Impact of Channel Icing Development on the Geomorphic Effects of Ice Breakup Along A Small Gravel Bedded Stream: south central Yukon Territory

by

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ABSTRACT

The study was undertaken in order to determine the geomorphic effects of ice breakup along a small gravel bedded river in the south central Yukon Territory. Observations and the results of level surveying indicated that the presence of overbank channel icing impacted significantly on the geomorphic effects of ice breakup. Where only minor or no channel icing developed breakup was dominated by the simple melting of ice in situ. However, where overbank icings developed, breakup was delayed to a time of near bankfull flows, resulting in the failure of the ice cover. Incorporated in the failed ice were frozen bank materials. It is hypothesized that the manner of ice failure (beam) is responsible for the resultant bank failure. Finally, a general two year cycle of erosion and deposition was identified for specific reaches, and it was suggested that the development of a channel icing may indirectly alter this cycle by reducing the effects of bed consolidation through flow separation during breakup. The effects of ice breakup observed in this study were determined to be minor and of only local significance at their present rate of occurrence.

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Chapter I

INTRODUCTION

1.1 INTRODUCTION

Due to their northern location, the rivers of Canada are subject to the annual accumulation and destruction of a winter ice cover which persists for a significant proportion of the year. It has only been within the past two decades that the potential geomorphic significance of river ice processes has begun to be examined intensively. Indeed, Newbury (1968) notes that his study originally intended to examine the effects of ice on fluvial processes only; however it soon became apparent "that the annual cycle of ice formation and destruction was a northern river process per se" (Newbury, 1968, p. iv.). In contrast to fluvial processes in general, river ice processes have been understudied. In view of continued northern development, and the need for this to occur without damage to the environment, an understanding of river ice processes and their potential impact on human activity and vice versa is essential.

A review of the literature indicated that the effects of ice breakup on smaller streams had been largely ignored and thus, it was determined that this study should focus upon the effects of ice breakup on a small gravel bedded stream. Unexpectedly and perhaps, fortuitously a channel icing developed on the study stream during the second year of the study (1982). Thus the focus of the study was redirected toward the examination of the differences in effect observed between icing affected reaches and those reaches unaffected by icings.

Chapter II presents a review of the literature with emphasis upon channel icings and the geomorphic effects of river ice breakup and is in effect , a purpose unto itself. In Chapter III the study area, located on Gravel Creek in the south-central Yukon Territory, is described with respect to geology, topography, climate and hydrology, and the reasons for site selection are outlined. Also in Chapter III the methodology employed is discussed, and observations made in the field are presented. Chapter IV presents the results of the study and a discussion of their significance in terms of the observed ice breakup processes. Finally, in Chapter V conclusions are presented along with some suggestions for future research.

Chapter II

LITERATURE REVIEW

2.1 LITERATURE REVIEW

During the past two decades the scientific research into river ice and its associated processes has increased greatly. However, as yet too few studies have focused upon the geomorphic significance of river ice processes.

This study investigates the effects of ice breakup along a gravel bedded stream which is periodically affected by channel icings. Therefore, this literature review will concentrate upon channel icings, their nature and significance, and the geomorphic effects of river ice as documented in the literature. Prior to this, however, the discussion will consider ice formation, decay-breakup, ice jams, and ice drives.

2.2 RIVER ICE

The literature concerning river ice is widely scattered throughout the journals of many disciplines, reflecting the varied interests of ice researchers. However, Ashton (1978) and Michel (1972) present excellent reviews of river ice, and Prowse (1985) presents an account of recent trends in Canadian ice research.

2.3 RIVER ICE FORMATION

Ice formation in rivers takes place through two distinct processes. The first, which is static and known as shore ice growth (Michel, 1972), involves the simple exchange of heat energy between the calm water surface and the atmosphere. The growth of a shore ice cover begins in contact with colder bank materials in areas of laminar flow and extends toward the center of flow. This type of ice cover is often further extended through the adhesion of frazil flocs to the irregular edge of the shore ice cover.

The second process of ice cover formation is dynamic and involves the production of frazil ice crystals in supercooled turbulent water. The process of frazil formation is still not clearly understood and a number of mechanisms of have been suggested including spontaneous heterogeneous nucleation (Devik, 1944), secondary nucleation (Michel, 1967), crystal multiplication processes (Chalmers and Williamson, 1965), mass exchange between surface water and atmosphere (Osterkamp, 1975), as well as combinations of these (Ashton, 1978). In any case it is known frazil ice crystals are formed in turbulent reaches of rivers where the air temperature is somewhat below 0°C. The disc-shaped frazil crystals agglomerate into irregular platelets (¬15 mm size) in the active zone of frazil production. In some cases, frazil production in a given reach can entirely block a channel cross-section and result in serious flooding (Ashton, 1978). Generally, however, frazil flocs float out of the zone of active production and agglomerate into pans and floes which jam and freeze together in less turbulent reaches. This, in combination with shore ice growth, produces an ice cover.

2.4 PREDICTION OF FREEZE-UP

Many of the early studies of river ice were devoted to the study of the temporal and spatial characteristics of river ice. Predictions of the formation and growth of a river ice cover are of two varieties. In the first method an energy budget approach is used (Billetto, 1964). However, an accurate prediction of all components of a river's energy budget is rarely possible, with the result that this method is useful only for short periods of time (Ashton, 1978). Furthermore, as noted by Newbury (1968), there is a need to distinguish between the date of a freeze-up and the date of freeze-over. Newbury suggests that freeze-up be interpreted as the date upon which ice first appears on a river, while freeze-over is the date upon which a complete ice cover is formed. In general most energy budget predictions are accurate only for freeze-up (Ashton, 1978).

The second method of prediction of ice formation, the historical approach, utilizes the statistical analysis of past-records of freeze-up dates. Mackay and Mackay (1965) in an attempt to discover long term climatic trends examined observations of ice conditions for the Churchill and Hayes Rivers from Hudson's Bay Company historical sources dating back to 1714. Moodie and Catchpole (1975) applied content analysis to historical documents in order to determine dates of freeze-up and break-up on estuaries of Hudson Bay. Allan (1964) determined the general trend of mean freeze-up and freeze-over dates across Canada based upon the records of 274 stations. Generally, this method is useful in determining length of navigable season, and such is used for long term planning of transportation etc.

2.5 BREAKUP

In contrast to early studies of ice formation, early studies of ice breakup focussed largely upon the description of the breakup process, and in particular ice jams. As ice breakup processes are discussed in the next section of this literature review, this section will confine itself to the description of river ice breakup.

