Intrinsic steady alternate bars in alluvial channels. Part 1: experimental observations and numerical tests

A. Crosato
Delft University of Technology, Section of Hydraulic Engineering and UNESCO-IHE, Delft, the Netherlands

F.B. Desta
Ethiopian Road Authority, Addis Ababa, Ethiopia and UNESCO-IHE, Delft, the Netherlands

ABSTRACT: Alternate bars in straight alluvial channels are migrating or steady. The currently accepted view is that they are steady only if the width-to-depth ratio is at the value of resonance or if the bars are forced by a steady local perturbation. Experimental observations, however, seem to indicate that steady bars are also present in cases of migrating bars in the absence of a persistent perturbation. The companion paper by Mosselman (2009) provides a theoretical explanation. We review some experimental observations as well as long-term numerical tests using a 2D depth-averaged morphological model of a straight channel with non-erodible banks. Small random variations in total discharge are imposed at the upstream boundary. Rapidly growing migrating bars are found to develop first, but slowly growing steady bars are found to evolve subsequently, starting either from upstream or from downstream. Since steady bars are seen as a prerequisite to explain meandering of alluvial rivers, our findings imply that neither resonant width-to-depth ratios nor steady local perturbations are necessary conditions for the onset of river meandering.

1 INTRODUCTION

River channels are often characterised by the presence of bars. These are large sediment deposits that are easily observable at low flow stages. Bars can be periodic or localised. Periodic bars are called “free bars”, because they represent the free river response to perturbations, and can be migrating or steady. Localised bars are usually called “forced bars”, because their development is forced by the local channel geometry, and they do not migrate. Point bars inside river bends are an example. Theoretical studies attribute the origin of free migrating bars to alluvial channel instability (e.g. Hansen, 1967; Callander, 1969; Engelund & Skovgaard; 1973, Parker, 1976; Fredsøe, 1978) and the origin of free steady bars to the presence of finite persistent flow perturbations, such as a local change in channel geometry (De Vriend & Struiksma, 1984).

With erodible banks, migrating bars mainly lead to channel widening; steady bars to localised bank erosion and bend growth. For this reason, initiation of meandering has been attributed to the formation of steady bars inside straight river channels (Olesen, 1984). This idea met the support of the “bend instability theory” (Ikeda et al., 1981). The wavelength of incipient meanders was found to be on the order of magnitude of the typical wavelengths of steady alternate bars, whereas the wavelengths of migrating bars, derived as the fastest growing ones (Colombini et al., 1987), proved too short to give rise to developing meanders. A resonance phenomenon maximizing bend growth was found to occur when the wavelength of incipient meanders coincides with the wavelength of steady alternate bars (Blondeaux & Seminara, 1985). This phenomenon was associated to meander formation. Later Tubino & Seminara (1990) found that migrating bars slow down due to river widening and assume the characteristics of free steady bars at resonant channel width. This led to the conclusion that river meandering follows from the bar instability through the formation of free migrating bars and channel widening.

Unfortunately, meanders are seen to form also in apparent absence of persistent disturbances and in non-resonant conditions (Friedkin, 1945; Rüther and Olsen, 2007). This means that existing theories do not provide a general explanation of why rivers tend to meander. Next to this, there is indication that steady bars may form also in a straight channel in the absence of observable persistent flow perturbations at the upstream boundary. Laboratory experiments for the study of alternate bar formation in straight flumes presented a bed deformation (Crosato, 2008) or the coexistence of two bar wavelengths (Lanzoni, 2000a and 2000b), also without permanent flow disturbances. These observations could be explained by the (undesired, in case of the experiments) development of steady bars in the channels. Are these steady bars intrinsic to alluvial systems or are they due to imperfections in the experimental set-up?

