profile that served as input to the zeroing process. The aggradation and degradation of the channel bed over a ten-year period under the assumed reference conditions are shown in Figure 6b.

Results in Figure 6a show that the zeroing process adjusts only slightly the longitudinal profile, resulting in a very small adjustment in channel gradient, which is the driving force for sediment transport. Results in Figure 6b show that channel bed aggrades and degrades at different reaches during different years, but over time the channel bed aggrades or degrades only modestly.

Dam removal simulation results for the base run (Run 1) are presented in Figure 7a for cumulative (net) aggradation/degradation, Figure 7b for annual aggradation/degradation, and Figure 7c for suspended sediment concentration. The annual aggradation/degradation is presented here because of its importance in ecological and biological evaluations. The results for suspended sediment concentration are presented only for days 1, 5, and 30 due to the difficulty in presenting large amount of data within the confines of a journal paper.

Results in Figures 7a and 7b indicate that sediment deposit occurs only in selected locations, including immediately downstream of the dam (0 – 3 km), the reach immediately downstream of the gorge (6 – 13 km) where the channel becomes wider as shown in Figure 2, and immediately downstream of the Bull Run River confluence (22 – 30 km) where the channel begin to have less bedrock outcrops (see Cui and Wilcox [in press] for detail). Spatially, the magnitude of aggradation in the three locations decreases in the downstream direction due to the attenuation of gravel transport (i.e., temporary storage in of sediment in upstream reaches) and abrasion of gravel (Figure 7a). Temporally, the annual aggradation decreases in time at all the three locations (Figure 7b). Results in 7c indicate that suspended sediment concentration increased to

15000 ppm on the first day following the removal near the dam. A 2000 ppm suspended sediment concentration is also predicted for day 30 following the dam removal for more than two thirds of the reach downstream of the dam.

Results of the other sample runs are compared with the base run (Run 1) above. It needs to be noted in advance, however, that the comparisons are made qualitatively in most cases, although quantitative comparisons are possible. The reason for the qualitative comparison is that it is often enough to infer the accuracy needed for a particular parameter, which is the focal point of most of the sample runs. In addition, a detailed quantitative comparison would be excessively long for a journal paper.

Run 2: Test for a Thinner Active Layer Thickness

The original publication of Parker [1990a,b] suggested that the active layer (surface layer) thickness varies in time. The implementation of a time-dependent active layer, however, requires iteration in numerical solution (e.g., Cui et al. 1996), and often results in instability in calculation if not handled carefully. Extensive tests by the first author indicate that model results are usually not sensitive to the choices of an active layer thickness. An example of such a test can be found in Figure 4 of the companion paper [Cui et al. submitted(c)], where the "simplified treatment" in the diagram also applied a fixed active layer thickness in addition to the simplified treatment to the flow, while Cui et al. [1996] and Cui and Parker [1997] treated the active layer as time dependent. The three sets of simulation produced almost identical results in bed elevation, grain size distribution and water surface profile. With that in mind, DREAM-2 employs a fixed active layer thickness while allowing the grain size distribution within the active layer to change in time. A similar practice has been used in Cui and Parker [submitted], Cui et al [submitted(b,c)], and Cui and Wilcox [in press]; this paper offers the first documented test on whether different fixed active layer thickness values produce different model results.

The default value for active layer thickness in DREAM-2 is 0.5 m. This value is reduced to 0.25 m in Run 2, or half of its default value in the base run (Run 1).

Results for Run 2 are given only as cumulative (net) aggradation/degradation, as shown in Figure 8. Comparison of results for Run 2 and the base run (Run 1) indicates that decreasing the active layer thickness by a factor of 2 results in very little change in modeling results, justifying a constant default value for active layer thickness in the model. It needs to be mentioned, however, that in the event that the gravel thickness above bedrock is less than the specified active layer thickness, the model automatically sets the local value to be equal to the thickness of the gravel deposit.

Run 3: Test for Altered Discharge Series

Run 3 tests the sensitivity of model results to the discharge record used for simulation. Because the years immediately after dam removal are most likely more important in the morphologic development following a dam removal, and because a dry period following dam removal is the most unfavorable scenario in that it may result in a longer period of time for channel recovery, Run 3 applies a dry-year series for years 1, 2 and 3 following the dam removal. The dry-year series was selected so that both annual run-off and annual peak flow have exceedance probabilities of approximately 90%. This selected dry-year series was applied to each of the first three years following dam removal, so replacing the first three years used in the simulation for the base run (Run 1).

The dry-year selected for the first three years following dam removal was water year 1987 (10/1/1986 to 9/30/1987), which had a peak flow of 230 m^3/s and annual run-off of 0.87×10^9 m^3, or exceedance probabilities of 83% and 91% for annual peak flow and annual run-off, respectively. Other than the discharge for the first three years following the dam removal, all the parameters are kept the same as in the base run (Run 1). The discharge for water year 1987 is shown in Figure 9.

Results for Run 3 are shown in Figure 10a for cumulative (net) aggradation/degradation and Figure 10b for suspended sediment concentration. Comparison of the results of Run 3 with that of the base run (Run 1) indicates that the spatial distributions of aggradation and degradation are approximately the same for Run 3 and the base run (Run 1), although there are observable differences in the magnitude of erosion and deposition. In particular, the magnitude of aggradation and degradation for Run 3 is smaller than those for the base run (Run 1) during the first three years, as expected. Those differences, however, become insignificant after year 3, when the discharge series for the two runs becomes identical. The implication is that the resulting channel morphology following dam removal is more dependent on the most recent high flow events and may be only very weakly correlated to previous hydrologic events. Suspended sediment concentrations for Run 3 for days 1, 5, and 30 are generally less than that for the base

Run (Run 1), indicating the strong correlation between suspended sediment concentration and water discharge.

Run 4: Test for Altered Bedload Supply

Run 4 tests the sensitivity of the bedload supply rate on the results of the simulation. The bedload supply in Run 4 is assumed to have the same distribution as that in the base run (Run 1), as shown in Figure 5. The bedload supply rate upstream of the dam, however, is increased from 10,000 m^3/year for the base run (Run 1) by 50% to 15,000 m^3/year. All the other input parameters are kept the same as the base run (Run 1). Due to the increase in bedload supply rate, a new zeroing process is performed, and the resulting post-zeroing process longitudinal profile is only slightly different from that of the base run (Run 1). The spatial distributions of aggradation and degradation under reference conditions for Run 4 and the base run (Run 1) are also differ only slightly.

Results for the dam removal simulation for Run 4 are given only for cumulative (net) aggradation/degradation, as shown in Figure 11. Comparison of results for Run 4 to that of the base run (Run 1) indicates that increasing bedload supply by 50% does not result in significant change in the magnitude and spatial distributions of the aggradation/degradation following the dam removal. Such results are expected because the sediment supply is relatively small compared to the amount of sediment stored in the reservoir. Having said that, however, one must realize that the rate of sediment supply is important in that it may alter the post-zeroing process longitudinal profile significantly if it is not chosen judiciously.

Run 5: Test for Altered Gravel Abrasion Coefficient

Run 5 tests the sensitivity of the results to gravel abrasion coefficient. Zeroing processes were performed for volumetric abrasion coefficients of 0.05 km^{-1} and 0.005 km^{-1}, an increase by a factor of 2.5 and a decrease by a factor of 4, respectively, from the base run (Run 1) value of 0.02 km^{-1}. In both cases the zeroing process could not produce a longitudinal profile that was close to that of the pre-zero process, indicating that the abrasion coefficients are not reasonably close to the actual value in the river.

The final volumetric abrasion coefficient adopted for Run 5 is 0.01 km^{-1}, or a decrease by a factor of 2 from the base run (Run 1) value. All the other input parameters except bedload supply are kept the same as in the base run (Run 1). Due to the decrease in abrasion coefficient, the bedload grain size in Run 5 can be expected to be coarser than that in the base run (Run 1), especially farther downstream of the sediment source. In addition, the bedload transport rate for Run 5 can be expected to be higher than that in the base run (Run 1) farther downstream from the sediment source if the rate of bedload supply is not reduced from that of the base run (Run 1) value.

Note that in Run 4 we have concluded that results of the simulation were not particularly sensitive to changes in bedload supply. The bedload supply, however, needs to be adjusted in order to achieve the quasi-equilibrium conditions under the reference conditions.

A new zeroing process is performed before implementing Run 5, in which bedload supply was adjusted so that the longitudinal profiles before and after the zeroing process are similar to each other. The adjusted bedload supply rate is 3,000 m^3/year, reflecting a 70% decrease from the 10,000 m^3/year value for the base run (Run 1). The comparison between pre- and post-zeroing process longitudinal profiles for Run 4 is only slightly different from that of the base run (Run 1), and channel responses under reference conditions for Run 4 is also similar to that of the base run (Run 1).

Results of the dam removal simulation for Run 5 are shown in Figure 12a for cumulative (net) aggradation/degradation, and Figure 12b for annual aggradation/degradation. Comparison of results in Run 5 to those of the base run (Run 1) indicates that decreasing the gravel abrasion coefficient by a factor of 2 does not change the spatial distribution of aggradation/degradation, although it visibly increases the magnitude of aggradation downstream of the dam. For example, the cumulative (net) aggradation for Run 5 at years 4 and 5 in the reach between approximately 8 km and 12 km downstream of the dam increases by about 30% from those in the base run (Run 1). One must realize, however, that a 30% increase in the magnitude of aggradation may not be considered significant in a sediment transport simulation, as long as the spatial distributions of aggradation/degradation are similar. In addition, the annual changes in bed elevation for Run 5 and the base run (Run 1) are very similar both in spatial distribution and magnitude, as shown in Figure 12b.

Runs 6a, 6b and 6c: Tests for altered Grain Size Distribution in the Reservoir Deposit

Runs 6a, 6b and 6c test the sensitivity to grain size distribution in the reservoir deposit. In Run 6a, all the grain sizes in the grain size distribution of the coarser portion (> 2 mm) of the reservoir deposit are doubled from the base run (Run 1) values. In Runs 6b and 6c, the reservoir sediment deposit is assumed to be composed completely of sand with a geometric mean grain size of 0.5 mm and a geometric standard deviation of 2.55. Run 6b was conducted with the unmodified DREAM-1 while in Run 6c the sediment transport capacity is augmented by a factor of 2.2 from that predicted with Brownlie's bed material equation (Brownlie 1982). The factor of 2.2 is tested here because it produced good result in simulating the SAFL sediment pulse experiment Run 4b [Cui et al. submitted(a)]. Details of the simulation of SAFL sediment pulse experiment Run 4b are presented in the companion paper, Cui et al. [submitted(c)]. Other than grain size distribution in reservoir deposit, all other parameters are kept the same as in the base run (Run 1). As discussed earlier, the grain size distribution of reservoir deposit and sediment supply can be expected to be strongly correlated. For the sensitivity test purposes, however, the grain size distributions of sediment supply for Runs 6a, 6b and 6c remain the same as the base run (run 1).

Results of Run 6a are shown in Figure 13a for cumulative (net) aggradation/degradation. Comparison of results in Run 6a to those of the base run (Run 1) indicates that model results are strongly dependent on the grain size distribution of the reservoir deposit. For example, the reservoir deposit in Run 6a quickly stabilized after two years following dam removal due to the much coarser sediment in the reservoir deposit, as shown in Figure 13b. Results in Figure 13b show that a large amount of reservoir deposit is left in the reservoir reach and the fan delta immediately downstream of the dam even ten years after the dam removal. The results of Run 6a indicate that modelers must be careful in acquiring reasonably accurate reservoir deposit grain size distributions before the modeling exercises. In addition to the possible coring in the reservoir deposit, modelers can often get additional information by grain size analysis of sediment deposits upstream and downstream of the reservoir.

It should be noted, however, that the modified grain size distribution of Run 6a (all sizes in the grain size distribution are doubled) represents a change that is probably much larger than the uncertainty in grain size distribution that can reasonably be in actual dam removal studies.

Runs 6b and 6c were conducted for 208 weeks, or approximately 4 years, in part because the current model structure for DREAM-1 only allows for a maximum of 208 weeks simulation. In addition, all of the excess sediment moved out of the modeled reach in Run 6c, and almost all in Run 6b, during the modeled period.

Results for Run 6b are shown in Figure 14a for cumulative (net) aggradation/degradation, and in Figure 14b for weekly maximum daily average suspended sediment concentration (i.e., the maximum daily average suspended sediment concentration in seven days), in which results are presented for only five weeks, week 1, 3, 5, 10 and 30. Results in Figure 14a indicate that the sediment deposit in the reservoir initially elongates and disperses, reducing its amplitude to several meters. Subsequently the tail of the sediment pulse translates downstream as the magnitude of the sediment deposit continues to decrease. The simulated evolution of reservoir sediment is very similar to that observed in the SAFL sediment pulse experiment Run 4b presented in Cui et al. [submitted(a,b)], which was used for DREAM-1 validation in the companion paper, Cui et al. [submitted(c)]. Based on the trend of movement of the sediment pulse, the sediment can be expected to move out of the modeled reach in 5 to 6 years. Results in Figure 14b indicate that Run 6b produces much higher suspended sediment concentrations (e.g., as high as 100,000 ppm) than the base run (Run 1), in which the reservoir deposit is composed of a gravel-sand mixture.

Results for Run 6c, which augments the sediment transport capacity calculated with Brownlie's bed material equation [Brownlie 1982] by a factor of 2.2, are shown in Figure 15a for cumulative (net) aggradation/degradation, and in Figure 15b for weekly maximum daily average suspended sediment concentration for weeks 1, 3, 5, 10 and 30. Results for Run 6c are similar to that for Run 6b except that the sediment moves out of the simulated reach much more quickly, i.e., approximately 1 year for Run 6c verses 5 to 6 years for Run 6b, with slightly higher suspended sediment concentrations. Comparison of results of Runs 6b and 6c indicate that it is very important to collect field data in a dam removal project so that the model can be validated and used with more confidence. In addition, results in Runs 6b and 6c indicate that consequences of removing dams with sand deposits may be far more serious than in the case of gravel deposits. In case of a gravel deposit in the reservoir, the attenuation of gravel transport and abrasion of gravel result in downstream sediment deposition only in relatively short and isolated reaches. In case of a sand deposit in the reservoir, however, a very long reach, i.e. the whole 50 km of the modeled reach in the cases of Runs 6b and 6c, are affected by sediment deposition, even though the duration of this deposit is shorter. In addition, the removal of a sandy reservoir deposit produces much higher suspended sediment concentrations, which can also be detrimental to aquatic biota.

Runs 7 and 8: Test for Altered Geometry of the Active Channel in the Reach Upstream of the Dam

As discussed earlier, the active channel in the reservoir reach is assumed to be trapezoidal, quantified by the bottom width of the channel and the slope angle of the two banks. The bank slope is set at 35° as a built-in parameter in the model. The width of the bottom of the active channel is allowed to change as the channel aggrades and degrades, within the restriction of a minimum width as discussed in the companion paper, Cui et al. [submitted(c)]. The rules as how the channel evolves during aggradation and degradation can be found in the companion paper, Cui et al. [submitted(c)], and are not described here. The minimum width is calculated by assuming similarities between the active channel in the reservoir reach and the channel immediately downstream of the dam. In Run 7 the bank slope is reduced from the default 35° to 15° for a sensitivity test. The minimum width at the bottom of the trapezoidal channel is calculated to be 42.0 m for the base run (Run 1). In Run 8 the value of minimum bottom width is increased by a factor of 2 to 84.0 m while retaining the 35° bank slope.

Detailed results for Runs 7 and 8 can be found in Stillwater Sciences [2002a] and are not presented here to conserve space. Only a brief summary of the results is given below. a) Decreasing the bank slope from 35° to 15° or increasing the minimum bottom width of the trapezoidal channel by a factor of 2 only slightly reduces the rate of reservoir erosion due to the wider erosional cross sections for the two runs. b) The annual aggradtion and degradation for the altered bank slope or minimum bottom width are very similar to those of the base run (Run 1). c) The depositional patterns for the altered bank slope and minimum bottom width are very similar to those of the base run (Run 1).

Run 9. Test for Altered Downstream Channel Width

Run 9 tests the sensitivity of bankfull channel width downstream of the dam to the model results. The bankfull channel width downstream of the dam is increased by 20% for Run 9 from its base run (Run 1) values. All the other parameters, except bedload supply rate, are kept the same as the base run (Run 1). It should be noted that the active channel width upstream of the dam is also increased by 20% because of the similarity assumption of the channels as discussed in the companion paper, Cui et al. [submitted(c)]. Due to the adjusted sediment transport capacity along the channel with the modification to channel width, the zeroing process must be implemented and the bedload supply adjusted in order to preserve similar longitudinal profiles before and after the zeroing process. The bedload supply rate is reduced from the base run (Run 1) value of 10,000 m^3/year by 50% to 5,000 m^3/year for Run 9.

Results of the dam removal simulation for Run 9 are presented only for cumulative (net) aggradation/degradation, as shown in Figure 16. Comparison of the results of Run 9 to those of the base run (Run 1) indicates that increasing bankfull channel width downstream of the dam by 20% results in only minor changes in the magnitude and pattern of sediment deposition downstream of the dam. Interestingly, the increase in bankfull channel width downstream of the dam also altered the erosion rate and pattern in the reach upstream of the dam. This result is caused in part by the increase of the active channel width upstream of the dam, so that a smaller amount of degradation with a wider channel results in same amount of sediment eroded as in the narrower channel of the base case.