Michel (1972) divides the breakup of a river into three broad phases: the pre-breakup period, the drive, and the wash. Not all of the three phases will necessarily occur on any one river in any one breakup season.

The pre-breakup period begins with the onset of increased discharge of the river due to runoff from snowmelt and rainfall. This results in the ice cover being subjected to uplift pressure, with water flowing on top of the ice. In areas of low velocity flow, fractures develop along the shoreline and water flows over the shore ice, while the central ice cover floats freely. Conversely, in areas of high velocity flow, the ice cover anchored to bed protuberances such as boulders, is submerged by the increased flow, as water rises through the numerous cracks in the ice cover (Michel, 1972).

The pre-breakup period ends when the ice cover has weakened sufficiently for increasing discharges to initiate an ice drive. For a thorough review of the deterioration process see Ashton (1978).

As noted previously, not all phases of the ice breakup process necessarily occur in a given year, and this is particularly the case with the ice drive phase. Smith (1979) suggests that channel width represents a threshold which controls the occurrence of ice drives. However, it appears likely that the relationship is more complex and involves channel width, channel depth, discharge, and ice thickness (or strength) at the time of maximum discharge (Kellerhals and Church, 1979). Michel (1972) suggests that the drive depends largely upon the combination of discharge and ice strength, and notes that where discharge is insufficient to lift the ice cover from its anchors the ice sheet will simply melt in place. In most cases, however, rain and intensive snowmelt contribute to greatly increased discharges, which in turn result in the clearing of an ice reach through ice drives (Kellerhals and Church, 1979).

Often several drives occur on a given river as the initial drives jam at downstream ice reaches. When the ice jams release, major ice drives often result. Ice drives of this nature will be discussed in the following section on ice jams.

The third phase of the ice breakup process, the wash, occurs when the spring flood clears up grounded ice from the banks and bars.

Prediction of ice breakup, depending as it does upon the onset of the increased discharges necessary to produce ice drives, is a difficult task. Allan, (1964), using the same sources used for freeze-up dates, mapped mean dates of ice breakup in Canada. Murakami (1972) suggests that there exists a critical number of days where air temperature rises above $0^{\circ}C$ and the time that breakup occurs. Present inability to forecast air temperature accurately for more than short periods of time reduces the utility of methods such as this.

2.6 ICE JAMS

Ice jams and the drives associated with their failure are without doubt the most dramatic of the river ice processes, and as a result have received considerable research attention.

Ice jams are classified in two basic manners. The first classification divides ice jams into winter and spring ice jams (Williams, 1973). Winter jams occur as an ice cover is forming on a river. Frazil ice produced in turbulent reaches accumulates into pans and floes which may form an underhanging dam when they come into contract with a downstream ice reach. In general winter jams are not as severe as spring jams, due to the generally decreased discharges at this time of year. Winter jams tend to occur at the same locations from year to year, and produce significant well documented morphological effects (Newbury, 1968), generally consisting of deep scour holes beneath the location of the ice jam (Kellerhals and Church, 1979). The second class of ice jams, spring or breakup jams, are much less predictable and can often be very destructive.

> The winter of 1874-75 was a bitter one, with deep snow and never a thaw until April. On the 2nd or 3rd of that month, however, a further heavy fall of snow was followed by a sudden rise in temperature. The change of weather and weight of melting snow caused the ice for the 85-mile stretch of rapids above the fort [Fort McMurray] to break-up, and it came down the Athabasca with terrific force. On striking the turn in the stream at the post it blocked the river and drove the ice 2 miles up the clearwater [River] in piles 40 or 50 feet high. In less than an hour the water rose 57 feet, flooding the whole flat and mowing down trees, some 3 feet in diameter, like grass...
>
> (Moberly and Cameron 1929)

> It's unknown the great Deluge that is in these parts, and the Damages that is occation'd by such Deluges or floods of water, at the Breaking up of

> the River's, with the Sudden thaw's in the Spring of the years, -- the Ice being froze to the ground confines the water that itt has not passage to vent itt self into the Sea, which occation's a Rising of water some fathom's Deep which in a small time spreads over the land, -- Blow's the Ice up with a Noise as terrible thunder, -- Breaks all the Bank's of the Rivers down, -- tear's trees Downe of great Substance by the Roots, -- for some distance in Land, Notwithstanding bank's on the Edge of the River's 20 or 30 feet perpenticular, -- its past Beleif to Ima'gine the damage that happened by such Deluges on floods, -- I have known the Ice when going out of the Rivers, to appear like a wood or grove of trees with the Perdigious Quantity of wood, which has been Brought of the shores by the water and Ice, when these floods has happn'd, which is frequent in the shole Rivers, that abounds with islands, tho not so Boistorious some years as others. --
>
> (Isham, 1747)

The preceding passages indicate the severity of the destructive forces that can be associated with spring ice jams and their subsequent failure. More recently, Nuttall (1969) reported a stage rise of 12 m in less than 30 minutes for one site in Alberta. That ice jams and the drives associated with their failure are dramatic events can hardly be argued. However, controversy does exist as to the significance of their geomorphic effects. This will be discussed in the section to follow.

The second classification of ice jams divides them into simple or dry jams (see Fig. 2.1) (Michel, 1972, Beltoas, 1978). The simple ice jam, or hanging dam, is characterized by the fact that it represents a surface jam, with flow continuing beneath the jam. Conversely, in a dry ice jam, blocks of ice forced under and over the ice reach at which