The companion paper by Mosselman (2009) provides a theoretical answer. We review here some experimental observations as well as long-term numerical tests using a 2D depth-averaged morphological model of a straight channel with non-erodible banks. In the simulations bars progressively formed with nothing more than a very small random perturbation of the discharge distribution at the upstream boundary to induce morphodynamic instability. Rapidly growing small migrating bars developed first, but slowly growing steady bars, characterized by larger wavelengths, evolved subsequently, starting either from upstream or from downstream. These steady bars tended to dominate the final bed topography. The findings imply that neither resonant width-to-depth ratios nor steady local perturbations are necessary conditions for the onset of river meandering. River meandering, following from free steady bar formation, can therefore be regarded as intrinsic to alluvial systems.

2 EXPERIMENTAL OBSERVATIONS

Some laboratory experiments for the study of alternate bar formation in straight flumes presented an undesired bed deformation also without detectable external disturbances. In the 1989 experiments described by Crosato (2008), the first author obtained a steady bed disturbance even after having tried to avoid any non-uniformity in incoming flow and sediment distribution and concluded that she had failed to obtain conditions with migrating bars only. Lanzoni (2000a and 2000b) reports the coexistence of two bar wavelengths, one almost twice the other. These observations could be explained by the development of free steady bars in the channels in addition to migrating bars.

Nelson & Smith (1989) report that Fujita & Muramoto (1985) observed that the wavelength of migrating bars increased during the evolution process in flume experiments. The figures reported show that bar propagation slowed down while bar wavelengths increased.

3 NUMERICAL TESTS

3.1 *Approach*

The formation of bars was studied using a fully non-linear, time-dependent, physics-based morphological model based on the 3-D Navier Stokes equations for incompressible fluid and shallow water (Lesser et al., 2004). The computations were carried out using a 2D depth-averaged version of the model with an appropriate parameterization of relevant 3D effects. In this case, the model accounts for two effects of the spiral motion that arises in curved flow (e.g. Blanckaert et al., 2003). First, the model corrects the direction of sediment transport through a modification in the direction of the bed shear stress, which would otherwise coincide with the direction of the flow velocity vector. Second, the model includes the effects of the transverse flow convection, causing transverse redistribution of main flow velocity, through a correction in the bed friction term. The model accounts for the effects of longitudinal and transverse bed slopes on bed load direction (Bagnold, 1966; Ikeda, 1982). The closure scheme for turbulence is a $k-\varepsilon$ model, in which k is the turbulent kinetic energy and ε is the turbulent dissipation.

The runs reproduced the evolution of the bed topography in straight river channels with non-erodible banks. The simulations reproduced two cases with different channel width-to-depth ratios and discharges. Sediment characteristics and longitudinal bed slope were the same as for the Waal River (Netherlands), for which the Engelund & Hansen transport formula (1967) is considered applicable. The other characteristics were selected based on the mode, m, of steady and migrating bars that should have developed. The mode represents the number of bars in the cross-section. Since we wanted to obtain an alluvial channel with both migrating and steady alternate bars ($m = 1$), the selected channel characteristics had to allow for the formation of both types of bars. To define the ranges pertaining to migrating alternate bars we used the results by Marra (2008), who applied the method by Tubino & Seminara (1990) to the Waal River. The ranges allowing for the formation of steady alternate bars were determined using the physics-based formula of Crosato & Mosselman (2009), which was derived from the simplified linear model by Struiksma et al. (1985).

The channel characteristics are summarized in Table 1, whereas the parameters describing the model set-up are summarized in Table 2.

Table 1. Characteristics of the simulated alluvial rivers.

variables	RUN1	RUN2
Q_W (m^3/s)	200	300
i (-)	0.0001	0.0001
B (m)	90	150
h_0 (m)	3	2.8
B/h_0 (-)	30	53
D_{50} (m)	0.002	0.002
steady bars m (-)*	1	1
migrat. bars m (-)**	1	1-2
length (m)	20,000	20,000
groyne length (m)***	30	30

* mode according to Crosato & Mosselman (2009); ** mode according to Marra (2008); *** control runs.

Table 2. Parameters of model set-up.

parameter	value
Grid cell size in transverse direction (m)	15
Grid cell size in longitudinal direction (m)	25
Time step (minutes)	0.5
Morphological factor*	10

* multiplication factor of bed level changes to speed up the

computations.