Run 10. Test for Dredging

Run 10 tests the effect of dredging on sediment transport characteristics. The deposit shown in Figure 3 is dredged to bedrock for the 3 km reach immediately upstream of the dam. The amount of excavated sediment is slightly more than half of the total deposit. Other parameters are kept the same as that in the base run (Run 1). Results for Run 10 are presented only as cumulative (net) aggradation/degradation, as shown in Figure 17. Results in Figure 17 indicate that dredging the 3 km reach upstream of the dam to bedrock reduced downstream aggradation significantly. The maximum deposition for the reach between 8 and 12 km downstream of the dam, for example, decreased to slightly more than 1 m from approximately 4 m for the base run (Run 1). It should be clarified, however, that the reduced downstream deposit is not completely due to the reduced pre-dam removal sediment volume. By dredging the 3 km reach upstream of the dam to bedrock, an additional 3 km for attenuation of sediment transport is made available. This is evidenced by the deposition upstream of the dam for years 1 to 6, which helped to significantly reduce the downstream sediment deposition. The effect of dredging is likely not as effective as demonstrated in Run 10 if dredging volume is small and additional space for attenuation is not provided. An example of such a case is provided in Stillwater Sciences [2002b], which shows that dredging 230,000 m^3 (300,000 cubic yards) of sediment in the Marmot Dam removal project will not provide significant benefit.

Runs 11a and 11b. Test for Staged Removal

Runs 11a and 11b test the effect of staged removal on sediment transport characteristics. In Run 11a the reservoir deposit is assumed to be the same as that in the base run (Run 1), i.e., the reservoir deposit is composed primarily of gravel. In Run 11b the reservoir deposit is assumed to be the same as that in Runs 6b and 6c, i.e., the reservoir deposit is composed primarily of sand. Run 11a is simulated with DREAM-2 and Run 11b is simulated with the unmodified DREAM-1.

In Run 11a the 30 m dam is removed in 5 stages, one each year for 5 consecutive years. The dam is assumed to be 50 m wide. In each stage a section of the dam is removed across its entire width. The first section removed is 10 meters high and each of the next 4 sections removed is 5 meters high. This removal scenario is arbitrary and for demonstration only, and does not represent any optimization of design. Other parameters in Run 11a are kept the same as those in the base Run (Run 1). The staged removal in Run 11b is essentially the same as that in Run 11a except that the removal interval is 26 weeks, or approximately 6 months, rather than 1 year. Other parameters in Run 11b are kept the same as those in Run 6b.

Results for Run 11a are presented only for cumulative (net) aggradation/degradation, as shown in Figure 18. Results in Run 11a indicate that by removing the dam in 5 stages in 5 years, channel deposition downstream of the dam decreases slightly for the first 5 years after the first stage removal. Upon completion of the last stage of the dam removal, the deposition pattern downstream of the dam becomes almost identical to that of the base run (Run 1). Although the simulation presented in Run 11a does not represent any optimization, it still indicates that staged removal for a reservoir with gravel deposit may not be the best choice, considering the large expenses involved in the staged removal processes and the relatively minor benefit.

Results for Run 11b are shown in Figure 19a for cumulative (net) aggradation/degradation, and in Figure 19b for weekly maximum daily average suspended sediment concentration for weeks 1, 3, 5, 10 and 30. In Figure 19a the results consist of five pairs of two profiles, with the first of each pair corresponding to 1 week after a staged removal, and the second to 4 weeks after the removal. Comparison of results for Runs 11b and 6b indicate that staged removal, even though not optimized, was able to reduce the magnitude of downstream aggradation and to limit the aggradation to a low-gradient reach farther downstream than in the base run. Staged removal also reduced suspended sediment concentrations significantly. Results in Run 11b indicate that there may be major benefits to a staged removal in case the reservoir deposit is composed primarily of sand and silt. Having said that, one must recognize that high suspended sediment concentration occurs only once for a period of time following a one-shot removal while it occurs following each removal stage of a staged dam removal, posing a major disadvantage.

5. Conclusions

This paper presents sample runs to serve as sensitivity tests for the Dam Removal Express Assessment Models (DREAM) presented in the companion paper, Cui et al. [submitted(c)]. Fourteen sample runs are performed, among them eleven runs for DREAM-2, the more complicated of the two models, which simulates sediment transport following the removal of a dam behind which the upper layer of the reservoir deposit is composed primarily of gravel. Three runs (Runs 6b, 6c and 11b) were performed for DREAM-1, which simulates sediment transport following the removal of a dam behind which the reservoir deposit is composed primarily of non-cohesive sand and silt.

Results of the sample runs indicate that, in case the upper layer of the reservoir deposit is composed primarily of gravel under the tested geomorphic and hydrologic conditions, the sediment deposit downstream of the dam occurs in isolated reaches not too far downstream of the dam where the sediment transport capacity is low (e.g., wider reaches). This result is partially dependent on the choice of conditions similar to the Sandy River near Marmot Dam, which is strongly controlled by bedrock both downstream of the dam and upstream of the existing reservoir deposit. Sediment deposition farther downstream of the dam decreases rapidly due to the attenuation of sediment transport and gravel abrasion. In case the reservoir deposit is composed primarily of fine sediment, however, the sediment deposit may cover the entire reach shortly after dam removal for an extended period of time under the geomorphic and hydrologic conditions tested. Although the total time of impact for the removal of a dam with fine sediment deposit is shorter than that in case of gravel deposit, the magnitude of such impact is much larger. In case of a gravel deposit, the sediment deposition downstream of the dam occurs progressively, and thus the annual aggradation and degradation is usually small. Sensitivity tests indicate that grain size distribution of the reservoir deposit is the most important piece of information to collect in the field. Inaccurate grain size distributions in the reservoir deposit may result in erroneous simulation results. Other parameters are relatively less sensitive to model results. Based on the sample runs under the assumed geomorphic and hydrologic conditions, errors within reasonable ranges in input parameters other than the grain size distribution of the reservoir deposit may not result in significant errors in the simulated downstream depositional patterns, although there may be minor differences in the magnitude of the deposit. The sample run under the scenario of dredging indicates that excavating sediment immediately upstream of the dam results in less downstream sediment deposition, as expected. This reduction of downstream sediment deposition is due to the combined effect of the reduced sediment volume in the reservoir and the extra distance for sediment transport attenuation provided by dredging. The sample runs in staged removal indicate that the benefit of staged removal for the case of a gravel reservoir deposit may be minimal under the geomorphic and hydrologic conditions tested, but may provide significant benefits in case the reservoir deposit is composed of fine sediment. The benefits for the later case include reduced magnitude of sediment deposition, reduced area of sediment deposition and reduced suspended sediment concentrations. Perturbations in the calculated sediment transport capacity for DREAM-1 indicate that potential errors in the sediment transport equation in the simple form of under- or over-prediction by a constant factor may result in a lengthened or shortened time frame for the evolution of reservoir sediment. The depositional patterns, however, are not significantly affected by potential errors in the sediment transport equation if such error comes in as an under- or over-prediction by a constant factor.

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Table 1. Major parameters in the model

Parameters	Modifiable in Zeroing Process?	Other Notes
Active layer thickness	No	Active layer thickness is not an end-user parameter. Active layer thickness is tested for sensitivity.
Discharge	No	Daily average discharge record. Discharge is tested for sensitivity.
Sediment supply	Yes	Sediment supply includes the rate of supply, its grain size distribution and abrasion coefficient. Sediment supply grain size distribution should be determined by the grain size distribution in the reservoir deposit. Sediment supply rate and abrasion coefficient are tested for sensitivity.
Downstream channel gradient	Yes	Downstream channel gradient is given through bedrock elevation and thickness of fluvial deposit. The thickness of fluvial deposit is adjusted automatically in the zeroing process in such a way that it is close to the surveyed data and experiences very small long-term aggradation or degradation. Downstream channel gradient cannot be tested for sensitivity.
Downstream channel width	Yes	Downstream channel width is adjustable by ±20% in the zeroing process, although such adjustment is not recommended. Downstream channel width is tested for sensitivity.
Amount and grain size distribution of reservoir deposit	No	The amount of reservoir deposit is specified through bedrock elevation, and width and thickness of the deposit. The grain size distribution of the reservoir deposit is specified at different locations and depths in the deposit. Because the width and depth of reservoir deposit can be estimated fairly accurately, only the grain size distribution of the reservoir deposit is tested for sensitivity.
Active channel geometry in the reservoir following dam removal	No	Active channel in reservoir after dam removal is assumed to be trapezoidal, which is defined by bottom width and bank slope. Bank slope is a built-in parameter in the model but is tested for sensitivity nevertheless. Bottom width is not a direct input parameter but is calculated by assuming the channel is similar to the reach immediately downstream of the dam. The sensitivity for bottom width is nevertheless tested by forcing it to different values.

Table 2. Water year series selected for the base run (Run 1), based on Stillwater Sciences [2000] and Cui and Wilcox [in press]

Year in Base Run (Run 1)	Water Year	Peak Flow (m^3/s)	Exceedance Probability of peak flow (%)	Annual Runoff ($\times 10^9$ m^3)	Exceedance Probability of Annual Runoff (%)
1	1991	371	55	1.2	59
2	1932	365	56	1.3	43
3	1951	215	91	1.5	15
4	1991	371	55	1.2	59
5	1988	456	38	1	77
6	1949	334	67	1.4	25
7	1997	393	53	1.6	4
8	1992	425	48	0.9	83
9	1932	365	56	1.3	43
10	1948	546	29	1.5	15

Table 3. Assumed sediment supply rates (in m^3/year) for the base run (Run 1)[a]

	Sandy River upstream of the dam	**Bull Run River**
Wash-load supply (< 62.5 microns)	50,000	30,000
Sand supply (62.5 microns – 2 mm)	3,000	700
Gravel supply (> 2 mm)	10,000	0

[a] *The sediment supply rates given here are for sensitivity tests only and may not represent the actual sediment supply rates in the Sandy River.*

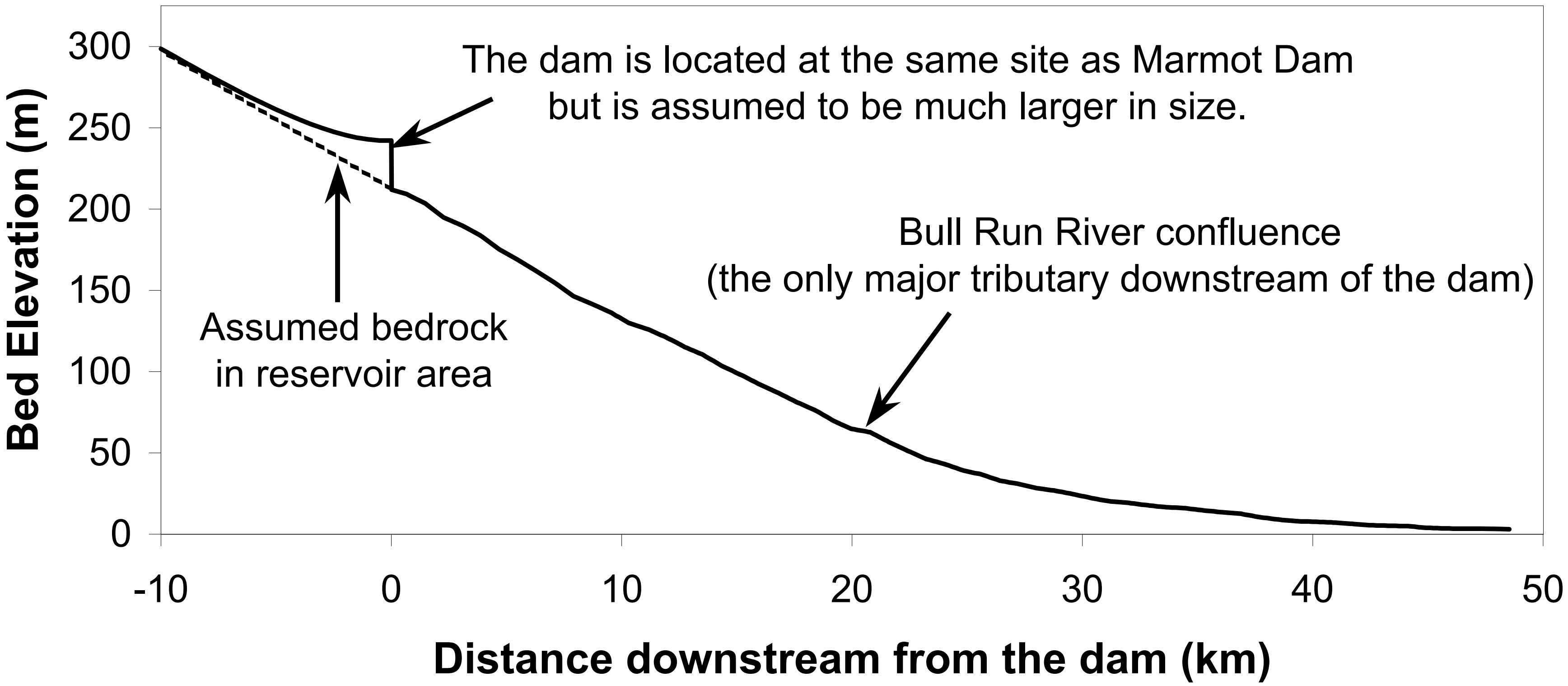

300
250
200
150
100
50
0
Bed Elevation (m)
-10
0
10
20
30
40
50
Distance downstream from the dam (km)
The dam is located at the same site as Marmot Dam
but is assumed to be much larger in size.
Assumed bedrock
in reservoir area
Bull Run River confluence
(the only major tributary downstream of the dam)