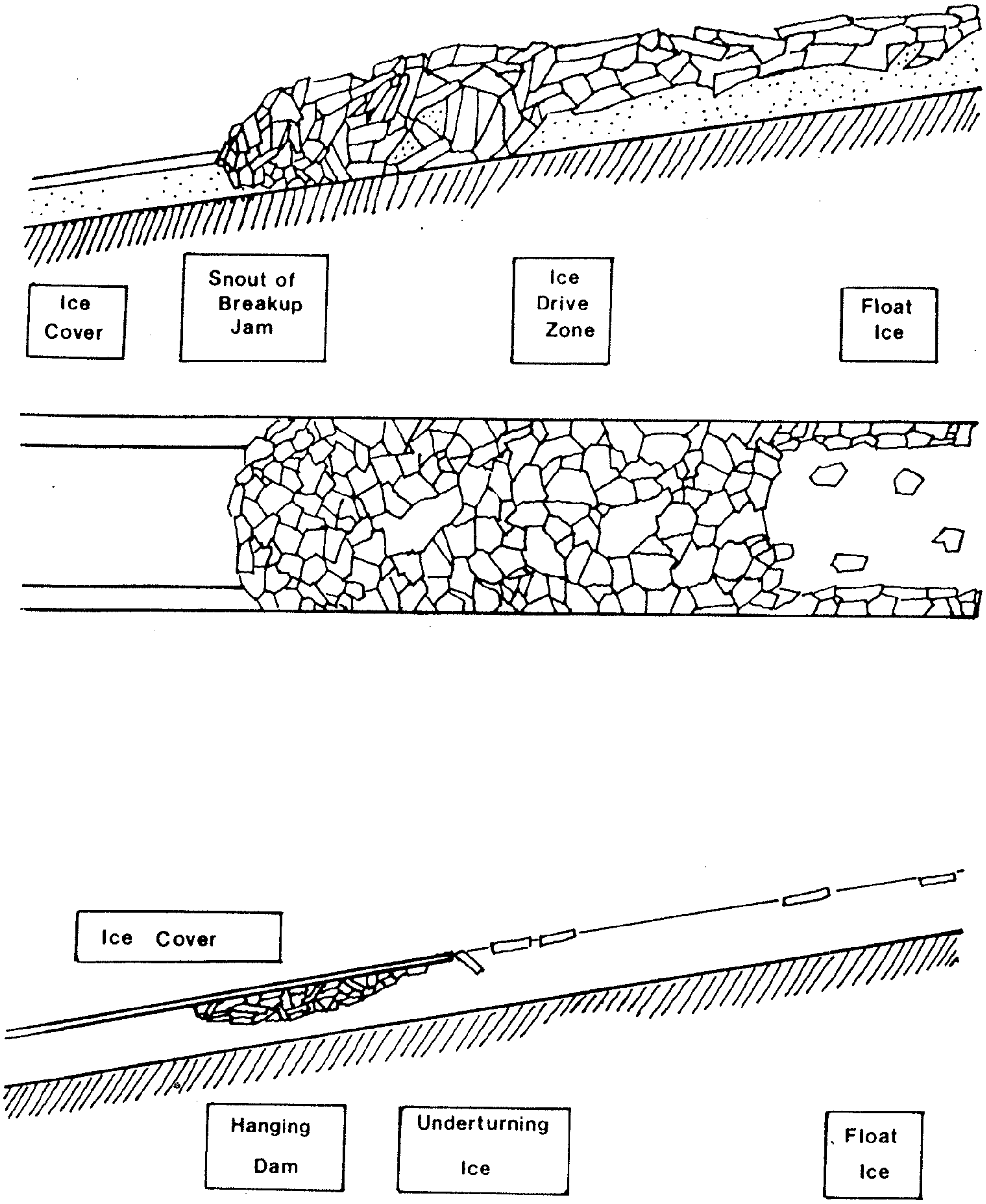


FIGURE 2.1 Idealized Comparison of Dry and Simple Ice Jams

(after Smith,1980, and Gerard,1975.)

the jam occurs completely blocks in-channel flow at that point, resulting in backwater effects and rapidly increasing stage. Gerard (1975) suggests the above classification as well as three others including: mechanism of jam initiation -- free or forced; jam extent -- vertical, horizontal; failure mode -- complete or partial failure; jam importance -- major, minor. These are defined as follows:

> "(i) Initiation of jam: free or forced. The term free denotes a jam formed by the accidental locking of ice floes on the river surface. Forced denotes ice floes forcibly halted by some obstruction. This latter group could be subdivided on the basis of the obstruction -- for example, geomorphic features (shoals, sharp bends), ice cover, hanging dam, ice bridge, structures, etc.
>
> (ii) Jam extent -- vertical: surface, thickened or dry. The first term refers to a jam of ice floes which remain on the surface, with no floe entrainment or buckling of the jam. The latter term applies when the channel has been more or less completely blocked by jam buckling or flow entrainment. Thickened refers to situations between these extremes. This feature of a jam has a strong influence on the behaviour of the water level and indicates whether scour under the jam is a possibility
>
> -- horizontal: partial or complete cover. This refers to whether the channel surface and/or flow is partially or completely blocked by the jam. It is particularly pertinent in reaches with islands or multiple channels and will have significant effects on scour and water level behaviours.
>
> (iii) Failure mode: complete or partial failure. This denotes whether a jam fails instantaneously across its entire width or whether just a portion of the channel is cleared. The latter condition indicates that severe scour and high velocities may have occurred just after failure because of the large hydraulic head and constricted channel. High velocities can also be associated with complete failure.
>
> (iv) Jam importance: Two groups are suggested for this -- major or minor -- based on the maximum stage achieved behind the jam, using

> the two year summer flood level or bankfull, whichever is less, as that dividing the two groups."
>
> (Gerard, 1975).

In general only the classification of jams on the basis of vertical extent and time of formation has been used widely in field studies of actual jams.

Numerous field studies have provided some meaningful qualitative data on breakup ice jam formation (Beltaos, 1978; Gerard, 1975; Mackay and Mackay, 1972, 1973; Williams and Mackay, 1973; Wong and Beltaos, 1983), and a general understanding of their method of formation has been developed. As the drive phase of river breakup begins, the ice cover is released from some ice reaches. Upon reaching an intact ice reach downstream the ice pans respond in one of the three ways which may lead to their entrainment in an ice jam. Firstly, the ice in the drive may simply jam into the downstream ice cover and remain floating on the surface, thus halting the drive until the downstream ice cover breaks up. Secondly, upturning of the ice pans may occur as they come into contact with the downstream ice cover. In this case the ice pans are thrust up onto the surface of the ice cover. Repeated occurrences of which can lead to rapid thickening of the ice cover at a given location. Thirdly, the ice floes may be entrained in an ice jam through underturning. In underturning the ice floes and pans are drawn under the ice cover and may become lodged, thus thickening the ice cover and possibly producing a jam at that location.

Laboratory studies have shown that a number of factors, including velocity (Devik, 1964), porosity (Michel, 1966), and shape and slope of buoyant blocks (Chee and Haggag, 1981) influence the behaviour of floating ice pans upon reaching an intact ice cover. However, field measurement of these variables has been unattainable, due to both the difficulty of predicting the time and place of ice jam occurrence, as well as the extreme danger of working on an ice jam. It would therefore appear that actual field measurement of the processes of ice jam formation is still far in the future.