The “morphological factor” (in Table 2) is a coefficient multiplying the bed level changes and is merely meant to reduce computational time. This coefficient was given the smallest possible value that was able to keep the simulations realistic and the computational time feasible. However, even with a morphological factor equal to 10, some runs took more than 20 days to be completed. Sensitivity analyses showed that the bar celerity increased for increasing morphological factor. The minor overestimation of bar celerities when using a morphological factor equal to 10 was considered an acceptable shortcoming, since the goal of the study was to ascertain the stabilization of migrating bars.

To reproduce migrating bars, the numerical model requires an unsteady forcing at the upstream boundary (e.g. Struiksma, 1998; Mosselman et al., 2003). For this reason, a random, very small, perturbation of the inflow was distributed in transverse direction over the computational grid-cells at the upstream boundary. The simulations considered two different intensities and time variability of the perturbation: 1) maximum amplitude equal to 1% of the discharge, varying every minute; and 2) maximum amplitude equal to 5% of the discharge, varying every 3.5 hours. Another type of simulations considered the presence of a permanent finite perturbation, as the one provided by the presence of a groyne obstructing part of the channel width. These simulations provided control conditions to assess the characteristics of the steady bars that are known to form downstream of geometric perturbations (Struiksma & Crosato, 1989; Lanzoni, 2000a). The downstream boundary condition was normal-flow water elevation.

3.2 *Results*

The simulations started with a flat channel bed and continued until the bed topography stabilized, at least partly. Alternate bars gradually developed. The first ones were rapidly growing short migrating bars. Subsequently, the bar wavelength gradually increased and their celerity decreased during the evolution process, a phenomenon that had been reproduced also by Nelson (1990) with another non-linear model. Slowly growing steady bars evolved at last. The time needed to reach this point depended on the sediment transport capacity of the flow and on the imposed upstream boundary conditions. This explains the different durations of the computations. The duration of the stabilization process was the shortest with the permanent perturbation. Bars started to develop after a certain distance from the upstream boundary with the random perturbation, but developed right at the upstream boundary with the permanent disturbance (groyne). This explains why steady bars could be easily obtained in experimental flumes downstream of a permanent disturbance (Struiksma & Crosato, 1989; Lanzoni 2000a). Since a relatively long time is required to obtain steady bars in the other cases, it is possible to assume that most experiments without permanent disturbance were stopped when the stabilization process was not complete yet.

The longitudinal bar wavelength was derived by means of spectral analyses. Tables 3 and 4 give the wavelengths of the two highest peaks at different time steps. The longitudinal bed level profiles of RUN1, 15 m from the right bank, are shown in Figures 1 and 2 for the three boundary conditions. Figure 1 shows the longitudinal near-bank profiles after 2 and 4 simulated years. Figure 2 shows the bed topography at the moment in which the bed was either fully stable, i.e. contained only steady bars, or only partly stable. The long computational time was the only reason to stop the computations when the bed was not completely stable yet.

The bar celerity was roughly estimated by recording bar top locations at different times. In the fist phases of the evolution, celerities had the order of magnitude of hundreds of meters per year. At the final stages they became of the order of meters per year or less.

Table 3. RUN1: bar wavelengths corresponding to the highest two peaks resulting from the spectral analysis at different times.

simulated time (years)	bar wavelength (m)					
	groyne		max random perturbation 1%		max random perturbation 5%	
	1st peak	2nd peak	1st peak	2nd peak	1st peak	2nd peak
2	907	453	798	384	only small bed oscillations	
4	907	453	997	767	950	767
8	907	453	798	384	831	998
12	907	475	798	384	867*	-
16	950	475	798	997	867	623
20	950	475	798	867	731	383
28	950	475	907	998	1050*	-
36	950	475	907	391	1108*	-
42	950	475	907*	-	1050*	-
54	950	475	950*	-	1050*	-

* second peak from spectral analysis very small or absent

Table 4. RUN2: bar wavelengths corresponding to the highest two peaks resulting from the spectral analysis at different times.