Figure 1

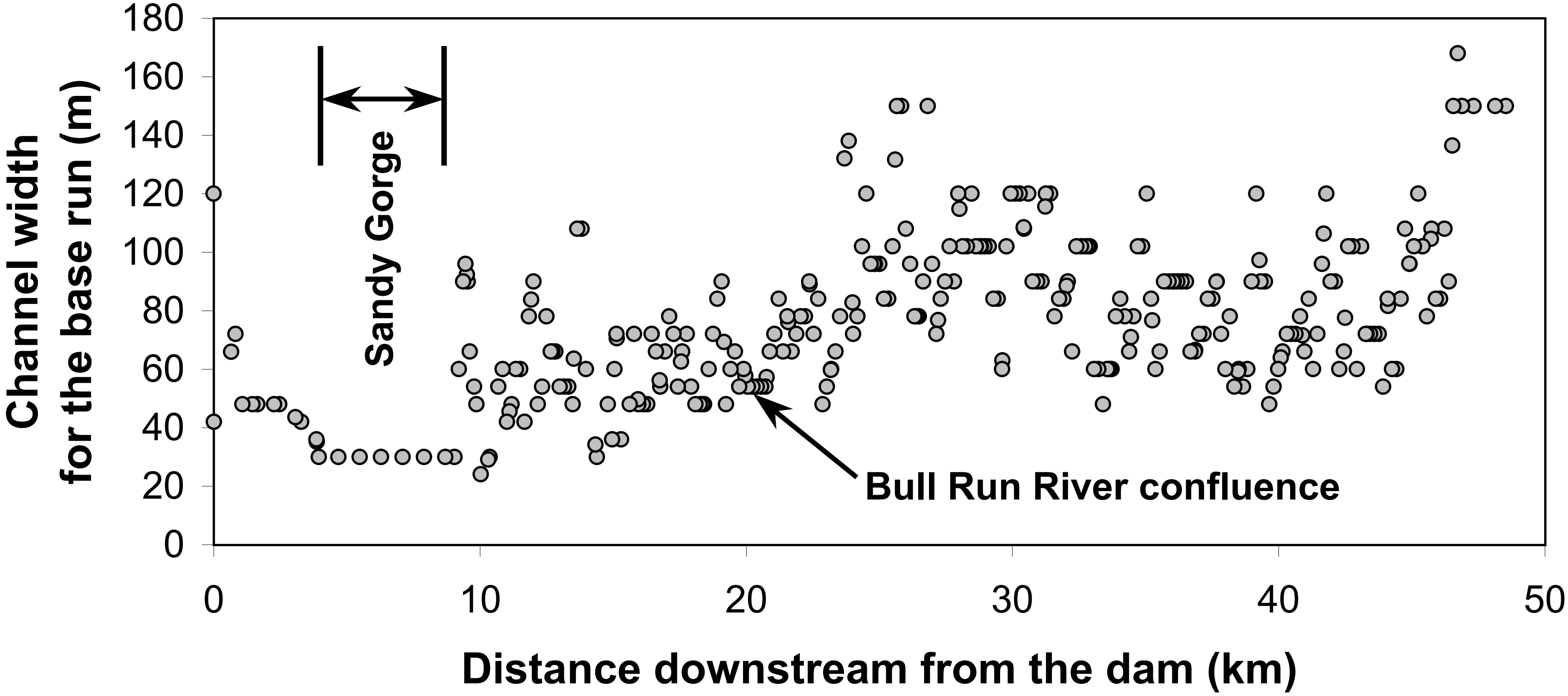
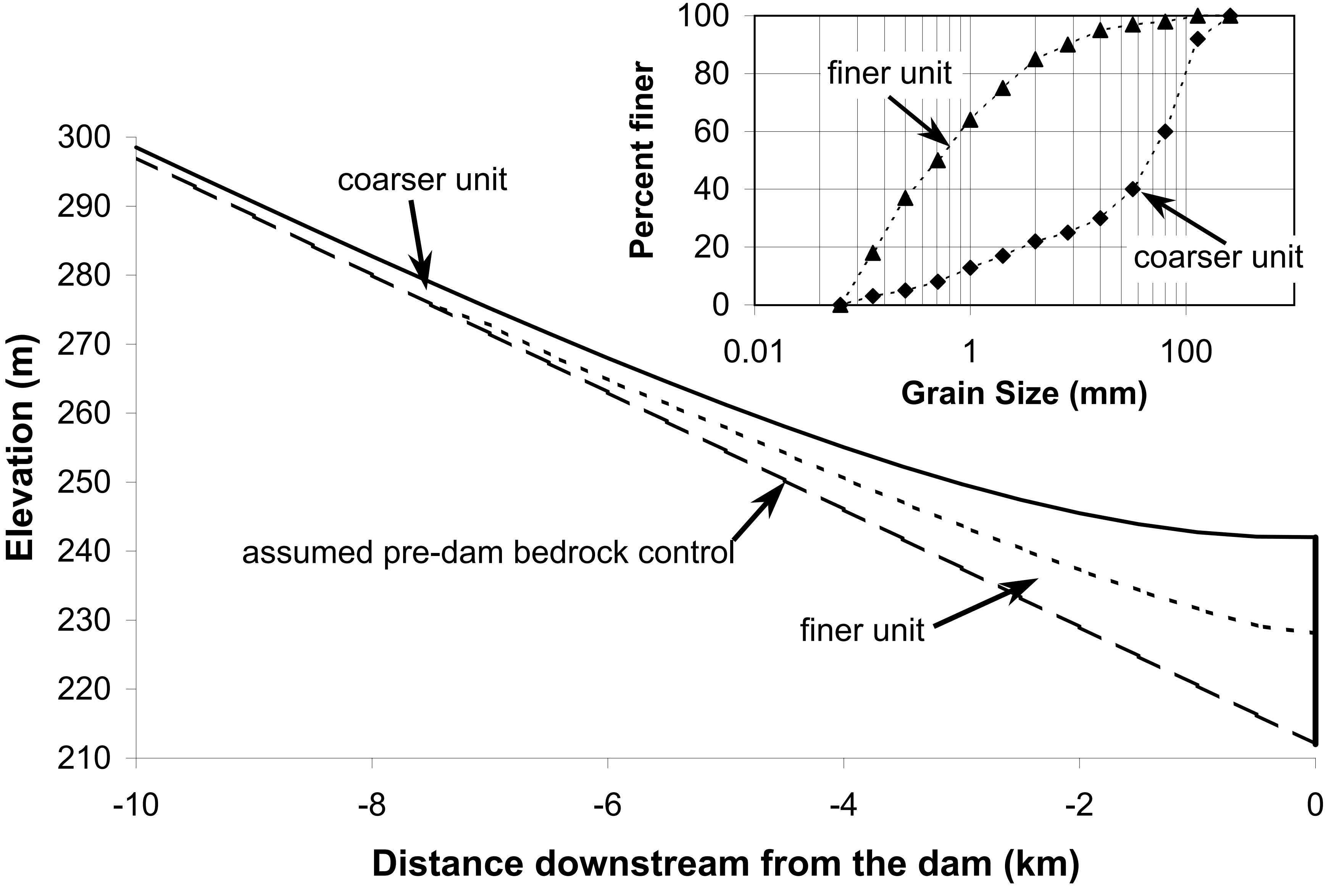

Channel width for the base run (m)
0
20
40
60
80
100
120
140
160
180
Sandy Gorge
Bull Run River confluence
0
10
20
30
40
50
Distance downstream from the dam (km)

Figure 2



100
80
60
40
20
0
Percent finer
0.01
1
100
Grain Size (mm)
finer unit
coarser unit
300
290
280
270
260
250
240
230
220
210
Elevation (m)
-10
-8
-6
-4
-2
0
Distance downstream from the dam (km)
coarser unit
assumed pre-dam bedrock control
finer unit

Figure 3

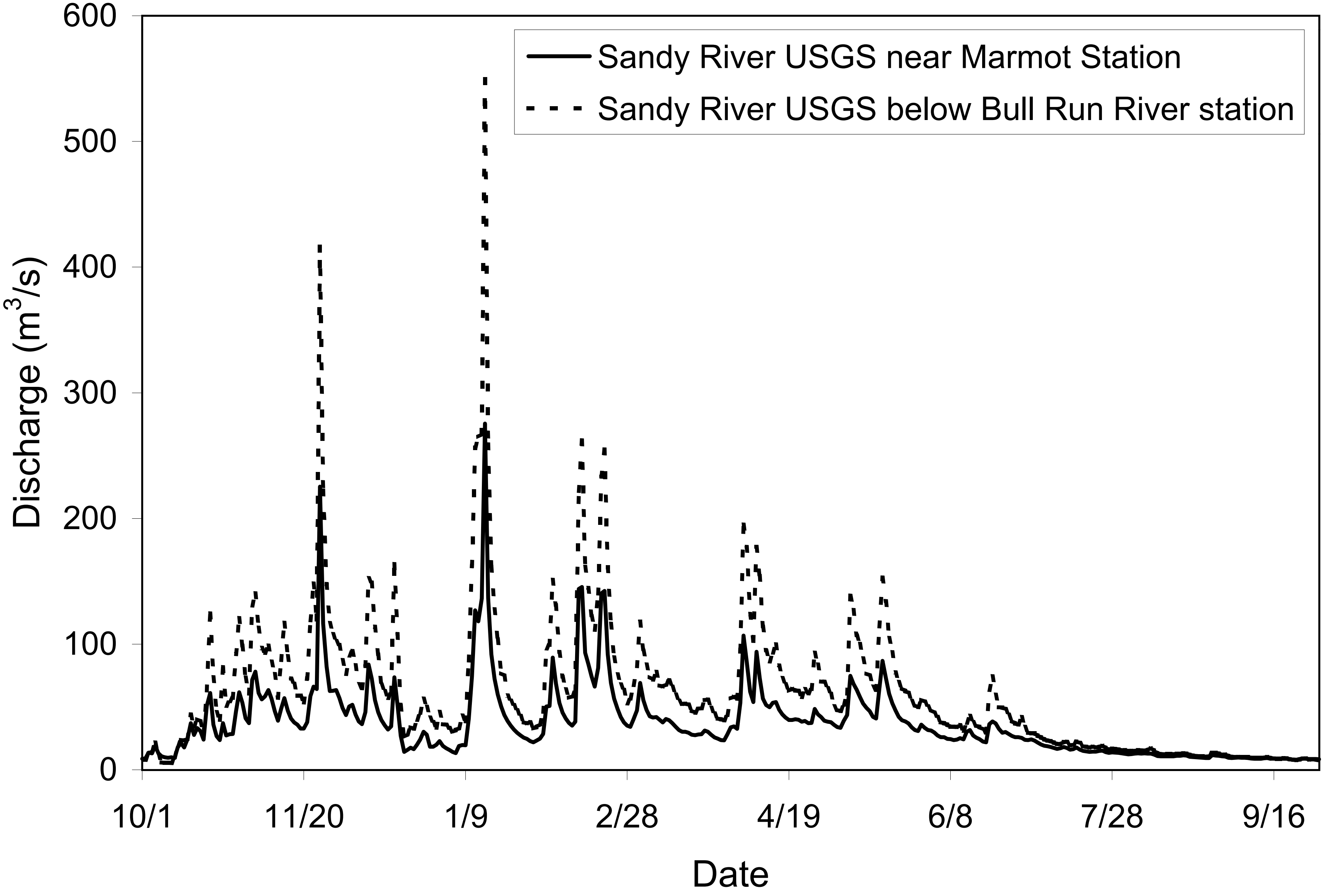

600
500
400
300
200
100
0
Discharge (m^3/s)
10/1
11/20
1/9
2/28
4/19
6/8
7/28
9/16
Date
Sandy River USGS near Marmot Station
Sandy River USGS below Bull Run River station

Figure 4

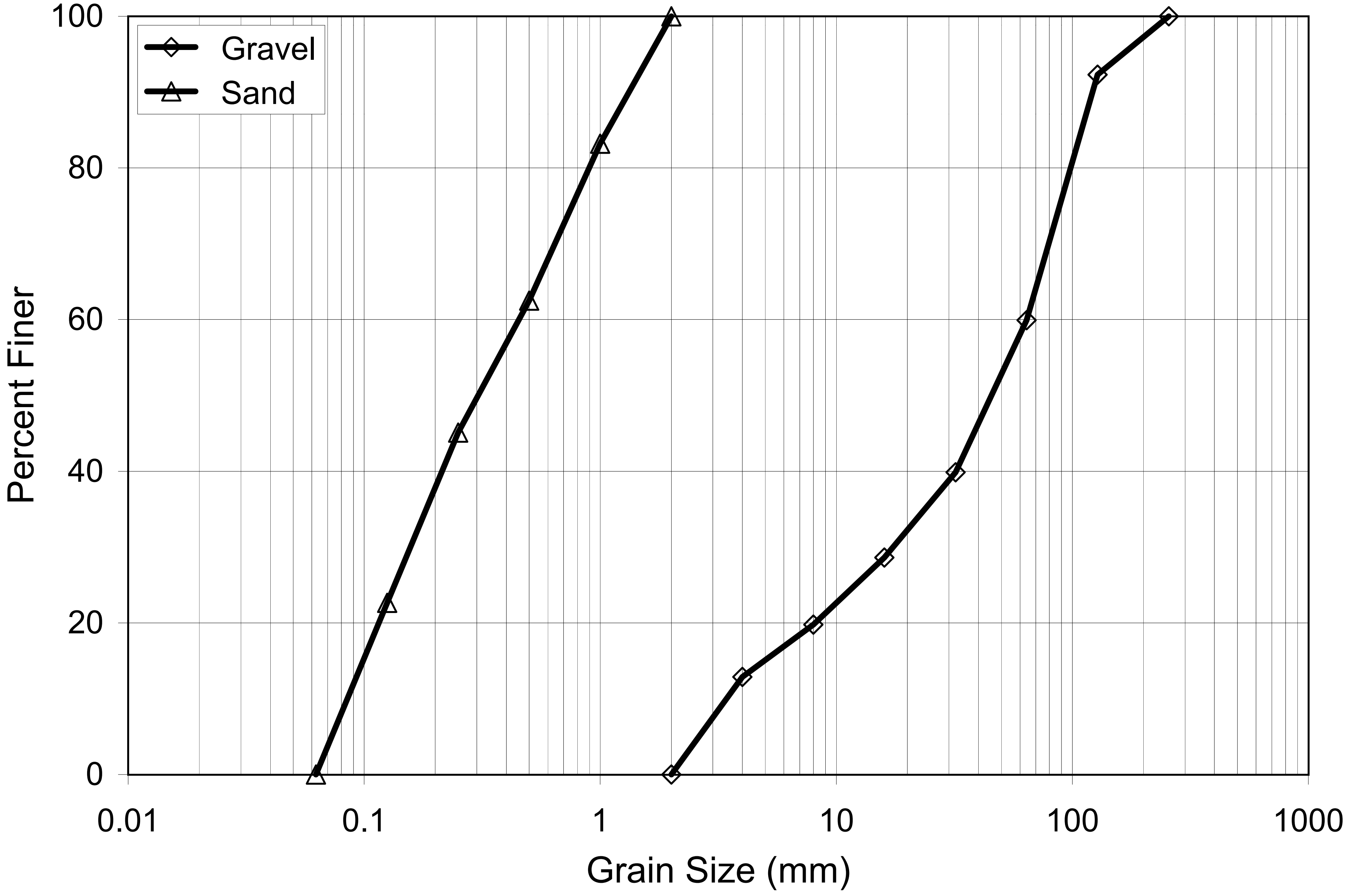
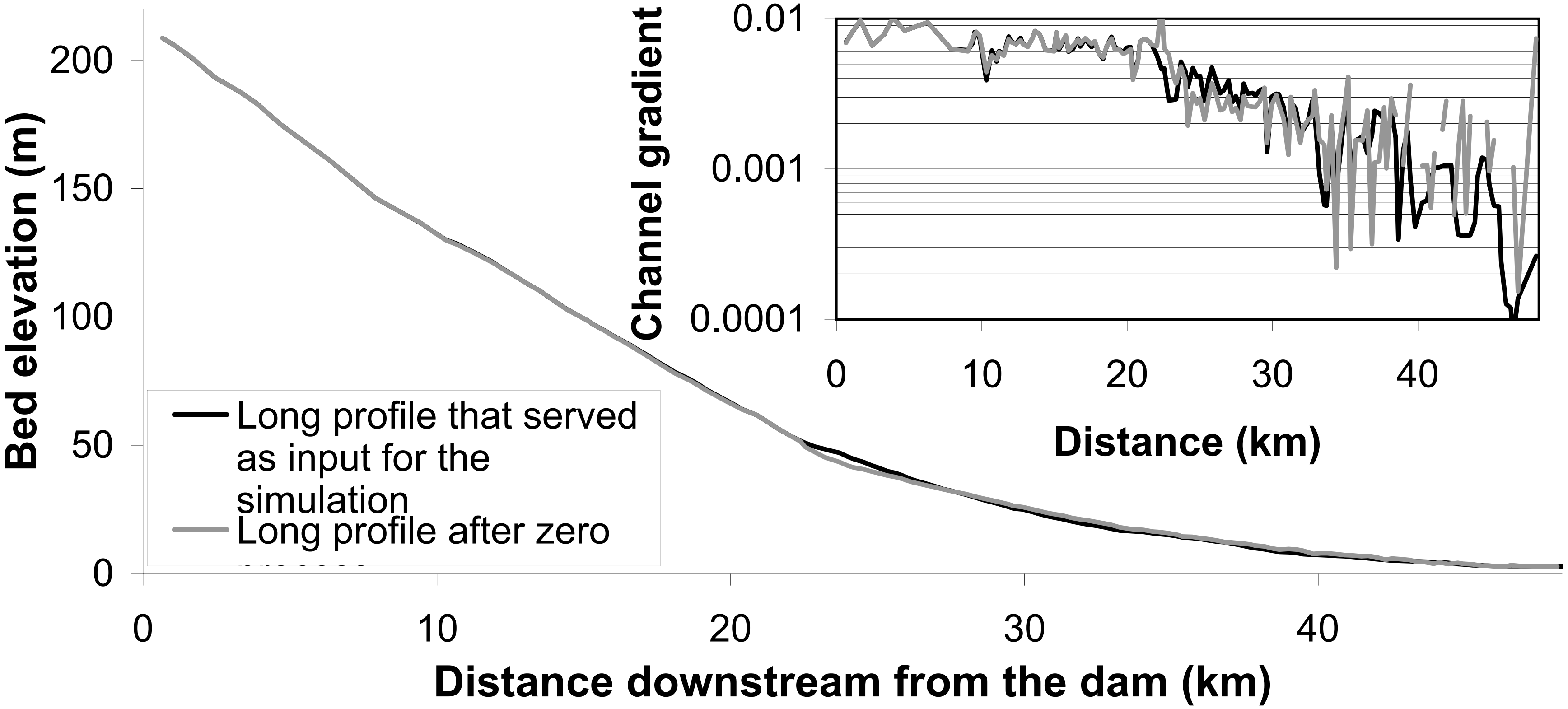

Gravel
Sand
Percent Finer
0
20
40
60
80
100
0.01
0.1
1
10
100
1000
Grain Size (mm)

Figure 5



Bed elevation (m)
200
150
100
50
0
0
10
20
30
40
Distance downstream from the dam (km)
Long profile that served as input for the simulation
Long profile after zero
Channel gradient
0.01
0.001
0.0001
0
10
20
30
40
Distance (km)