While the majority of ice jam research to date has focused upon the jam itself and the upstream effects, Beltaos and Krishnappan (1981) have begun studies of surges from ice jam releases. The surge, or rapid discharge of water, is caused when an ice jam fails. A number of study areas have been identified with regard to ice jam releases, including short and long-term prediction of peak stages, possible bed scour, and bank erosion due to severe ice drives. While prediction of peak flows due to surges is still lacking, controversy does exist over the effectiveness of ice drives as a geomorphic agent. This will be discussed in a section to follow.

In conclusion, it is apparent that ice jams are a significant process in many rivers in which winter ice cover forms. Researchers from a variety of disciplines have gained greater insight into ice jams and drives, although much remains to be known.

2.7 CHANNEL ICINGS

Many stream channels and valley locations in Arctic and sub-Arctic regions are subject to the annual accumulation of large masses of ice knows as icings. The icings (Russian naleds, German aufeis) are formed as a result of processes entirely different from those which produce the annual winter ice cover of rivers and streams.

Icings have been classified (Bol'Shakov, 1966) according to physical and geological indicators into four categories: surface water (river and stream), groundwater (suprapermafrost water), subterranean water (springs), and subterranean water (interpermafrost and subpermafrost). As these fours categories are not mutually exclusive it is simpler to use Johnson's (1950) three part classification of: river icing, ground icing (water source above permafrost), and spring icing (water source below permafrost). Kane and Slaughter (1972) suggest a further simplification, and differentiate (for practical purposes) only between those icings formed primarily by the winter long contribution of groundwater, and those formed by water derived from fall runoff and active layer sources. The preceding classification systems all stress the importance of water source in icing formation. Source of water determines the length of the growth period of an icing and hence, the size of the resulting icing.

For the purposes of this discussion, the only category of icing that need be considered is that of the river or channel icing, and the remainder of this discussion will focus solely upon river icings.

River icings are defined as the mass of superimposed ice which accumulates on an existing river ice cover, resulting from the repeated overflow of water (Grey and Mackay, 1979). The inability of a river channel under an ice cover to convey water arriving from upstream results in the buildup of hydrostatic pressures. The ice cover deforms and cracks, and water breaks through its surface and overflows the ice cover, freezing to form an ice cover superimposed on the primary ice cover (Sokolov, 1979). Channel water conveyance reduction may be brought about by two general conditions. Firstly, a sharp increase in discharge may increase flow resistance, and thus reduce conveyance relative to changing flow conditions (Sokolov,1979) Secondly, a decrease in channel conveyance may occur as a result of the constriction of flow area. Commonly, the flowpath is squeezed between a freezing front advancing from the surface and an impermeable layer below (usually, but not necessarily, permafrost).

As noted previously, icings fed by subpermafrost groundwater discharging into the river bed are generally the largest, as this provides a continuous source of water throughout the winter. Water supply to icings fed by suprapermafrost groundwater may be cut off when the freezing front reaches the top of the permafrost (or other impermeable layer).

Carey (1973) and Grey and Mackay (1979) identify factors conducive to icing formation as: local components, seasonal components, and hydrological components. They note that there is a degree of interaction between these factors, particularly where permafrost is present, as permafrost itself is a consequence of local (geologic), seasonal (climatic), and hydrologic conditions. Local factors are viewed as determinate in the spatial arrangement of icings and are considered invariate over short time spans. Seasonal factors are temporally determinate, in that they determine whether an icing will occur in a given year along with their extent. Hydrological factors are, for the most part, determined by the first two sets of factors (Grey and Mackay, 1979).

The local factors are defined as the geology and topography of the area. Geology is important in that it determines the availability of groundwater and possibly the existence of impermeable bedrock near the surface. Permafrost is noted as an ideal base and as such, partly explains the prevalence of icings within permafrost zones.

Topography is also important in that streams and groundwater in steeper terrain flow under higher hydraulic gradients, thus producing greater hydrostatic pressures. Also, mountain streams are generally shallow, wide, and often braided, conditions which allows their freezing to the streambed. Finally, mountain valleys are often subjected to low temperatures as a result of inversions. The above conditions are common to northwestern North America, where the largest icings of this continent develop (Grey and Mackay, 1979).

The seasonal components of air temperature and precipitation are more complex and more variable in their effects on icing formation. Low temperatures are necessary to initiate the development of the primary river ice cover and the surface freezing front. Where icings are fed by subpermafrost groundwater, low temperatures early in the icing season will initiate icing formation through freezing of the stream to its bed early in the winter, producing an extensive channel icing. Conversely, where icings are fed largely by surface water, low temperatures early in the icing season can prevent substantial icing formation, as a result of complete freezing of the water source medium (Grey and Mackay, 1979). Finally, low temperatures cause the thermal contraction of the ice cover, thus producing avenues of escape for water under hydrostatic pressure.

Precipitation affects icing development both in its amount and timing. Rainfall during the late summer and early fall recharges groundwater sources before freeze-up, thus ensuring a good supply of water to the river throughout the winter. Snowfall also affects icing development significantly. Little snow during the early winter favours icing development through reduced insulation. Thus, the primary river ice cover and the freezing front may advance rapidly, reducing channel conveyance. If heavy snowfall occurs during the latter part of the winter the insulating effects protect the established thermal regime and thus the icing can continue to develop despite changing temperature. Conversely, heavy snows during early winter diminish the possibility of icing formation regardless of air temperature (Grey and Mackay, 1979).

As noted previously, hydrologic factors are the result of local and seasonal factors and as such are generally only variable temporally.

Sokolov (1979) suggests distinguishing between three modes of icing occurrence: (i) annual formation; (ii) formation in some years; and (iii) their total absence. In the case of an icing forming every year, it is apparent that an underlying internal (local) factor dominates the system and an icing forms under even the most adverse hydrometeorological conditions. When icings never form, no underlying factor exists or it is so weak that an icing will not develop even under the most favorable hydrometeorological conditions. In the case of icing formation in some years and not in others, hydrometeorological conditions dominate and dictate whether an icing will form or not. Given the above assumptions, the probability of icing development at a given site should be determinable. Furthermore, it should eventually be possible to determine the limiting hydrometeorological conditions responsible for icing formation at a given site, and consequently (given necessary advances in long-term weather forecasting) icing prediction may be possible for specific sites.

While the underlying hydrological (local) conditions are, in the above case, considered to be stable over the long term, human activity can alter these characteristics and thus produce new areas of icing formation. van Everdingen and Allan (1982) conducted a study of icing activity on a small steam along the Alaska Highway in the Yukon Territory. In their study van Everdingen and Allan used timelapse photography to record icing development and employed dendrogeomorphology (distribution of reaction wood) to determine the past existence of icings at the site. Reaction wood is noted as dark wedges within the tree ring structure resulting from the disturbance of tree growth. The results of their study indicated while icings most likely occurred prior to highway realignment across the stream, the severity of icings was greatly aggravated as a result of this realignment. This increased icing activity appeared most likely due to an increased groundwater potential upstream of the highway as a direct result of compaction of water bearing materials underneath the highway embankment.