simulated time (years)	bar wavelength (m)					
	groyne		max random perturbation 1%		max random perturbation 5%	
	1st peak	2nd peak	1st peak	2nd peak	1st peak	2nd peak
2	1050	525	867*	-	1050	512
4	907	453	1174	907	1050	512
8	1663	1425	1247	1425	1425	1174
12	1535	2850	1535	3325	1425	1663
16	1535	2850	1663	3325	1535	798
20	1663	2494	1663	2850	1535	1814
28	1663*	-	1814*	-	1663	1425
36	1814*	-	1663	1425	Run stopped after 28 years	
42	1814*	-	1663	1425		

* second peak from spectral analysis very small or absent

Given the large wavelengths and considering the overestimation of bar celerity caused by the morphological factor, bars having celerity of a few meters per year can be reasonably considered steady.

The average values of the bar celerity computed for either the upstream or the downstream half of the channel were used to assess whether bars started to stabilize from upstream or from downstream (Table 5). For a random perturbation up to 5%, the steady bars started to develop from downstream. In the other cases, bars became steady either from upstream or downstream.

The bar wavelengths show gradual convergence in time. Their slight differences (less than 10% when the control runs are taken as reference) at the final stages of the bed evolution can be attributed to non-linear effects, since in linear models (e.g. Crosato & Mosselman, 2009) the bar wavelength does not depend on the boundary conditions. Also the bar amplitude shows a slight dependency on the boundary conditions. It is known that bar amplitude is determined by non-linear effects (Colombini et al., 1987).

4 CONCLUSIONS AND DISCUSSION

Alternate bar formation was studied using a fully non-linear morphological model. The computations were carried out using a 2D version of the model with an appropriate parameterization of relevant 3D effects. In the simulations bars progressively formed in a straight channel with non erodible banks and a very small random perturbation of the discharge distribution at the upstream boundary to induce morphodynamic instability. Rapidly growing, short, migrating bars developed first, but slowly growing larger and slower bars evolved subsequently, starting either from upstream or from downstream. Steady bars tended to dominate the final bed topography. Their final wavelength appeared slightly dependent on the boundary conditions, which can be attributed to non-linear effects not accounted for in linear models. Similar computational results were obtained by Nelson (1990), while experimental observations confirm the computed evolutionary trend (e.g. Fujita & Muramoto, 1985). Similar results were obtained also by Hibma et al. (2004), but in long estuaries with symmetrical tides.

The results show that the fastest growing migrating bars (Colombini et al., 1987) do not characterize the final channel bed topography.

The finding that steady alternate bars can be induced by nothing more than a very small random flow disturbance at the upstream boundary implies that neither resonant width-to-depth ratios nor external forcing are necessary conditions for the onset of river meandering. The companion paper by Mosselman (2009) proposes a theoretical explanation. For rivers with low bank erodibility, steady bars stabilize on the same time scale as the formation of incipient meanders. We recently found that simulations with easily erodible banks, not presented here, produce these steady bars too, well before channel widening can lead to resonant conditions. We think that an initial bank deformation of arbitrary wavelength acts as a permanent forcing, similar to an external one, but now resulting as an intrinsic response. Meandering thus arises from both cases as an intrinsic response.

Table 5. Averaged bar celerity at final configuration computed for the first 10 km (upstream half) and for the second 10 km (downstream half) of the channel in m/year.

Run	averaged bar celerity (m/year)					
	groyne		max random perturbation 5%		max random perturbation 1%	
	1st 10 km	2nd 10 km	1st 10 km	2nd 10 km	1st 10 km	2nd 10 km
RUN1	0.5	0.8	50	2.5	153.7*	125
RUN2	28.7	2.85	40	2	1.4	3.9

* the run was stopped when only a few bars had become steady. These steady bars cannot be recognized from the average value of bar celerity over a 10 km-long reach.