Figure 6a

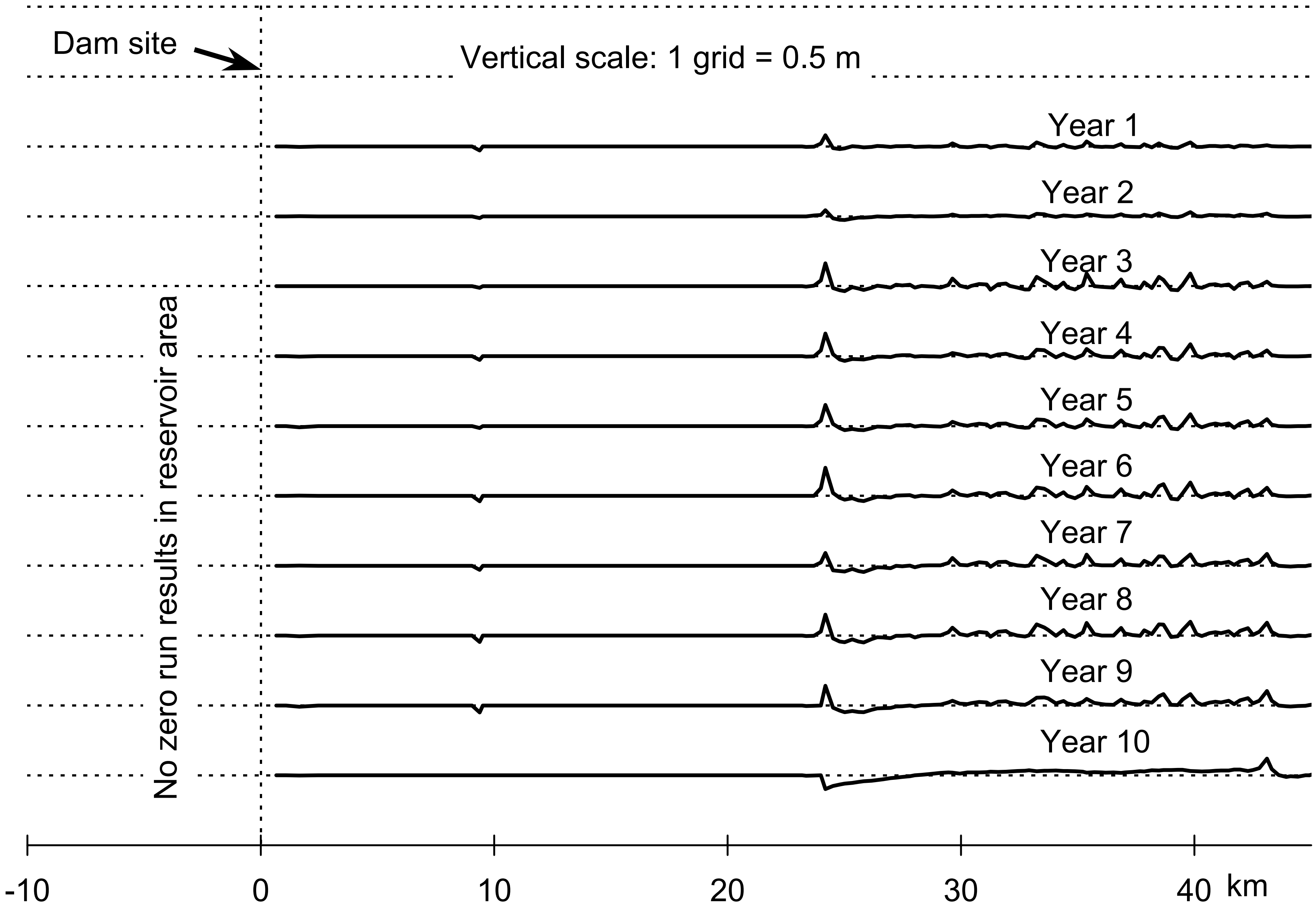

Dam site
Vertical scale: 1 grid = 0.5 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
No zero run results in reservoir area
-10
0
10
20
30
40
km

Figure 6b

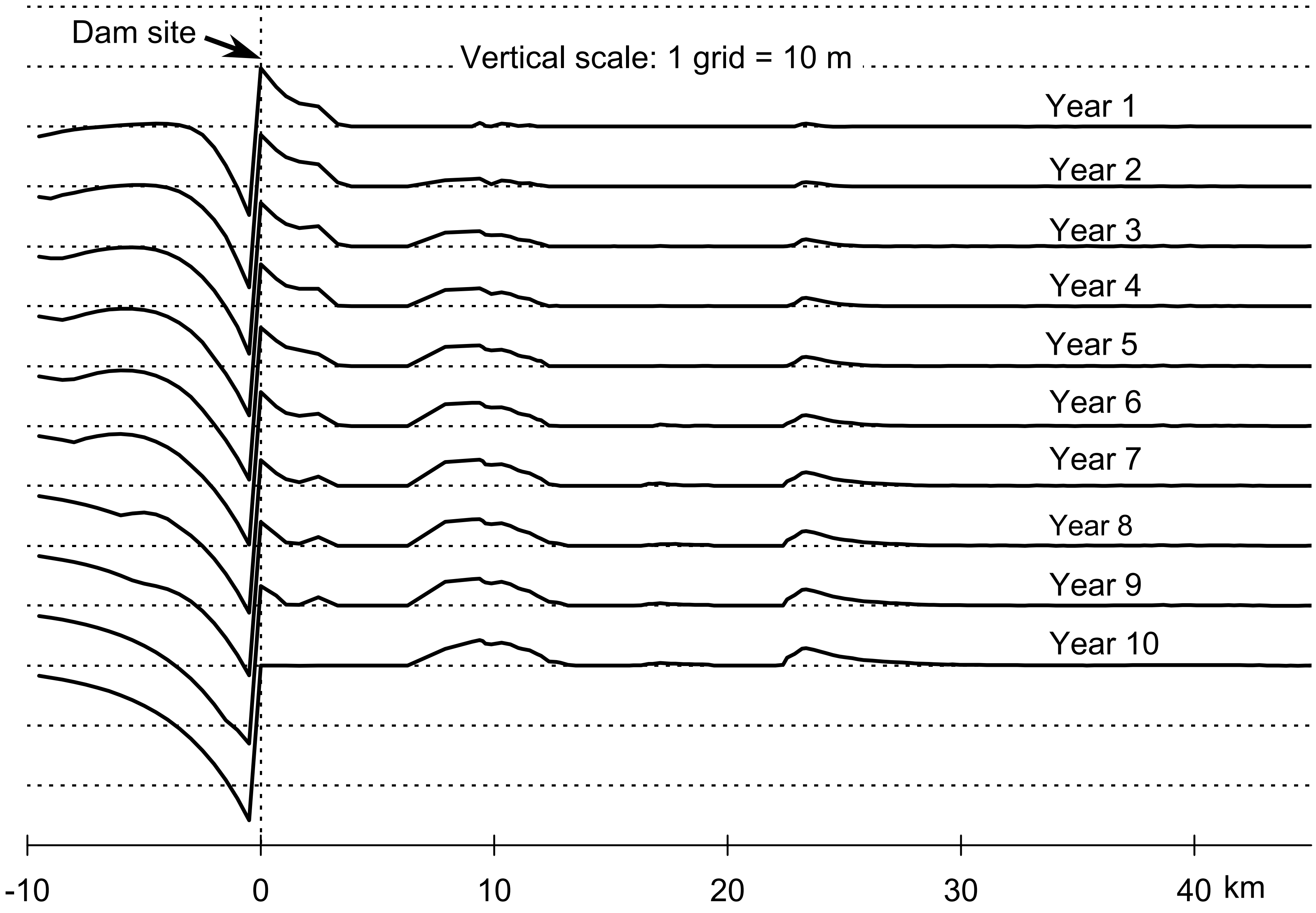

Dam site
Vertical scale: 1 grid = 10 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
-10
0
10
20
30
40
km

Figure 7a

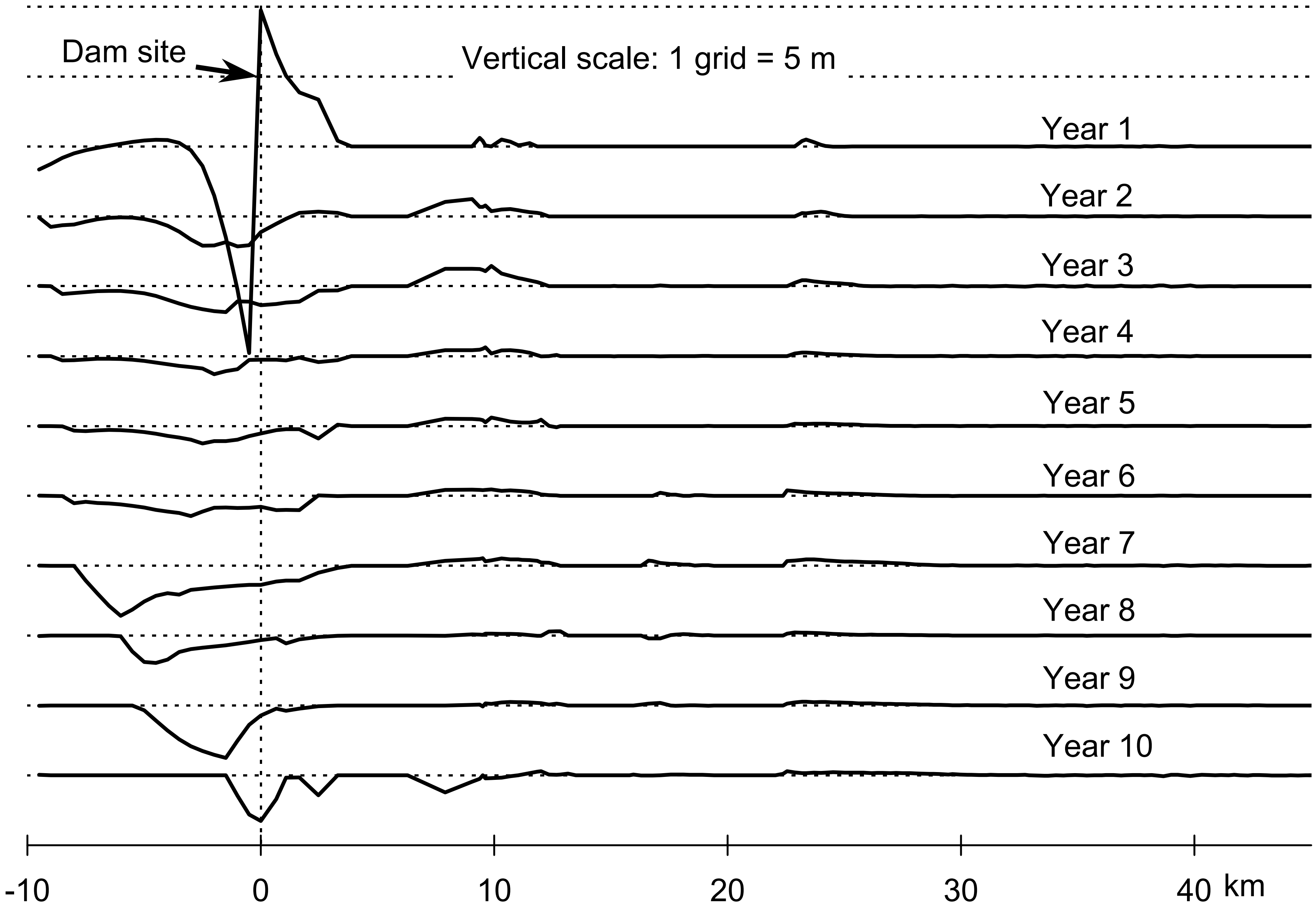
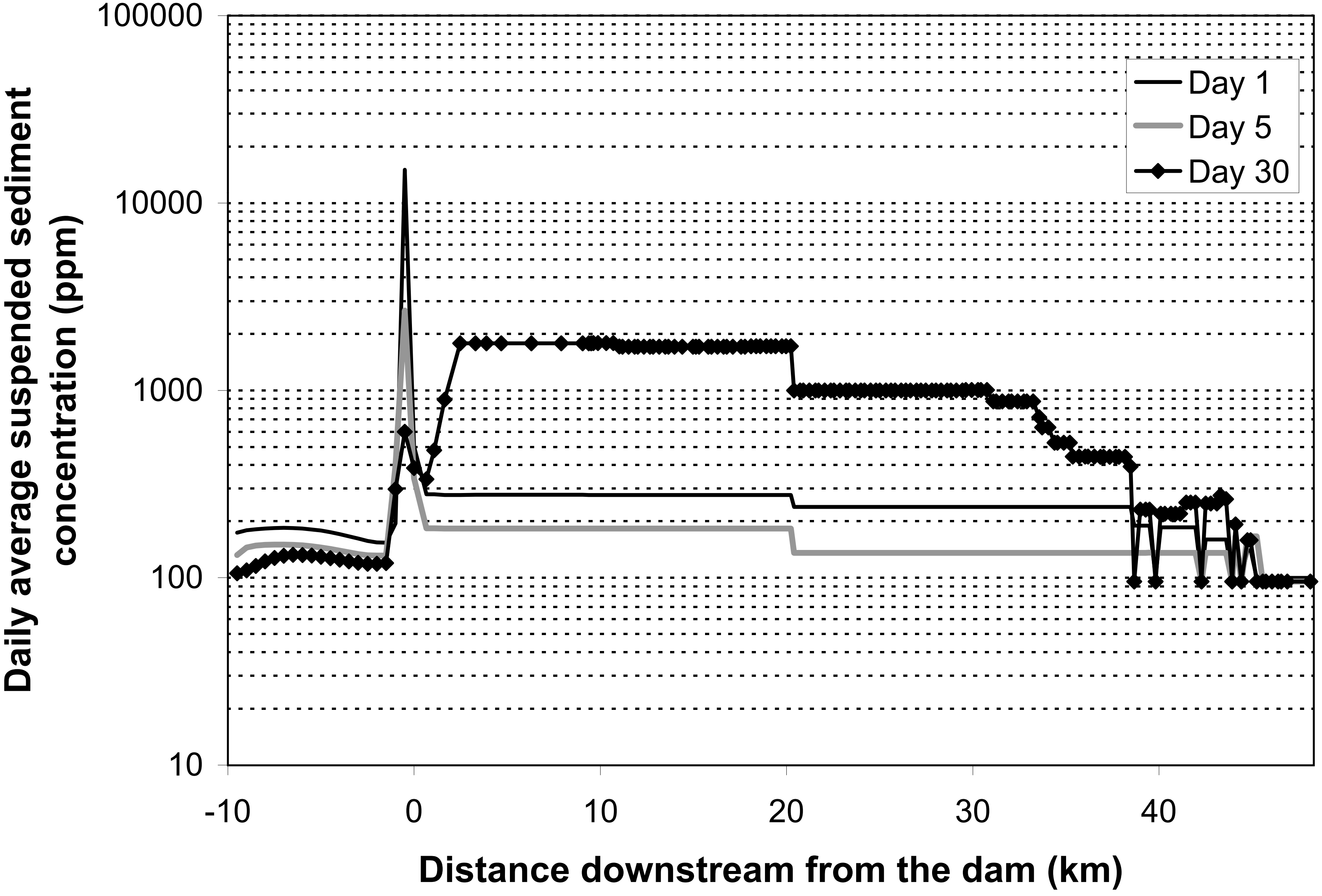

Dam site
Vertical scale: 1 grid = 5 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
-10
0
10
20
30
40
km

Figure 7b



Daily average suspended sediment concentration (ppm)
100000
10000
1000
100
10
-10
0
10
20
30
40
Distance downstream from the dam (km)
Day 1
Day 5
Day 30

Figure 7c

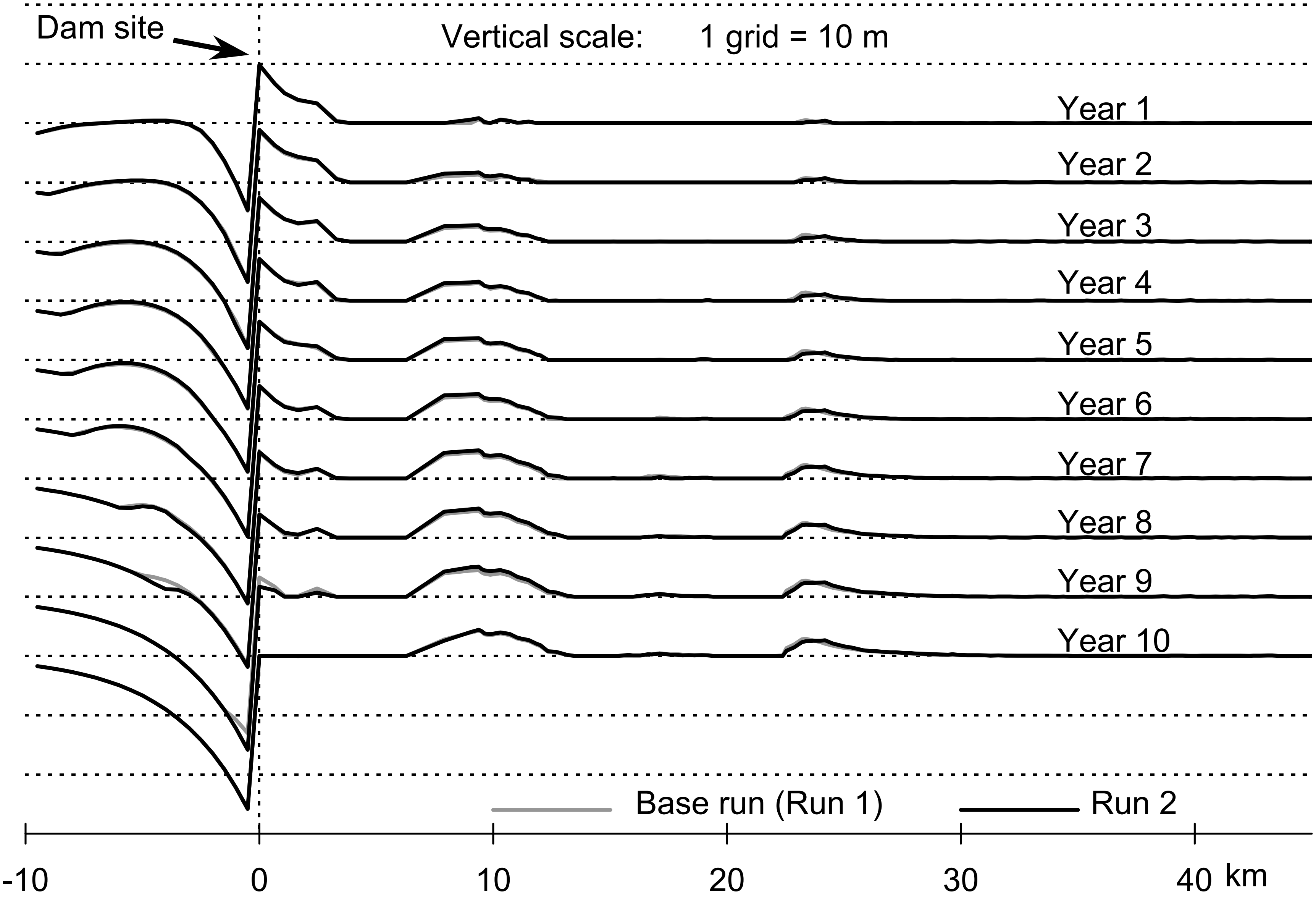

Dam site
Vertical scale: 1 grid = 10 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
Base run (Run 1)
Run 2
-10
0
10
20
30
40
km