More dramatic evidence of the effects of human activity on channel icings is presented by Thompson (1966). Thompson noted that an icing some six feet thick developed on a Yukon stream after someone had walked across the creek in snowshoes. It was suggested that trampling of the snow resulted in reduction of its insulation value thus allowing the stream to freeze to its bed at that location. Consequently, a channel icing developed.

Carey (1970) presents an extensive bibliography concerning icings, much of it early Russian work concerned with methods of icing control. More recent work has tended to concentrate on the hydrology of icings, and their manner of formation and their significance in terms of impact on engineering concerns (Kane and Slaughter, 1972; van Everdingen, 1982; Church, 1974). Extensive reviews of icings are presented by Carey (1973) and Grey and Mackay (1979).

A large number of measures to control icings have been developed. Control measures may be either passive or active. Passive measures seek to reduce the road hazards associated with icing development and are implemented only after the icing threatens the roadway. Active measures, conversely, attempt to alter the preexisting hydrodynamic conditions responsible for icing formation in order to eliminate or reduce icing development. Active measures are generally undertaken during the summer (Thompson, 1966). Passive measures include: steaming, the construction of hessian cloth dams, blasting, grading, and fire pots. Most passive methods of icing control require frequent visits to the site and as such are very costly. Active measures of icing control include: drainage, the creation of freezing belts and ponding areas, grade raises, road relocation, culverts, and channel correction. (See Thompson, 1966 for a complete review of these methods).

Kane and Slaughter (1972) identify two hydrologic roles of stream icings. Firstly, they note that icings are indicative of the source of subsurface water yield. Secondly, icings are a means of water storage and delayed water yield during the ablation season. Icings greatest impact on basin water yield is in timing. As icings persist long after the disappearance of snow, icings can, in the absence of precipitation (a common situation during Yukon springs -- Vershuren and Bristol, 1974) constitute the major addition to baseflow of upland streams after the melting of the snowpack. Kane and Slaughter (1972) calculated that the volume of water accumulated in icings for the entire Caribou-Poker Creek drainage complex accounted for almost 40% of the total estimated winter streamflow and 4% of the estimated annual flow for the entire watershed. Similar calculations for Russian rivers affected by icings indicated that the volume of water accumulated in river icings could amount to 120 - 200% of the mean winter low flow in rivers that do not freeze to the bottom and, 20 - 40% of the annual volume of groundwater flow to these rivers (Sokolov, 1979). These differences reflect the consideration of different variables of water flow and are not necessarily contradictory. Sokolov did not expand upon his methods of obtaining these values. In any event, the ablation of icings after the spring snowmelt would noticeably augment late spring-early summer stream flow.

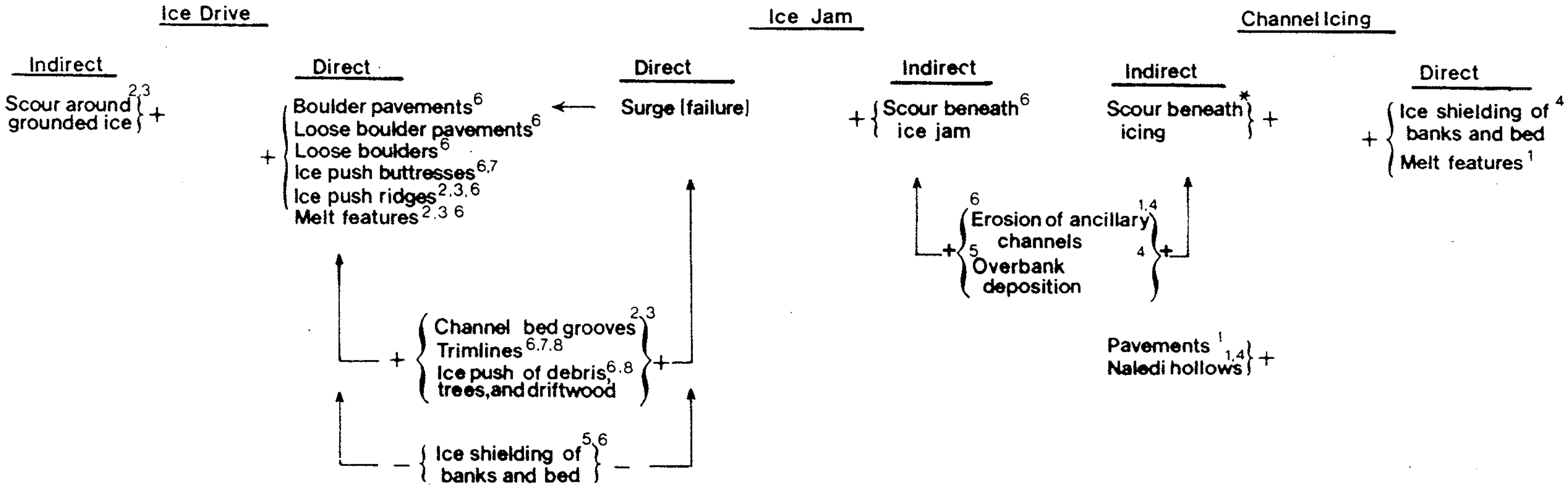
A number of other effects associated with channel icings have been identified (Kane and Slaughter, 1972; Slaughter, 1982). During the spring snowmelt flood the existence of an icing in a stream channel often forces the flood event to flow on top of the channel icing, thus contributing to stages which are not indicative of actual discharges. These floods are often responsible for the destruction of bridges and road embankments. Channels develop within, beneath, and on top of the icing thus making discharge measurement impossible. Icings may also retard spring vegetative development by retarding growth through low ground surface temperatures and the physical presence of ice. Aquatic organisms may be affected through the presence of ice and low water temperatures. Given the wide variety of effects associated with channel icing and the fact that they are a ubiquitous feature of arctic and sub-arctic regions, it is noteworthy that they are still poorly understood, particularly with reference to their geomorphic and biological significance. Prediction of icing formation which is still not possible, would be of great value as northern development increases. It is known that if icings are ever observed at a location they can be expected to occur again, and this will definitely assist researchers in future studies of channel icings.