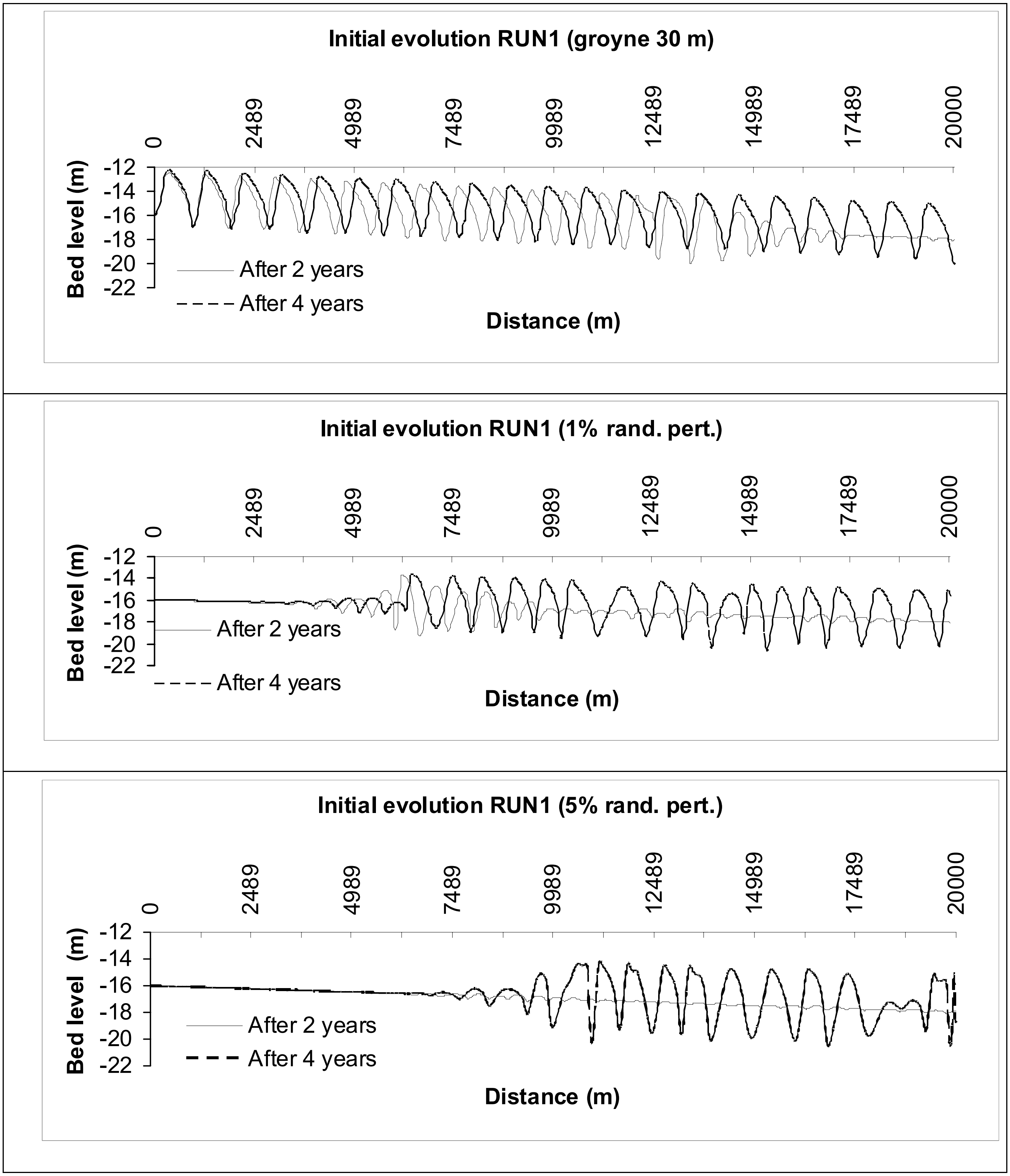

Figure 1. RUN1: initial longitudinal bed level profiles 15 m from the left bank after 2 years (continuous line) and after 4 years (dotted line) from the start of the simulation.