Figure 8

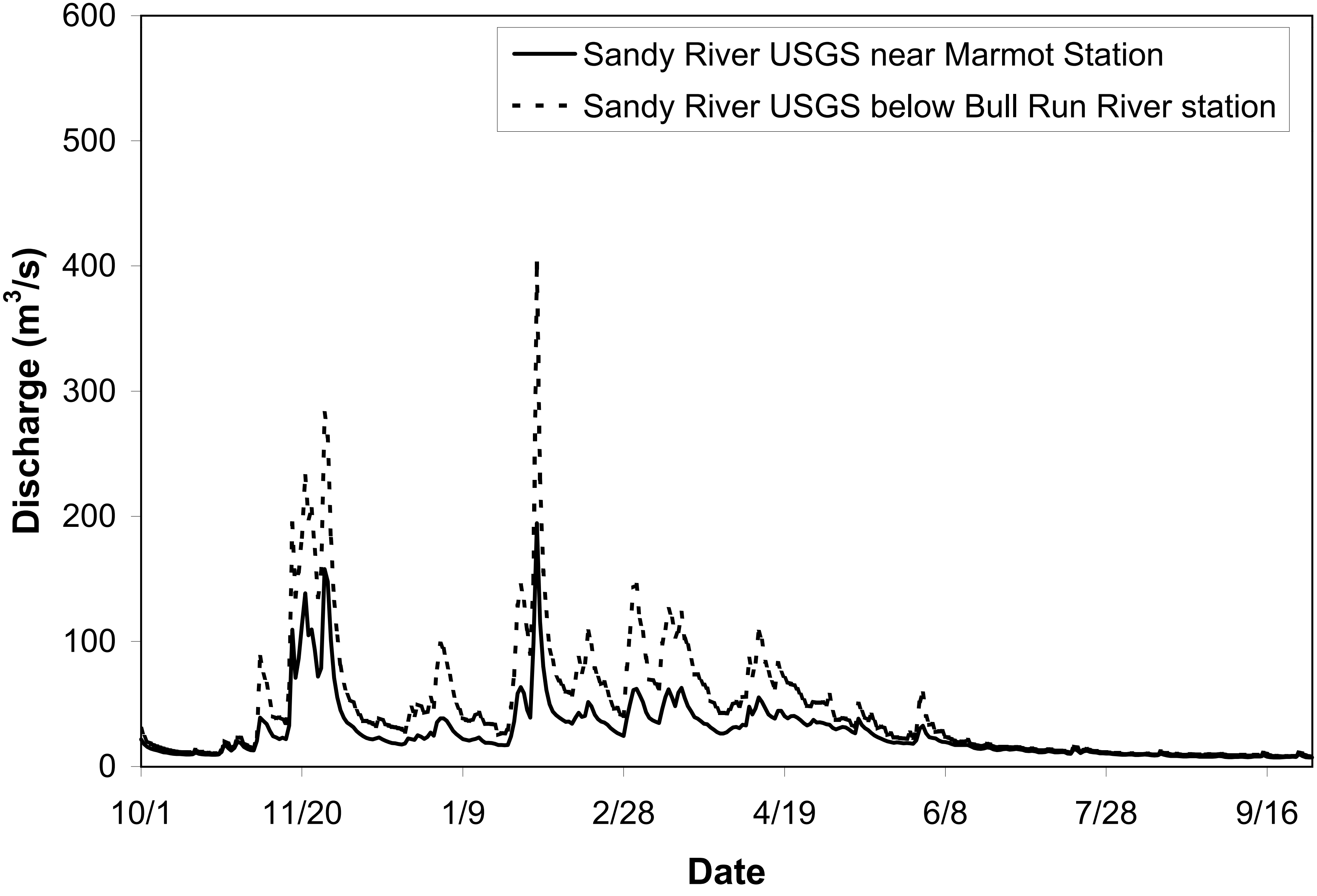

Sandy River USGS near Marmot Station
Sandy River USGS below Bull Run River station
Discharge (m^3/s)
600
500
400
300
200
100
0
10/1
11/20
1/9
2/28
4/19
6/8
7/28
9/16
Date

Figure 9

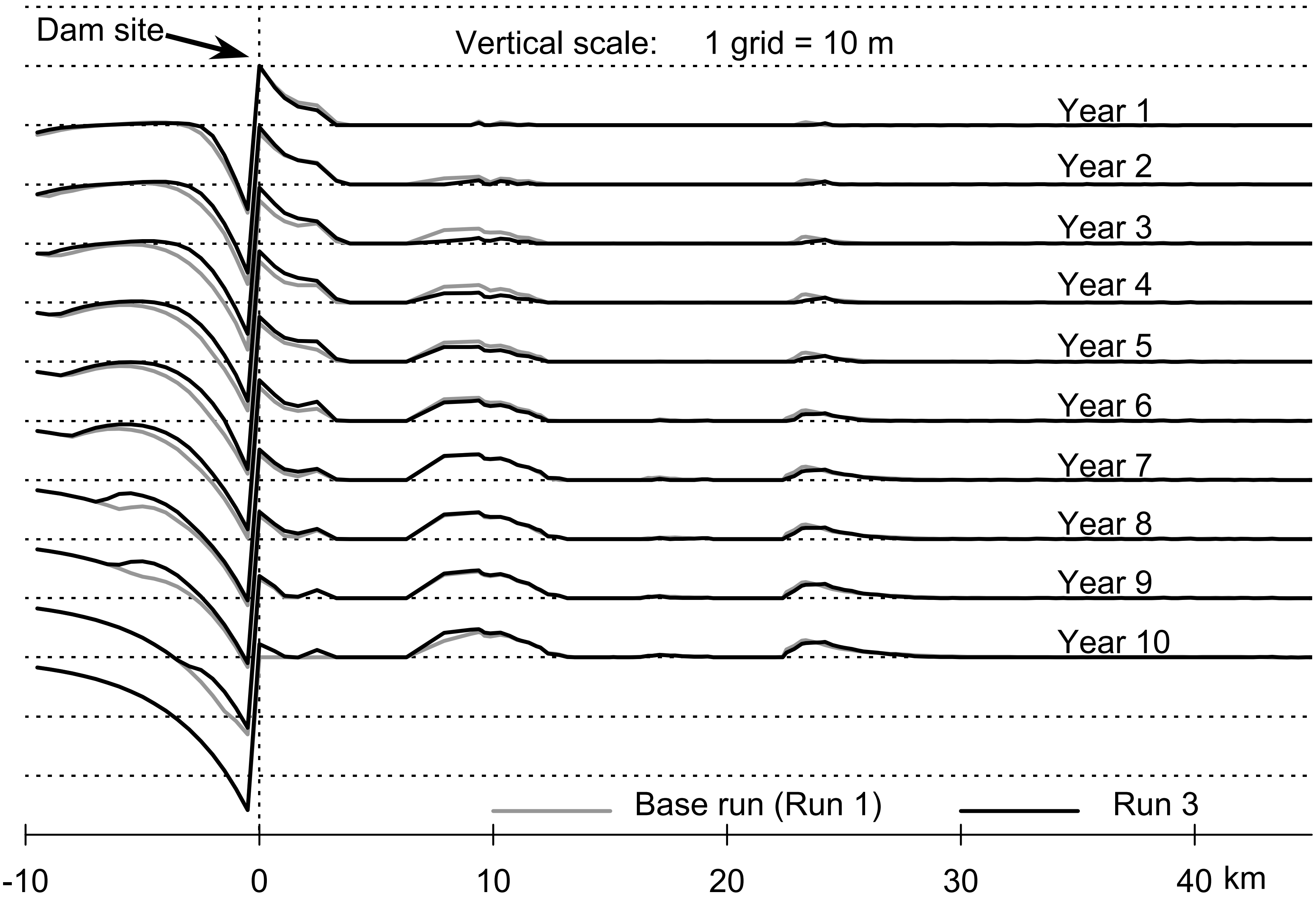

Dam site
Vertical scale: 1 grid = 10 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
Base run (Run 1)
Run 3
-10
0
10
20
30
40
km

Figure 10a

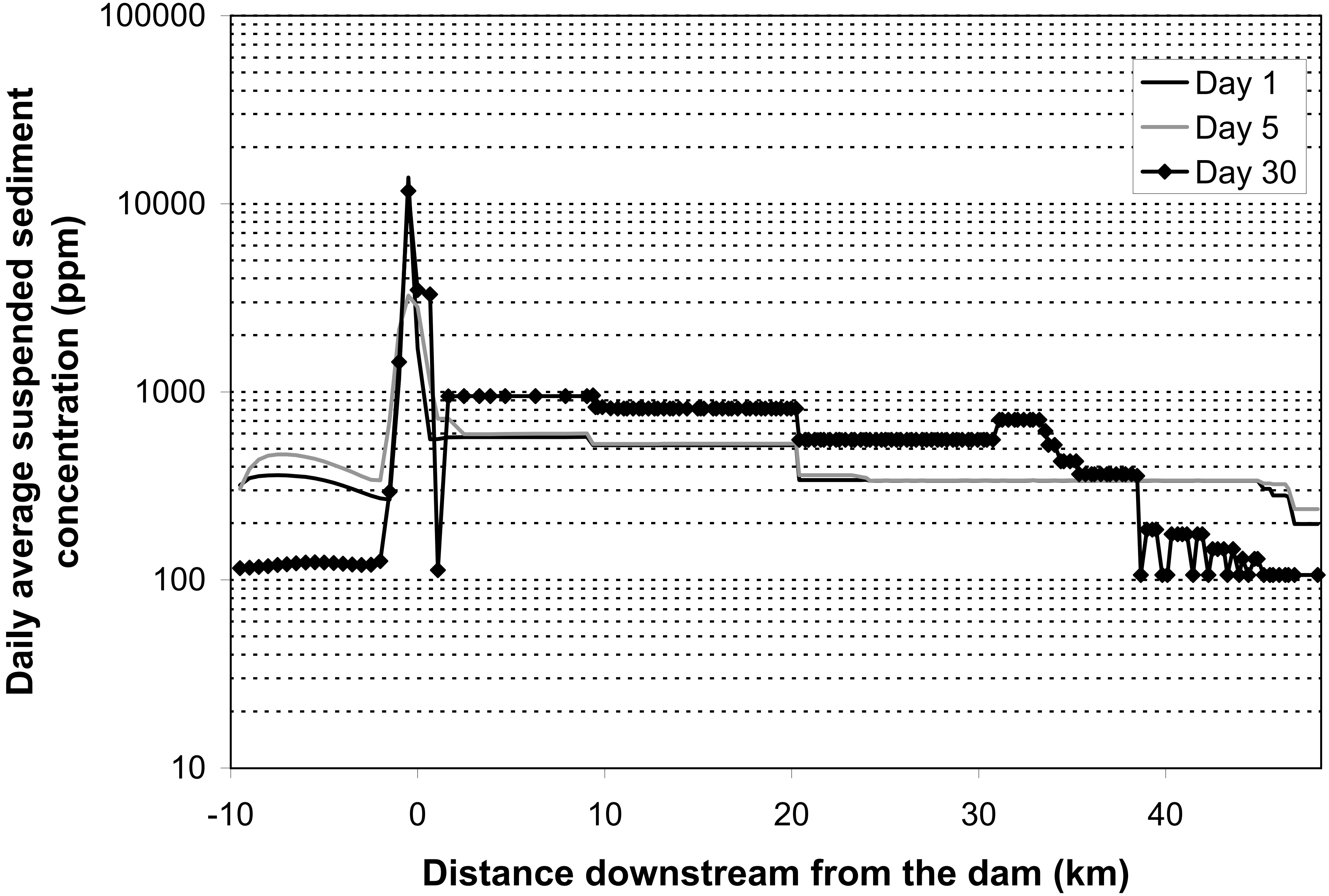

Daily average suspended sediment concentration (ppm)
100000
10000
1000
100
10
-10
0
10
20
30
40
Distance downstream from the dam (km)
Day 1
Day 5
Day 30

Figure 10b

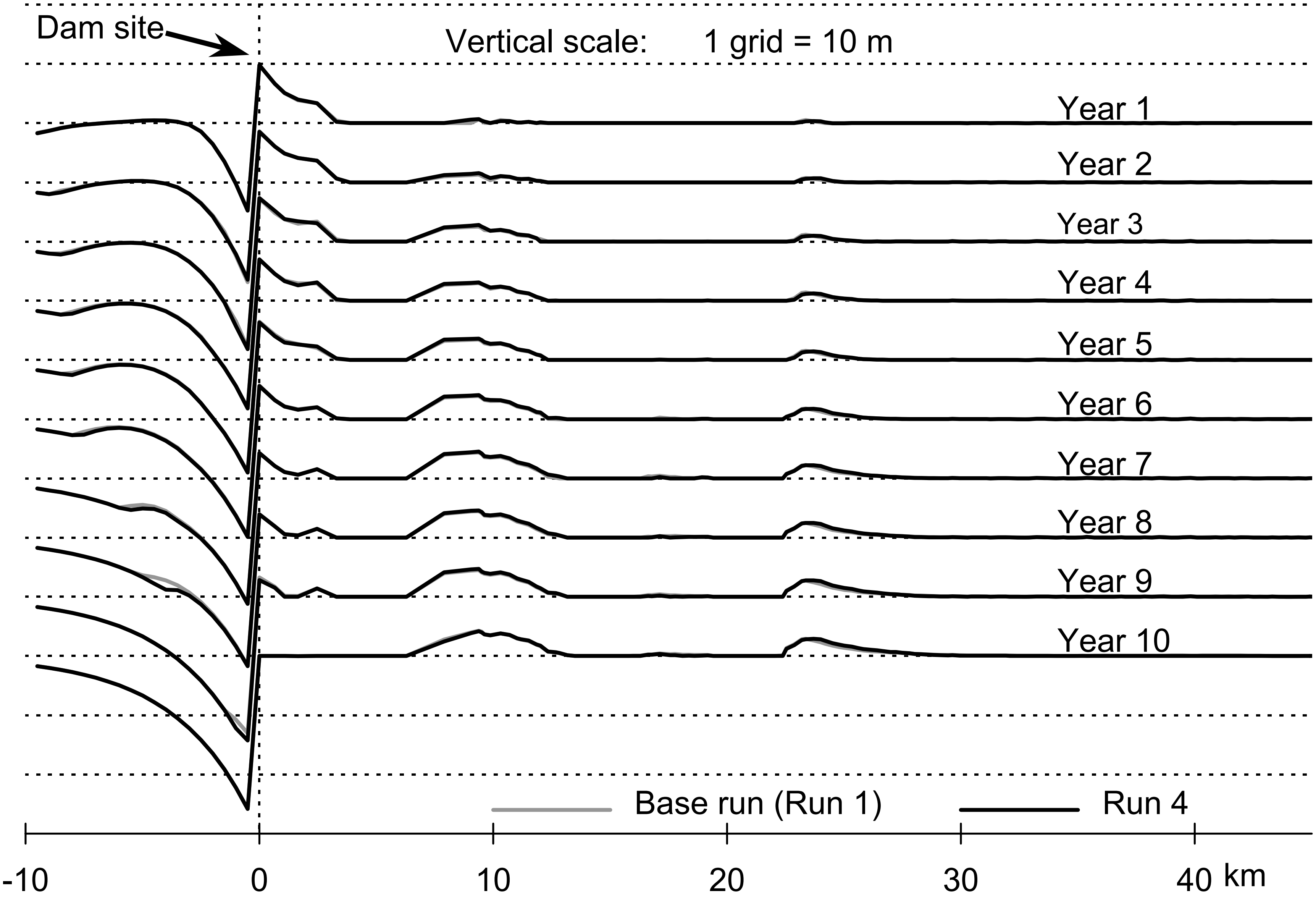

Dam site
Vertical scale: 1 grid = 10 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
Base run (Run 1)
Run 4
-10
0
10
20
30
40
km