2.7.1 Geomorphic Effects of River Ice Breakup

The geomorphic effects of river ice breakup have seen only limited study, particularly in contrast to the attention received by fluvial systems in general. As a result considerable disagreement exists as to the significance of ice breakup processes as agents of geomorphic change. Further compounding the problem is the fact that river ice may inhibit, or magnify the effects of other processes. Ackerman (1982) noted that the geomorphic effects of channel icings may be direct or indirect, and positive or negative. Direct effects are those produced by the direct action of ice against a river's bed and banks.

Indirect effects are those produced by other processes as directed by the existence of ice in the channel. Ackerman (1982) defines positive effects as those in which the ice has given rise to a specific geomorphic form. Negative effects are defined as those in which the ice has suppressed or prevented another process from producing a landform. Newbury (1968) noted the existence of direct and indirect effects of ice formation and breakup on the Nelson River in Manitoba. Ackerman's classification would therefore appear to represent a desirable framework within which to discuss the effects of all ice breakup processes. However, there are certain inherent problems in the application of Ackerman's classification to the fluvial system. These are most evident when one considers indirect effects of ice breakup. Indirect effects must, by definition, be produced by other processes through the direction of ice. In the fluvial environment these processes are, for the most part those of scour and fill. Therefore, all indirect effects of ice breakup will result in scour or fill, regardless of the ice breakup process which directed them. Furthermore, one individual ice process may result in a number of effects both direct and indirect, and positive and negative. Finally, it is doubtful whether a negative indirect effect can be identified, and the literature does not yield one example. For this reason, in the following discussion the geomorphic effects of ice breakup will be considered firstly in terms of the responsible river ice process, and secondly in terms of Ackerman's classification. The processes considered here, and previously identified are: ice drives, ice jams and channel icings. (see Table 2.1).

TABLE 2.1 Geomorphic Effects of Ice Breakup Processes



1 Ackerman, 1982
2 Collinson, 1971
3 Day and Anderson, 1976
4 Froelich and Stupik, 1982
5 Kellerhals and Church, 1979
6 Mackay and Mackay, 1977
7 Newbury, 1968
8 Smith, 1979, 1980
* Carlson, 1979

+ positive
— negative

2.7.2 Ice Drives

For the purpose of this discussion the meaning of the term ice drive will be expanded to include all movement of ice downstream within stream flow. The severity of the effect of ice drives is in large part dependent upon the ice breakup temporal relationship and the snowmelt flood. Direct positive effects of ice drives include boulder pavements, loose boulder pavements, loose boulders, ice push buttresses, ice push grooves, trim lines, ice push of driftwood, trees, and debris, and melt features; as well as the negative effects of ice shielding the banks and bed from erosion. The stability of many of these features has been studied by Mackay and Mackay (1977) on the Mackenzie River, N.W.T.

Boulder pavements produced by ice drives are similar in appearance to glacial boulder pavements. Faces of boulders are striated, abraded, and sometimes faceted. The pavements consist of closely packed boulders pressed firmly into a stony mud along the banks of the river. Individual boulders in the pavement are occasionally removed and replaced through ice activity. Mackay and Mackay's (1977) findings indicated that boulder pavements occurred downstream from a boulder source, usually a stony till. The rate of boulder supply usually exceeds net loss and as such loose boulders are continually moving across the pavement surface. Thus, when boulders are removed from the pavement there is a ready supply of "travelling boulders" which fill the gap and preserve the pavement's identity. Mackay and Mackay noted two general pavement trends; firstly, there is a downstream decrease in boulder size, and secondly, the long axes of the boulders parallel the river bank. Results of nine years of study indicated that a century or more would be required for all the original pavement boulders to be removed and replaced.

Loose boulder pavements are described by Mackay and Mackay as closely spaced boulders lying freely on top of bouldery ground. In most cases Mackay and Mackay found that loose boulder pavements were much more susceptible to complete reworking by ice drives than true boulder pavements, and some were almost completely reworked by ice in a period of six years. It was suggested that the texture of the underlying material determines whether a true boulder pavement or a loose boulder pavement results at a site, given a steady supply of boulders. Loose boulder pavements develop where the subsurface material does not allow boulders to penetrate the ground surface. Clay banks favor the development of true boulder pavements, whereas coarser banks result in loose boulder pavements. This in turn affects the pavement stability. Mackay and Mackay (1977) suggest that depth of boulder burial determines pavement stability. Therefore, true boulder pavements are much more stable than loose boulder pavements. It should be noted however, that the stability referred to by Mackay and Mackay indicates only the stability of individual components (boulders) of the feature (pavement) and not the feature itself.

Mackay and Mackay (1977) note that islands and shoals in the Mackenzie River can be affected by ice in a variety of ways as a result of ice push during drives, including the development of buttresses and the planing of island surfaces. Similar effects were noted by Newbury (1968) on the Nelson River in Manitoba. In many cases islands of alluvial origin develop ice-push buttresses on their upstream ends. The buttresses consist of a veneer of small boulders (25-50 cm) on the upstream faces of islands. Mackay and Mackay documented changes of buttress slopes of up to 8^0 within seven years, and the complete disappearance of identifiable buttress components in some cases. They did not, however, note whether the buttress itself was removed, or simply rearranged in such a manner that identified components were destroyed. Newbury (1968) noted that ice drives significantly modified the shape of some islands on the Nelson River. Low islands were eroded into drumlin shapes by ice drives.

Ice blocks that ground upon the bed of the channel produce characteristic features including linear grooves, and linear and crescentic ridges (Collinson, 1971, Day and Anderson, 1976). The work of both Collinson (1971) on the

Tana River in Norway, and Day and Anderson (1976) on the Thomsen River, Banks Island, N.W.T. was conducted on rivers with nival runoff regimes (Church, 1972). The nival runoff regime is characterized by peak flows associated with snowmelt. Ice breakup occurs at this time. Therefore, direct observation of the bed is possible after the snowmelt event.

Grounding of ice pans occurs when water depth decreases (over shoals, bars, etc.) or as the water level drops with the waning of the snowmelt flood. As the ice pan grounds it most commonly produces a linear groove paralleling the current (Collinson, 1971). Grooves are usually only a few centimeters deep and are as wide as that part of the pan (ice block) in contact with the channel bed. Often linear ridges of sediment are produced along the edges of grooves, and crescentic ridges of sediment are pushed in front of the ice at the point where the ice block is completely grounded. Collinson noted that these features were most completely developed in gravel and sand, whereas silt seemed to inhibit their development. Collinson notes that the preservation potential of these features is likely to be low, while Day and Anderson noted that they are minor features of apparently only local significance.