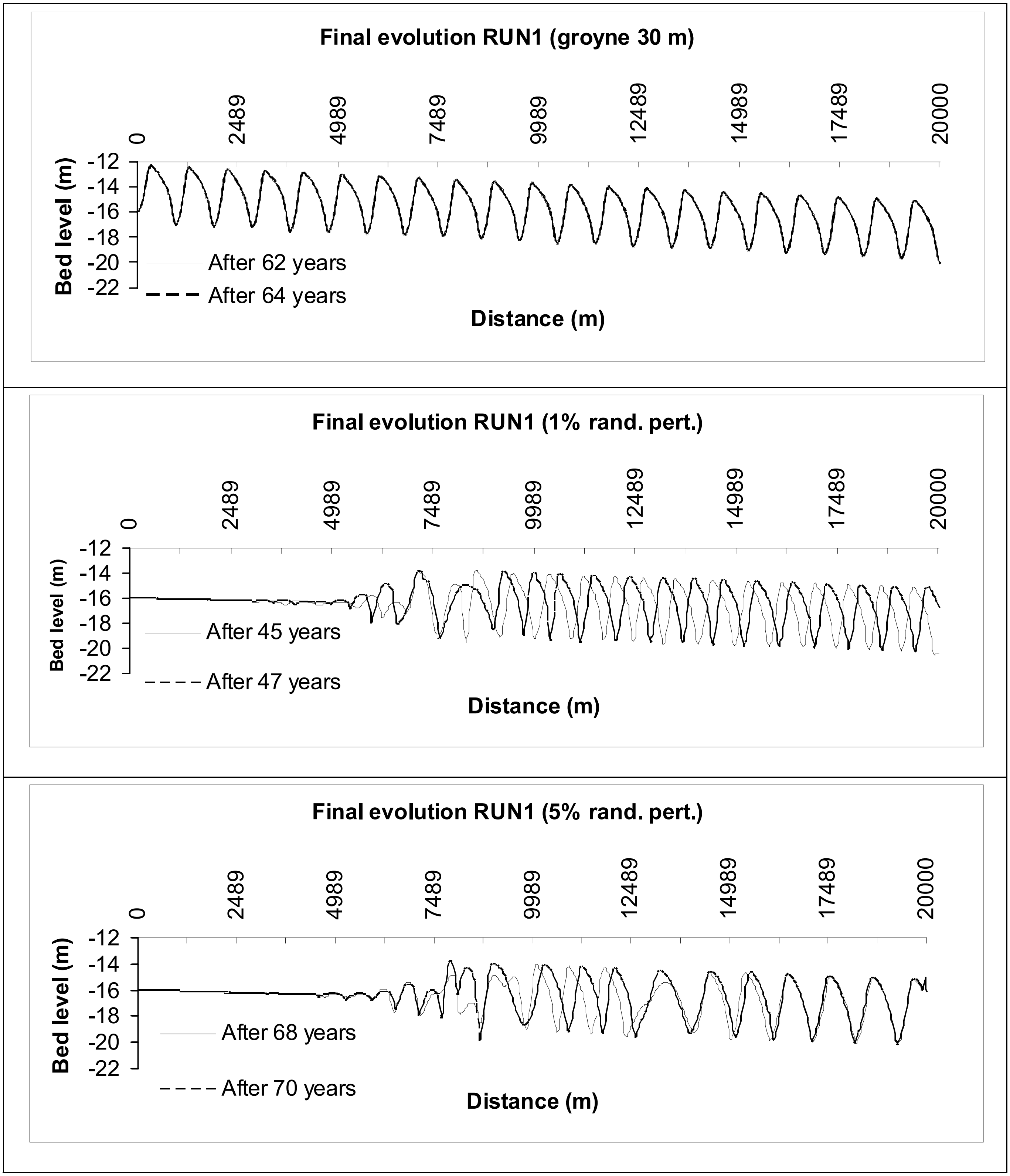

Figure 2. RUN1: longitudinal bed level profiles 15 m from the left bank when the channel bed was either fully stabilized or started to stabilize.

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