Figure 11

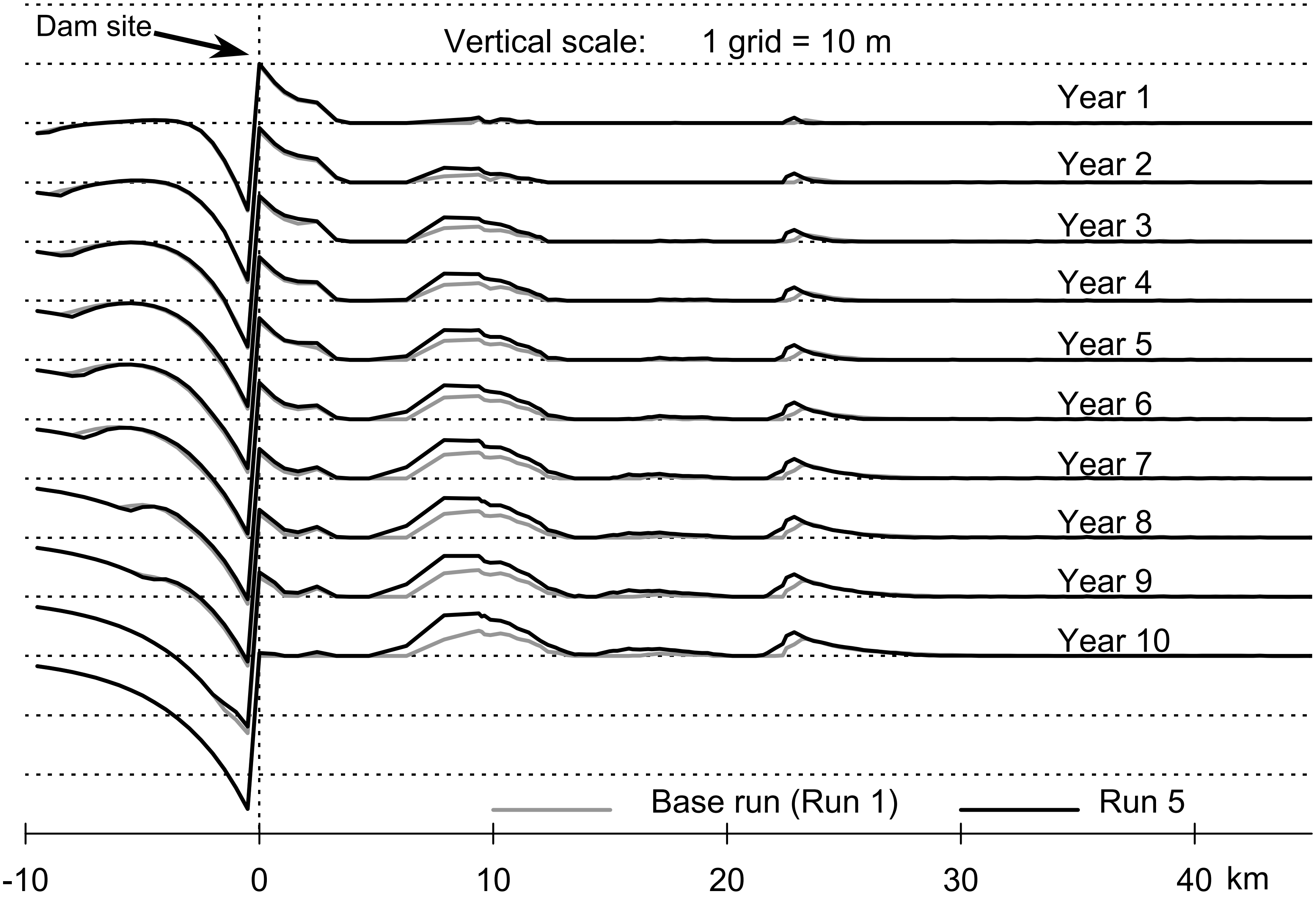

Dam site
Vertical scale: 1 grid = 10 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
Base run (Run 1)
Run 5
-10
0
10
20
30
40
km

Figure 12a

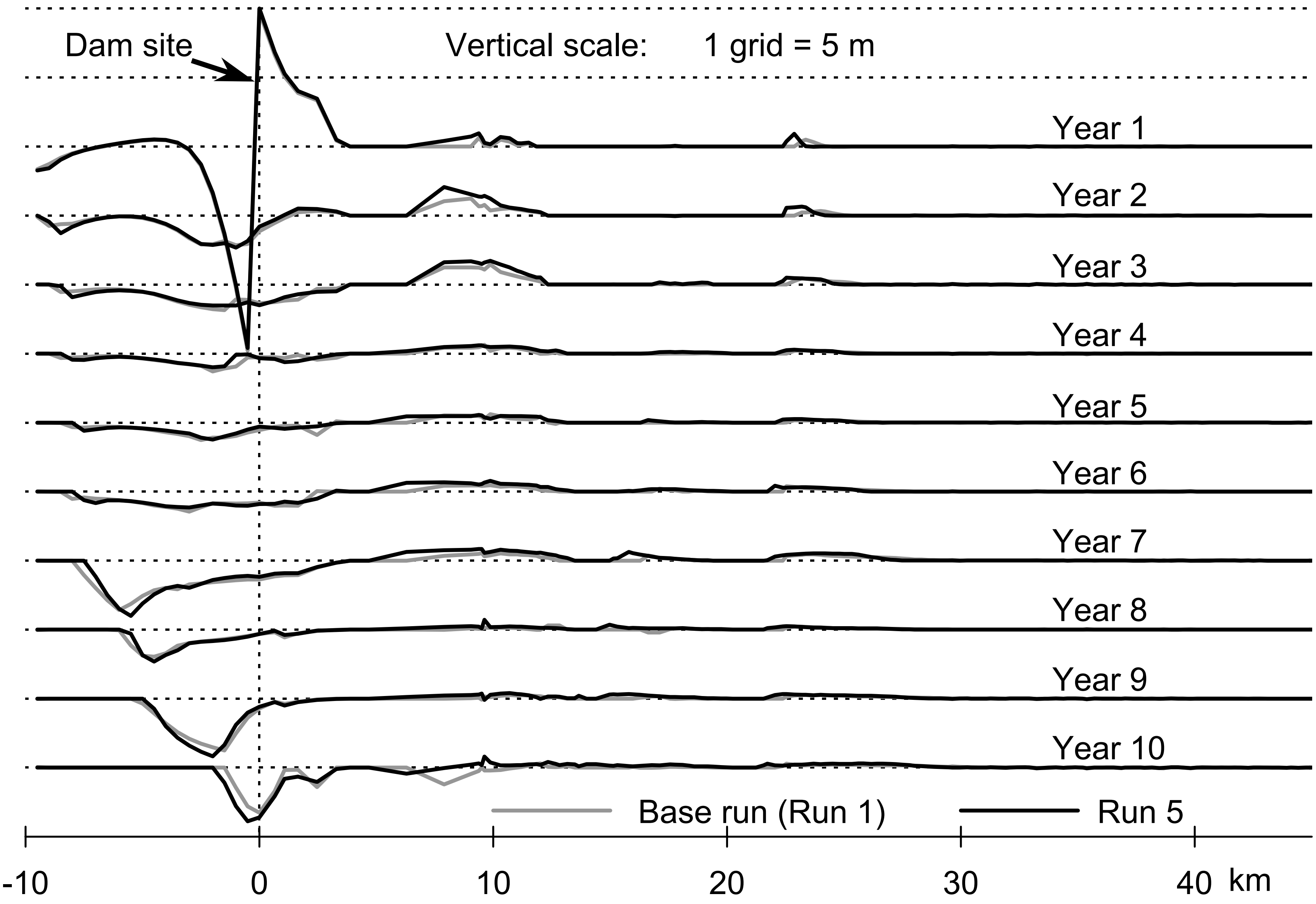

Dam site
Vertical scale: 1 grid = 5 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
Base run (Run 1)
Run 5
-10
0
10
20
30
40
km

Figure 12b

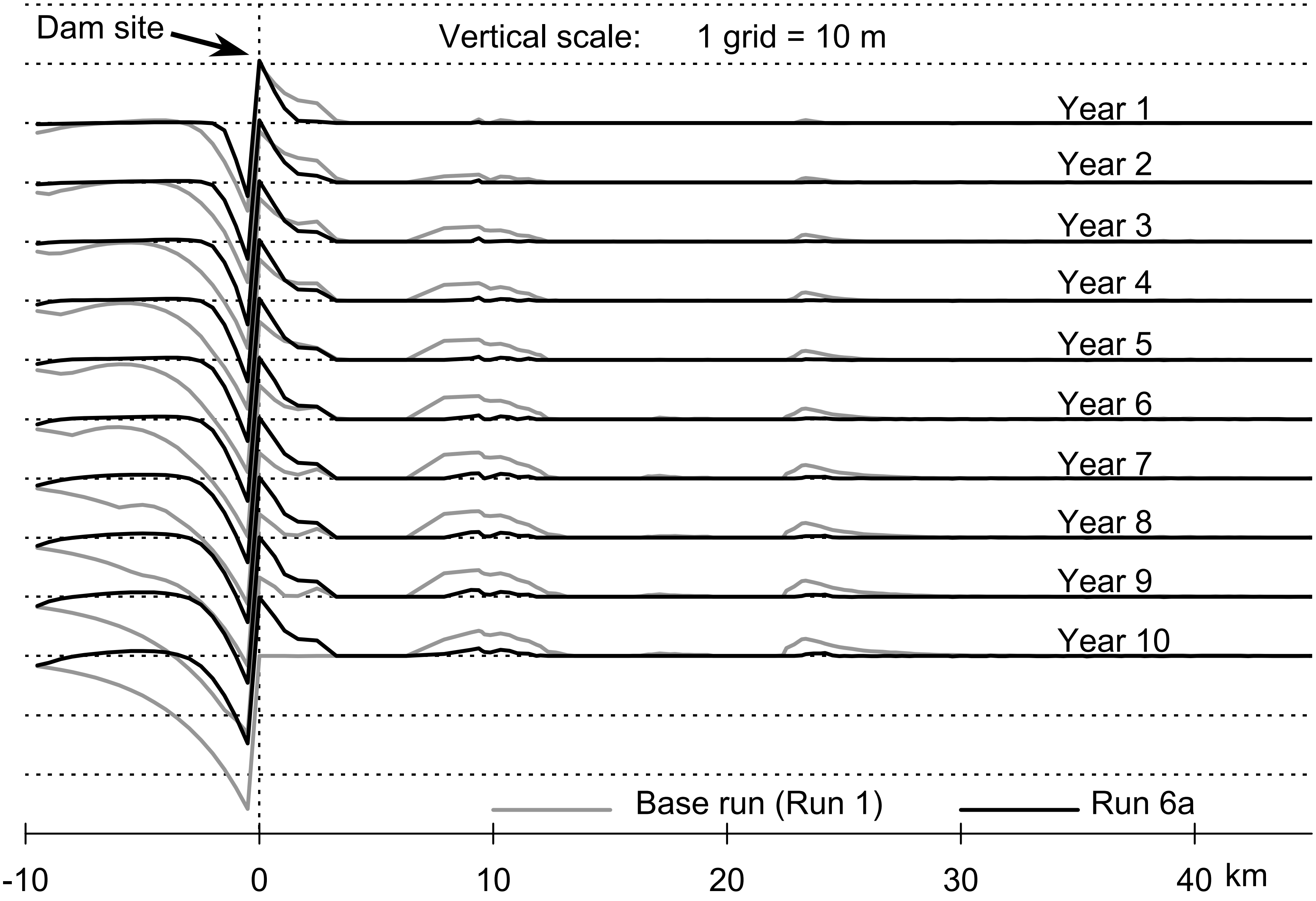

Dam site
Vertical scale: 1 grid = 10 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
Base run (Run 1)
Run 6a
-10
0
10
20
30
40
km

Figure 13a

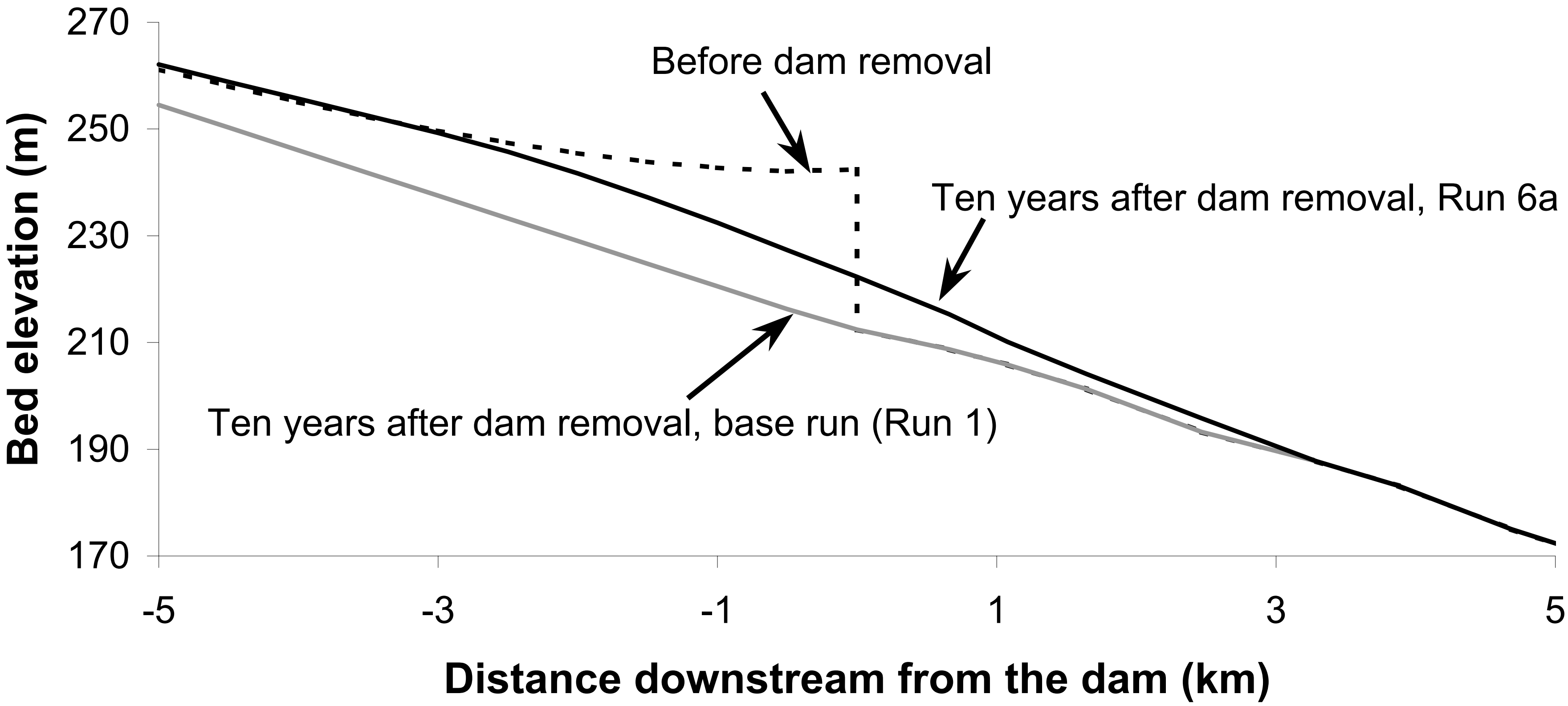

270
250
230
210
190
170
Bed elevation (m)
-5
-3
-1
1
3
5
Distance downstream from the dam (km)
Before dam removal
Ten years after dam removal, Run 6a
Ten years after dam removal, base run (Run 1)