The grounding of ice blocks in shallow water also produces significant indirect effects upon the channel bed (Collinson, 1971; Day and Anderson, 1976). Where ice blocks ground while still in the current they alter the flow regime in the immediate area through flow separation and/or locally increasing water velocities (Collinson, 1971) resulting in differential scour and fill. The scour develops in a crescentic shape on the upstream side of the ice obstruction. Often linear ridges of sediment are also produced downstream of the obstruction (Collinson, 1971). Both Collinson (1971) and Day and Anderson (1976) noted the amplitude of ice-induced scour and fill to measure as much as one meter. Collinson suggested that extreme scour and fill features are the most likely of the ice effects he observed to be preserved in the geologic record. They cannot, however, be considered characteristic of ice processes alone. Collinson also noted that severe scour often occurrs in troughs where an ice block spanned two sediment ridges. Downstream of such occurrences sediment ripple fans developed.

The nature of the nival runnoff regime is such that the features described above are often exposed after the snowmelt flood has passed. In general, succeeding flows are not of high enough stage to remove these features. Miles (1976) noted that the Thompson River occasionally experienced summer storm flow events and as such ice induced scour and fill would not likely remain intact after such events. This suggests a possible effect of ice much more indirect than those presented above. Ice breakup produces a number of features on the channel bed and banks which have been identified as being largely ephemeral. The removal of these features requires an input of energy from the river. For any given discharge and slope the river has a fixed amount of energy to expend transporting sediment and water, and in maintaining bed and bank morphology. Therefore, the effects of ice breakup reduce the river's ability to conduct work by an amount equivalent to the energy required to remove the effects of ice breakup. For the sake of simplicity, this effect will be referred to as the tertiary ice effect in future discussions.

The features described above may be produced during a true ice drive. However, they may also be produced under more gentle ice breakup conditions, and in years when a true ice drive does not occur. True ice drives, while producing the effects described above, also produce much more dramatic effects, including the creation of trimlines and ice push of debris and trees. The quotation from Isham's observations at York Factory 1743-1749, presented on pages 9-10, illustrates the destructive effects ice drives can have on vegetation. Mackay and Mackay (1977) describe the upper limit of ice-push on the Mackenzie as often being marked by a forest trimline well above flood level. The trimline may be defined as the line along a river's bank below which most vegetation has been removed by ice. Newbury (1968) noted extensive trimlines on the Nelson River and its tributaries in Manitoba:

> "a characteristic boundary is developed between the vegetation trim-line and the open-water surface of mid-summer. Along reaches subject to ice movements, a shallow, concave upward groove is formed that is terminated by the slope of the bank at the vegetation trimline and the usually milder slope of the channel section below the open water section." (Newbury,1968,p.228) (See Fig. 2.2).

He attributed the trimlines to rising stage and ice push during the ice accumulation stage, noting that the trimline correlates with maximum winter stage, as well as to areas of severe ice breakup drives. Smith (1979) suggested that trimlines on the Red Deer River near Red Deer, Alberta are the result of breakup ice drives. There are some significant differences between the Nelson and Red Deer Rivers, most notably in that the Nelson River is much larger and bedrock controlled. The Nelson River consists of a series of sub-critical and critical or supercritical flow reaches separated by bedrock controlled outlets. Thus frazil ice formation takes place in critical or supercritical flow reaches and accumulation in subcritical flow zones. Ice accumulating near outlets raises the river's stage upstream thus allowing the accumulating ice cover to encroach upon the banks. Newbury (1968) notes that these accumulation zones suffer substantial ice effects. Smith (1980) notes that rivers that experience ice drives undergo breakup from the headwaters in a downstream direction. These include northward flowing rivers such as the Mackenzie, Nelson, and Yukon, and many rivers with their headwaters in the chinook belt of the Rockies. Smith (1979)

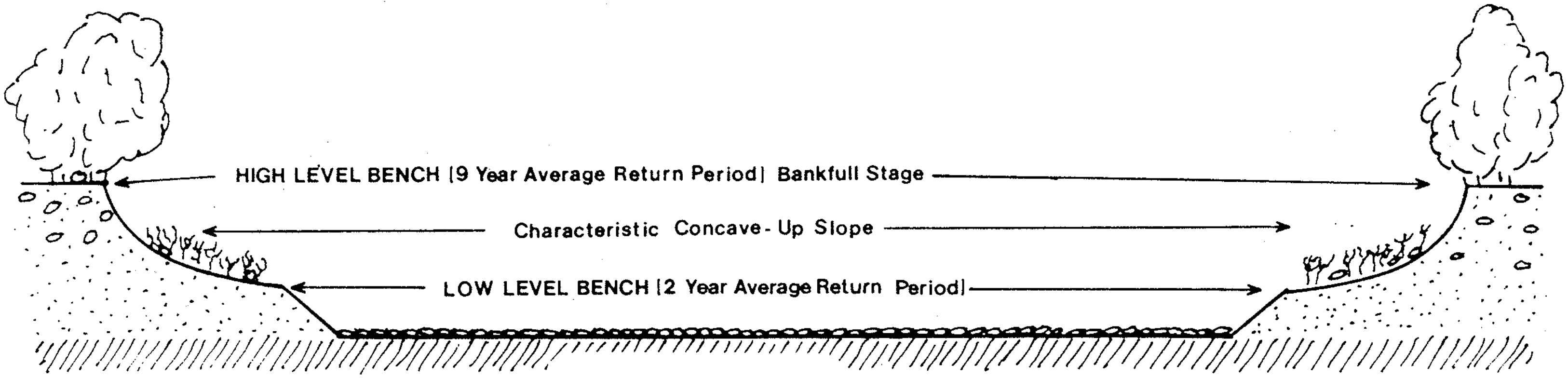


FIGURE 2.2 Idealized Channel Cross Section - Displaying the Characteristic Slope Produced by Ice Drives [After Smith, 1980.]

introduced the hypothesis of channel enlargement by river ice drives. In that study he suggested that river ice drives are responsible for the apparently high bankfull return period (16.7 yrs) of many large Albertan rivers. Kellerhals and Church (1979) argued that Smith may have been using low level terraces (ubiquitous features on Albertan streams) in determining bankfull conditions, and hence arrived at inordinately high return intervals. Smith (1980) modified his hypothesis and arrived at a return interval of nine years for the high level bench associated with ice drives, and two years for the low level bench (Fig. 2.2). He suggested that the two benches are shaped and maintained by two different processes, with summer floods maintaining the low level bench and ice drives maintaining the upper level bench.