Figure 13b

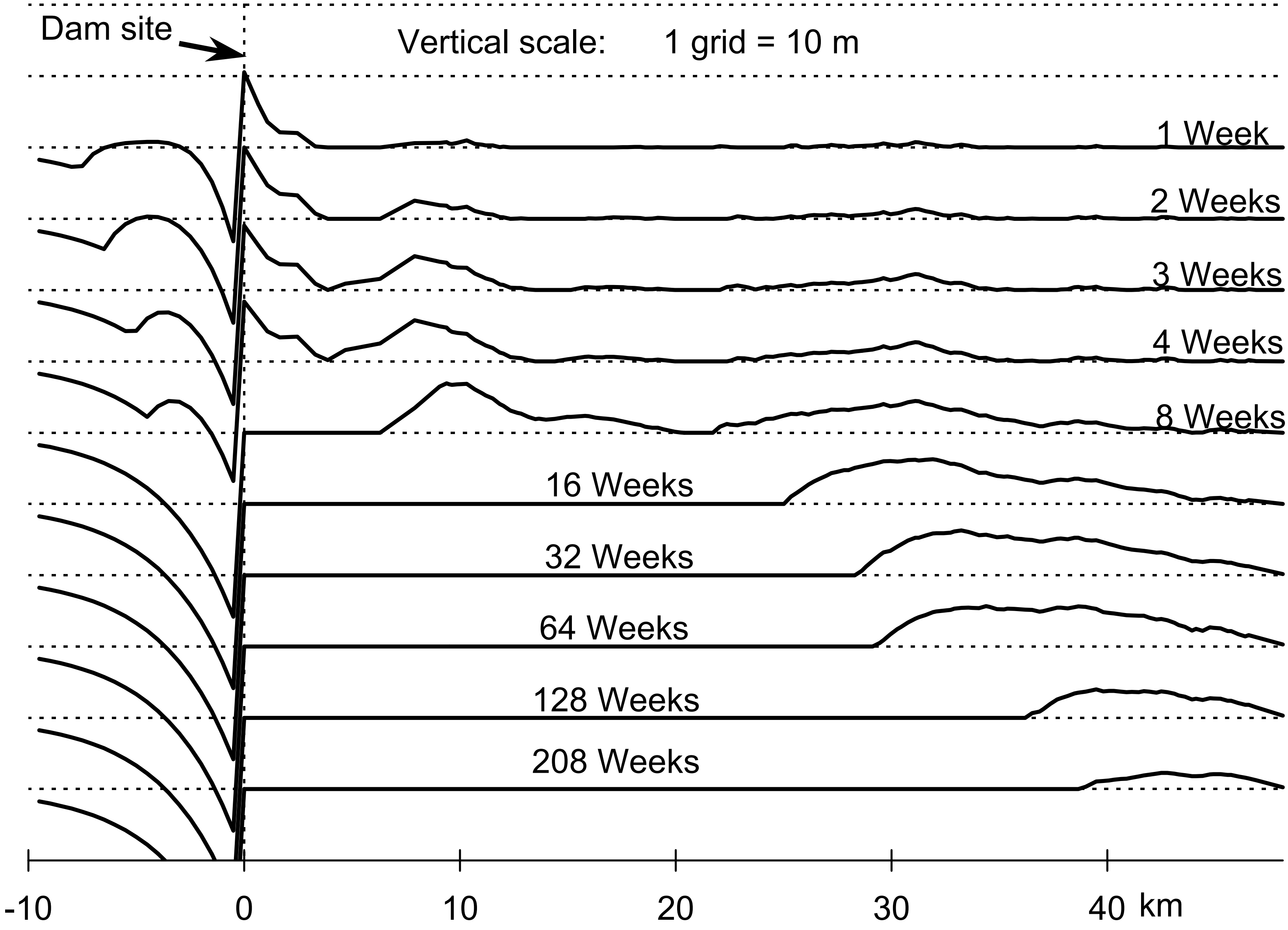

Dam site
Vertical scale: 1 grid = 10 m
1 Week
2 Weeks
3 Weeks
4 Weeks
8 Weeks
16 Weeks
32 Weeks
64 Weeks
128 Weeks
208 Weeks
-10
0
10
20
30
40
km

Figure 14a

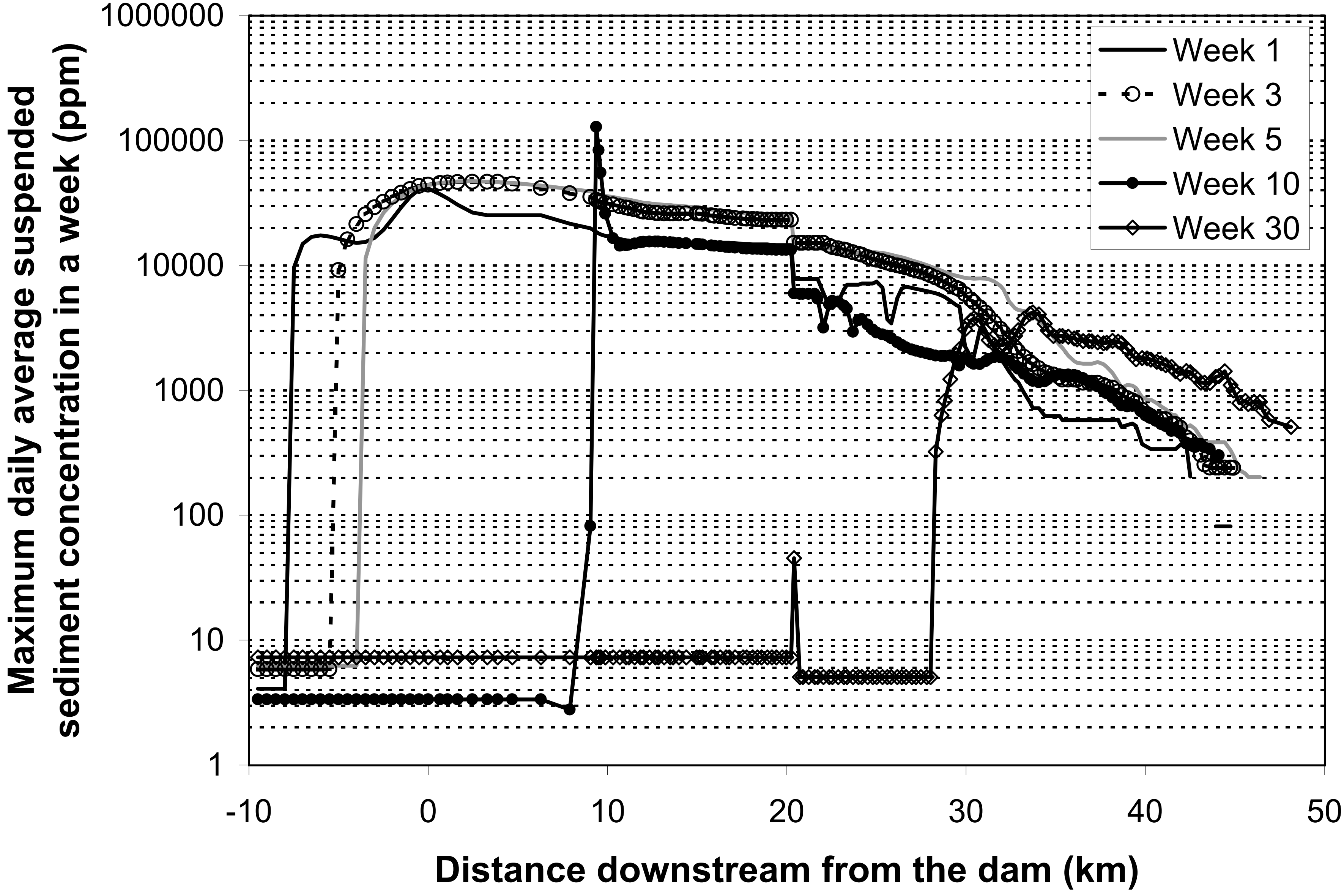
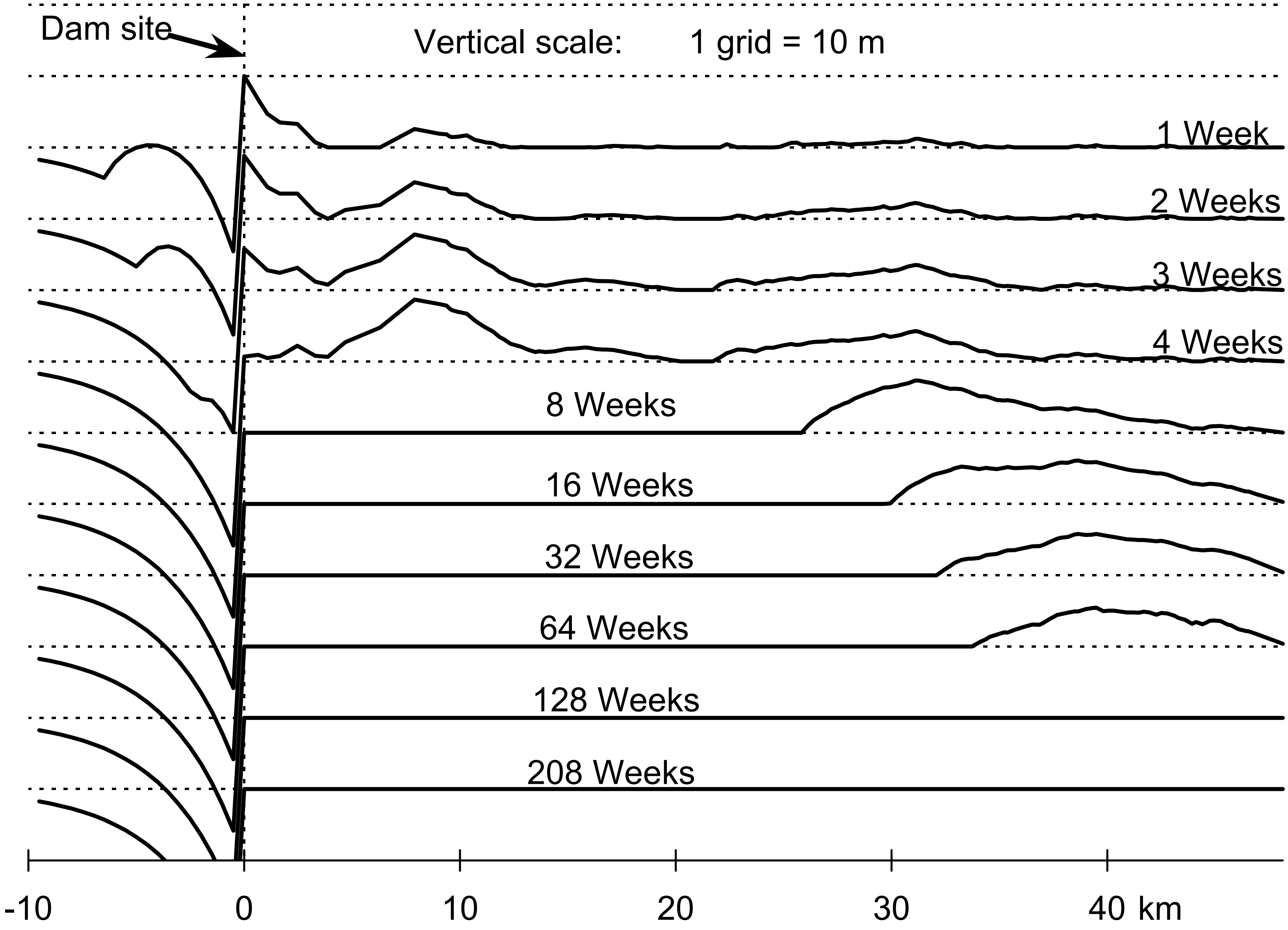

Maximum daily average suspended sediment concentration in a week (ppm)
1000000
100000
10000
1000
100
10
1
-10
0
10
20
30
40
50
Distance downstream from the dam (km)
Week 1
Week 3
Week 5
Week 10
Week 30

Figure 14b



Dam site
Vertical scale: 1 grid = 10 m
1 Week
2 Weeks
3 Weeks
4 Weeks
8 Weeks
16 Weeks
32 Weeks
64 Weeks
128 Weeks
208 Weeks
-10
0
10
20
30
40 km

Figure 15a

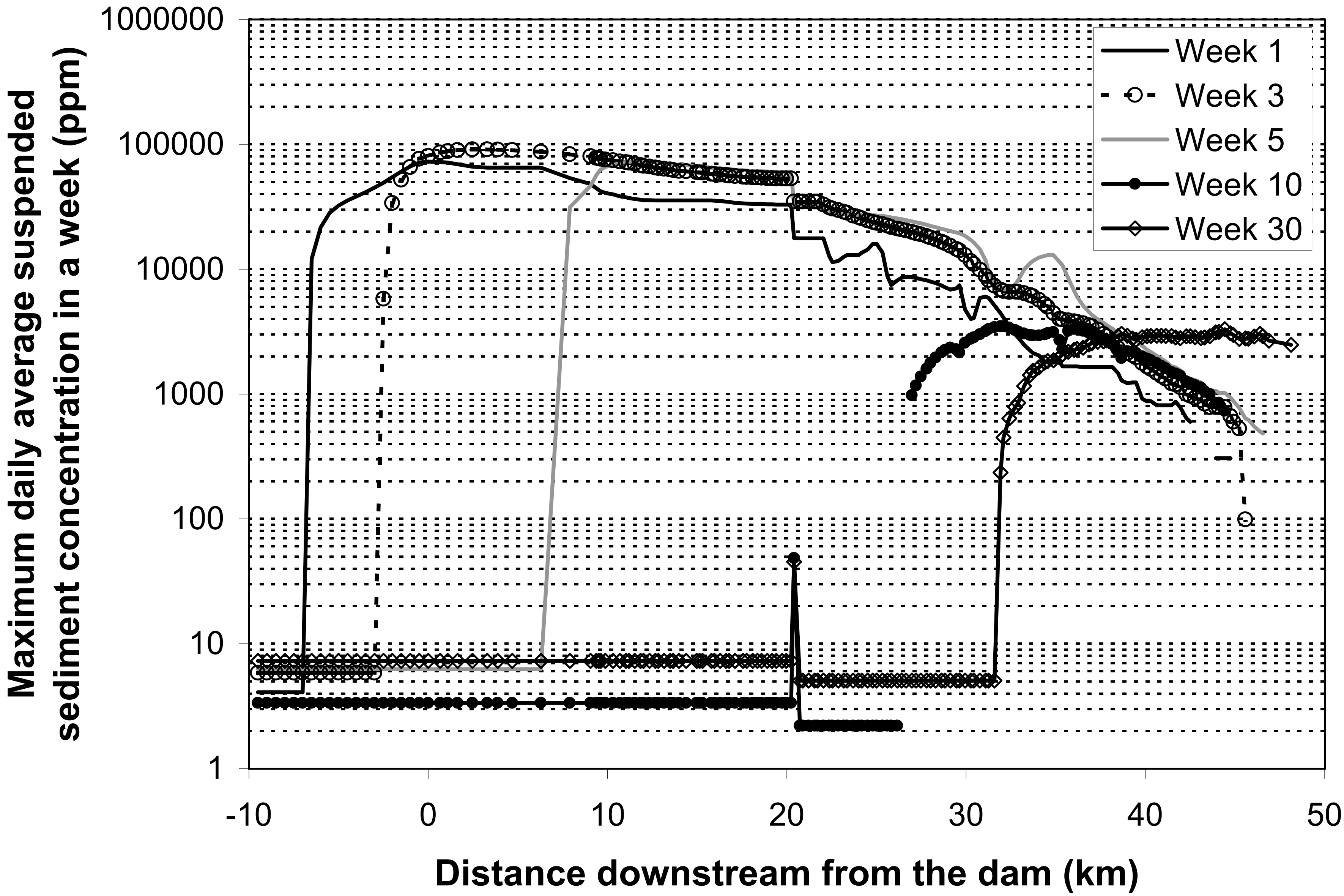

Maximum daily average suspended sediment concentration in a week (ppm)
1000000
100000
10000
1000
100
10
1
-10
0
10
20
30
40
50
Distance downstream from the dam (km)
Week 1
Week 3
Week 5
Week 10
Week 30

Figure 15b

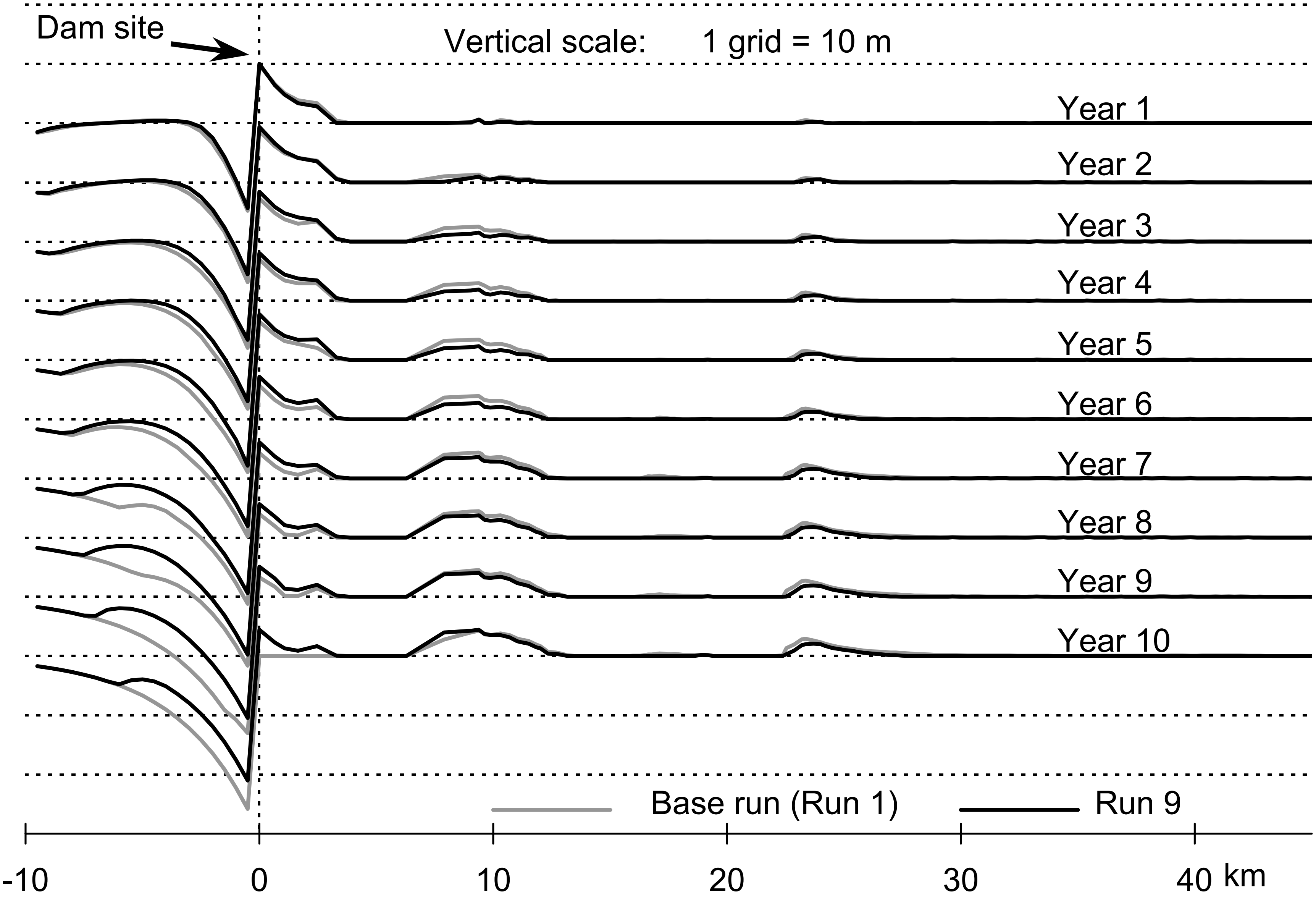

Dam site
Vertical scale: 1 grid = 10 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
Base run (Run 1)
Run 9
-10
0
10
20
30
40
km

Figure 16

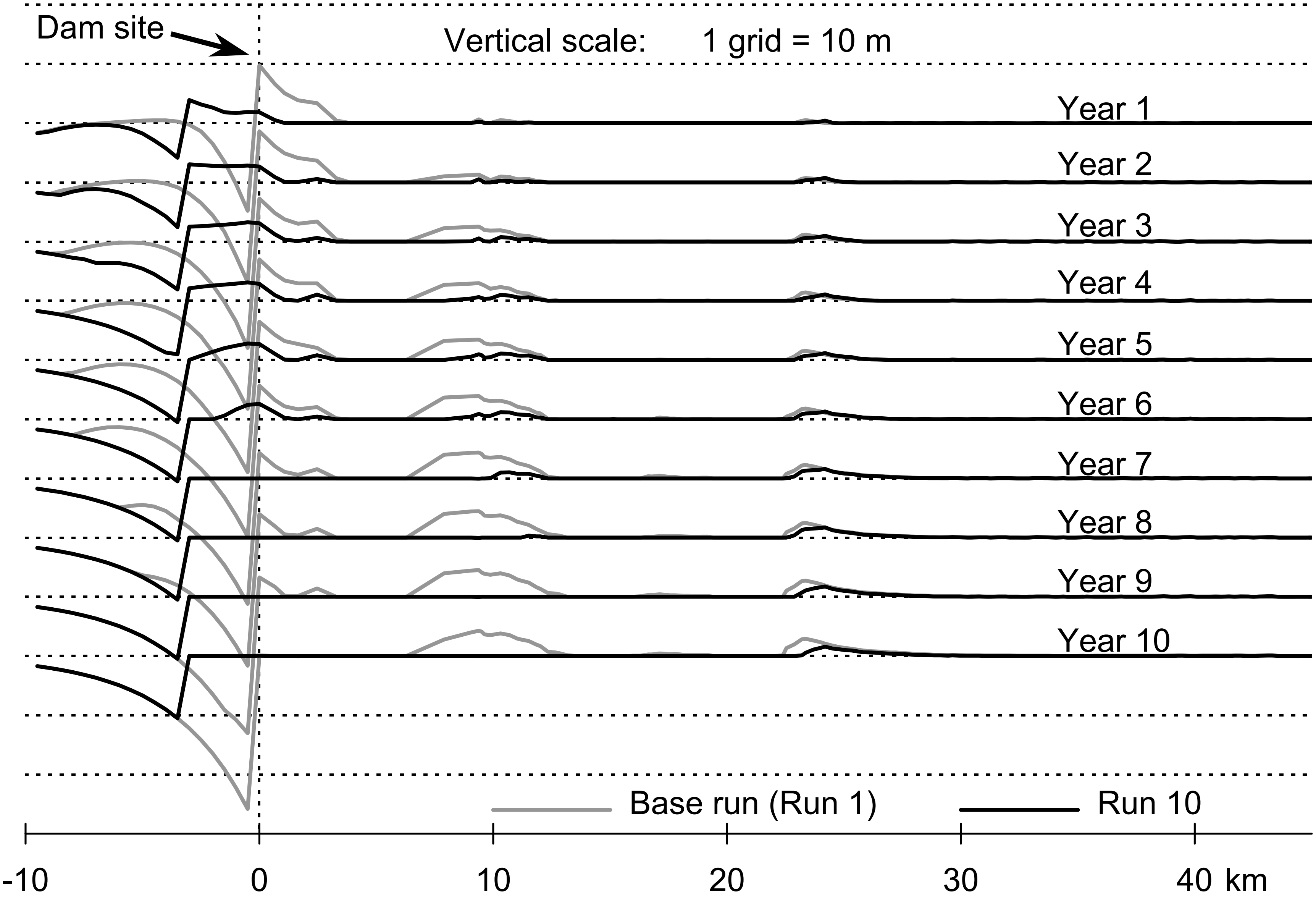

Dam site
Vertical scale: 1 grid = 10 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
Base run (Run 1)
Run 10
-10
0
10
20
30
40 km

Figure 17

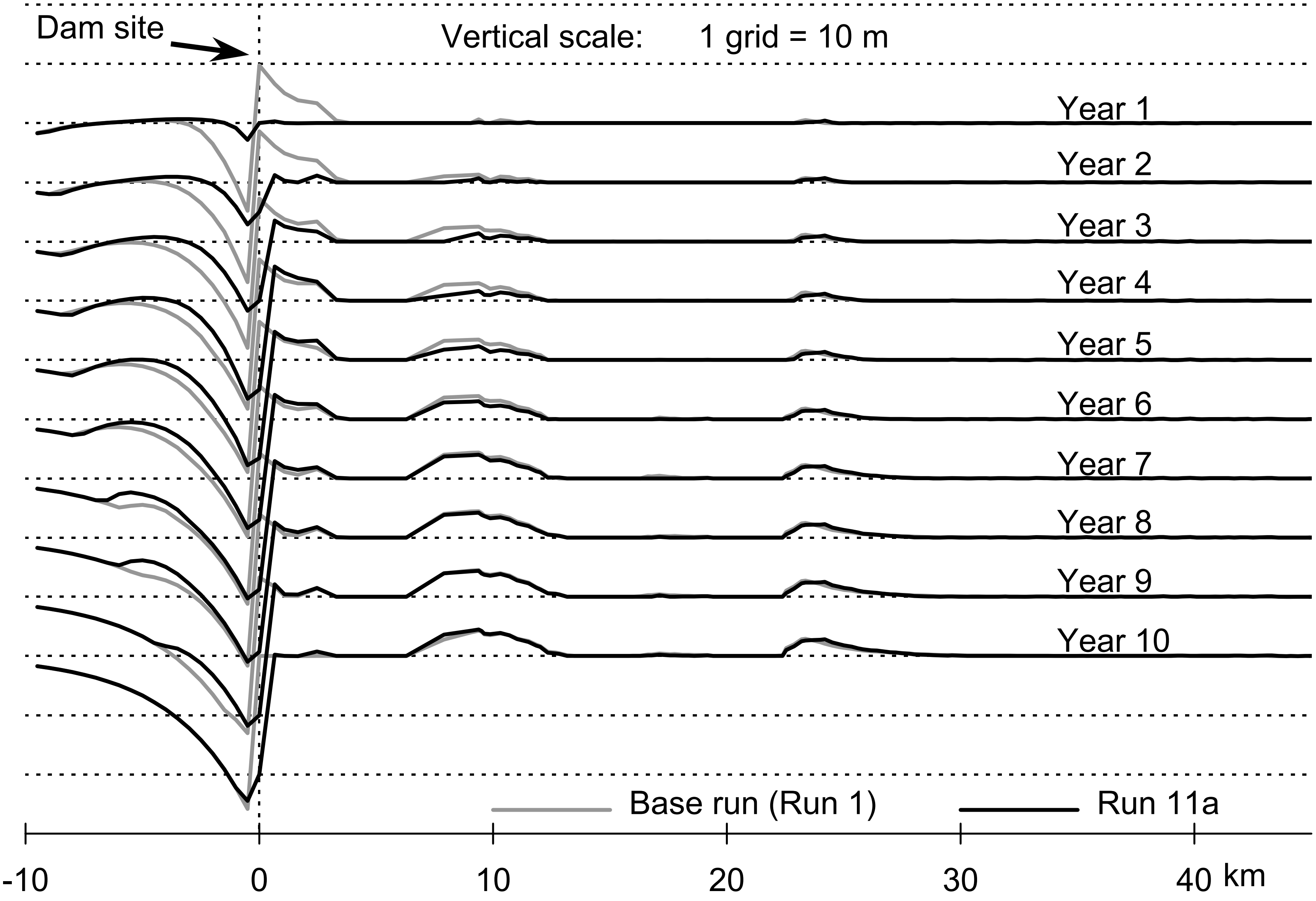

Dam site
Vertical scale: 1 grid = 10 m
Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
Year 7
Year 8
Year 9
Year 10
Base run (Run 1)
Run 11a
-10
0
10
20
30
40
km

Figure 18

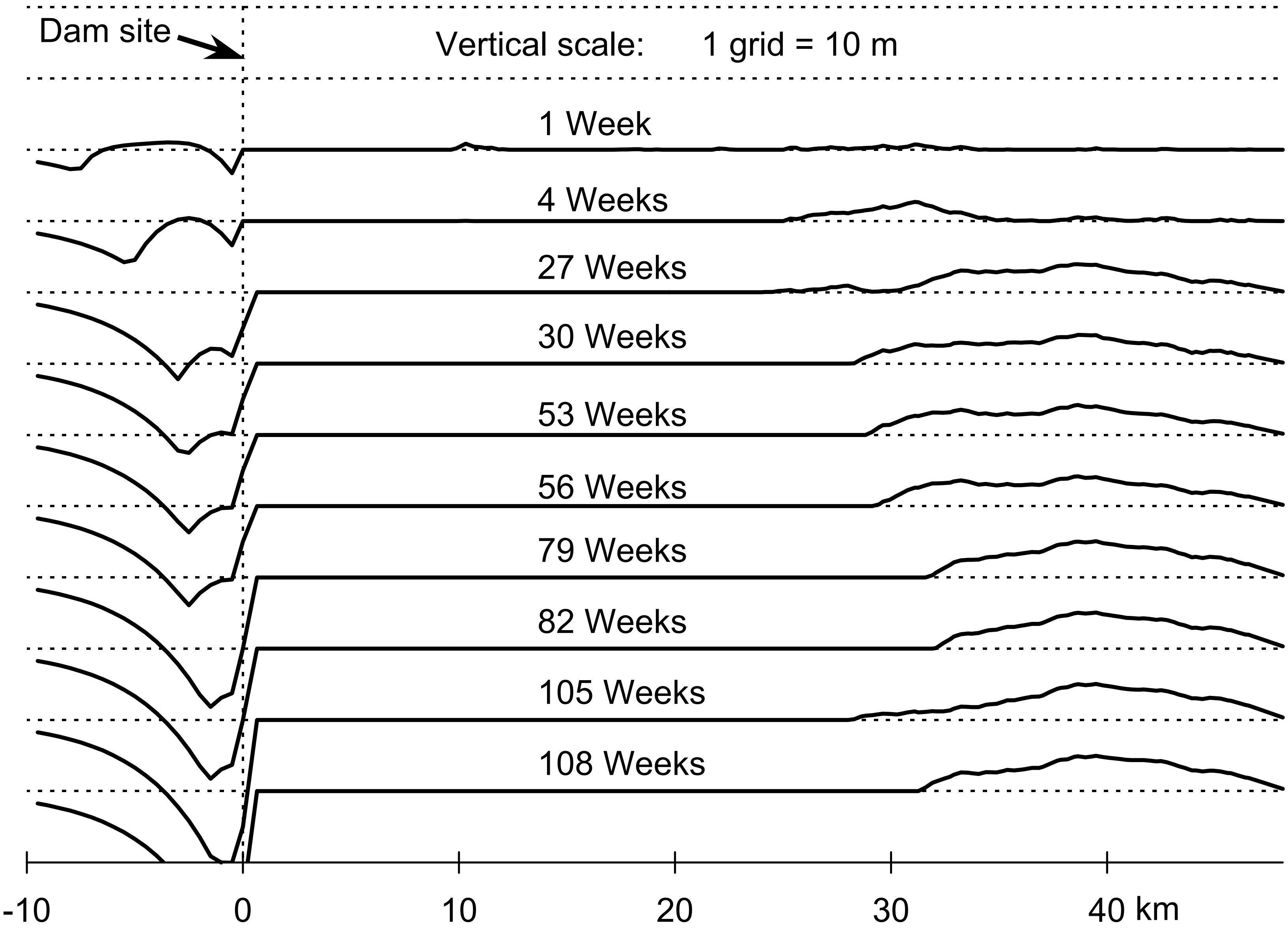
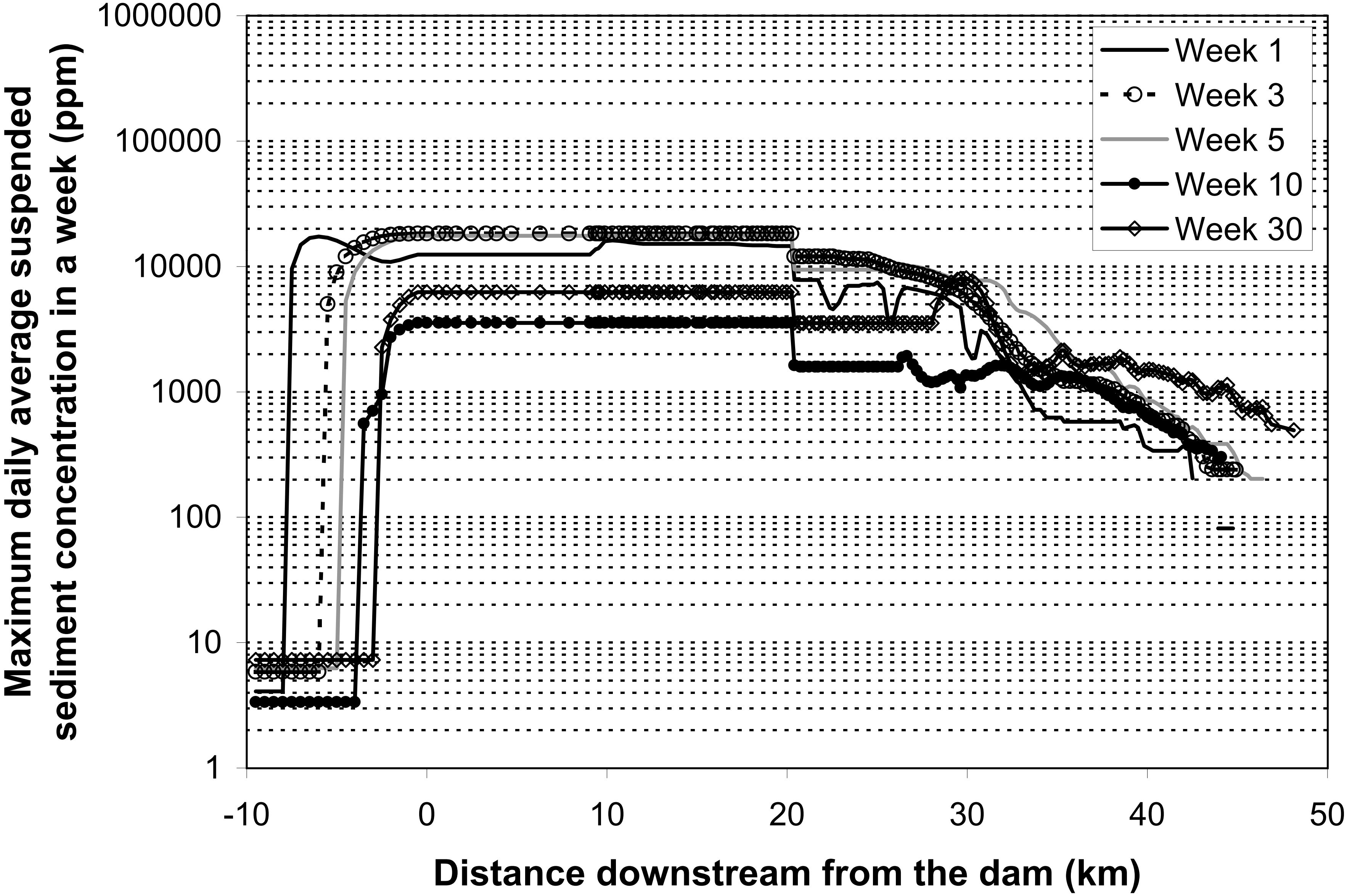

Dam site
Vertical scale: 1 grid = 10 m
1 Week
4 Weeks
27 Weeks
30 Weeks
53 Weeks
56 Weeks
79 Weeks
82 Weeks
105 Weeks
108 Weeks
-10
0
10
20
30
40 km

Figure 19a



Maximum daily average suspended sediment concentration in a week (ppm)
1000000
100000
10000
1000
100
10
1
-10
0
10
20
30
40
50
Distance downstream from the dam (km)
Week 1
Week 3
Week 5
Week 10
Week 30

Figure 19b