Smith (1980) further suggests that channel width represents a threshold which determines whether an ice drive will occur or not, and that once this threshold is reached rapid channel widening will occur. This, Smith suggests, accounts for the lack of medium sized rivers in Alberta. Smith further notes that when control structures are placed on ice-drive widened channels, the reduced or negated ice drives will lead to sedimentation and plant recolonization of the outer channel. This, Smith asserts, is happening at present on the Bow River near Calgary.

As well as creating a trimline or a distinctive second bench (or outer channel) ice drives frequently scar trees and damage vegetation near the trimline. Mackay and Mackay (1977) noted that new growth among the debris and driftwood near the trimline can be used to date ice drive events. Newbury (1968) determined that one section of the Nelson River must have been devoid of significant ice activity for at least 84 years, based upon analysis of tree cores. The use of debris scarred and deformed riverbank trees as indicators of flood stage was pioneered by Sigafoos (1964) and has been applied to ice drive events on the Mackenzie River by Henoch (1973), Parker and Josza (1973), Egginton and Day (1977), and Egginton (1980). Smith (1983) extended the use of this method by comparing the results of tree scar flood assessment with recorded data of ice jam flood stage for the Red Deer River near Red Deer, Alberta. In this study Smith found that for moderate magnitude ice drives (jams), stage as recorded by tree scars averaged 1.4 meters higher than the actual measured flood stage, while for extreme events, near perfect correlation was observed between the recorded stages and the botanical evidence. This discrepancy can be explained by the morphology of riparian vegetation. Smith noted that the vegetation of the lower level bench consists entirely of willows, while poplar dominates above the trimline. The effect of the ice drive is such that only the most resilient plants (such as willows) could withstand repeated events without being mowed down. One effect of this resilience is that the willows are flexible and will bend under the forces of ice, thus often recording an ice scar further up the trunk than a less flexible tree would. This was observed by the author during breakup on the Red River in Winnipeg in 1985. A willow tree, 18 cm in diameter, was pushed to a 45^0 angle by river ice at breakup and severely scarred. Immediately after the ice cleared the tree was upright again, displaying several old scars, as well as the new scar now well above the actual stage at which it had been scarred. It is suggested that the bending of the willows and their resulting scarring by ice drives occurred upon Smith's lower bench, thus invalidating a correlation of scar height with ice drive heights.

After the ice drive has passed and stage drops, a number of minor features may be produced as a result of ice being stranded upon the bed and banks. Features include: radial patterning of fine sediments by candling ice; de-imbrication under the weight of ice blocks; small fine grained stalagtitic structures formed through wet sediments being forced up into cavities of stranded ice; and occasional depressions formed as a result of the melting out of ice blocks buried in the channel bed (Mackay and Mackay, 1977, Collinson, 1971). These features are all short lived and are of only local significance.

Boulder ridges are features produced by episodic ice jamming and release, and as such are considered here prior to the section on ice jam effects. Indeed the effects of ice jams can never be totally separated from those of ice drives, for as noted in the review of ice breakup they are inherently linked, and the failure or release of an ice jam invariably results in a significant ice drive. Mackay and Mackay (1977) observed "rhythmically" spaced (10's - 100's m) boulder ridges along several reaches of the Mackenzie River affected by ice jams. The ridges trend perpendicular to the banks and extend from the trimline, 10-14 m above river level, to below the water surface, and terminate in hooks pointing downstream. Mackay and Mackay note that the ridges appear to move as a unit downstream, with boulders being transported from the upstream end to the downstream end. This suggests some integrity of the feature with episodic transport of feature components (boulders). As such boulder ridges appear to represent the morphological expression of an ice-jam-release sediment transport process.

2.8 ICE JAMS

The geomorphic effects of ice jams are largely indirect, resulting from the fact that ice jams are, in effect, obstructions to flow, whether complete or partial. Actual studies measuring the effects of ice jams on river channels have not, per se, been conducted, as the geomorphic aspects of ice jams have, to date, been a secondary concern.

However, some geomorphic effects of ice jams have been hypothesized and at least one laboratory study conducted. Kellerhals and Church (1979) in their comment on Smith's (1979) paper on the effect of channel enlargement by river ice, contend that the upper level bench may be actively building through overbank deposition due to ice jam flooding, and suggest it is not an erosional feature due to ice drives. They suggest that ice in the center of the channel during ice drives shears pas the stationary ice in contact with the bank and point to the existence of shear lines paralleling the banks in Smith's Figure 4. More significant, however, is the possibility of severe scour beneath ice jams hypothesized by a number of authors (Gerard, 1975; Ashton, 1975). Mackay _et_ _al_. (1974) note that ice jams in the main channel of the Mackenzie River may result in appreciable scour occurring in ancillary channels eventually causing the ancillary channel to become the main channel. They further note that partial jams can redirect flow, thus altering the pattern of erosion and deposition, and resulting in marked changes in channel cross-section. Donachuk (1975) conducted flume experiments to determine the effects of scour beneath hanging dams. (Fig. 2.1). His findings indicate that scour in gravel bedded rivers, occurs as pothole scour in the vicinity of the hanging dam, and never approaches depth of flow. However, the model suggests that in sand bed rivers, severe scour equalling or exceeding flow depth, was possible.

The preceding discussion of ice jam effects presented only indirect effects. As noted previously the separation of ice jams and ice drives is somewhat difficult due to the relationship between these two processes. An ice jam may be viewed as a temporarily inactive ice drive and as such all the effects of both processes could essentially be treated together.

2.9 CHANNEL ICINGS

The geomorphic effects of channel icings have been a secondary concern in icing research. However, due to the nature of icing effects on highways, etc., numerous engineering studies have identified some geomorphic effects of channel icings (Thompson, 1966; Carey, 1973). Consequently, some recent research on channel icings has attempted to identify and document the geomorphic effects of channel icings (Froelich and Slupik, 1983; Ackerman, 1983).

As stated earlier, Ackerman (1983) noted that the geomorphic effects of icings in general may be direct or indirect, and positive or negative. By and large the most significant effects of channel icing revealed in the literature are indirect. Thus, there is a parallelism of effect between icings and ice jam, brought about largely through obstruction of flow.

The most significant indirect effect of channel icings is the blocking of flow in channels during the spring freshet, r;sulting in overbank flooding and the erosion of auxiliary channels (Smith, 1979, Kellerhals and Church, 1979; Anderson and Gell, 1980). Depending upon the amount of erosion and frequency of occurrence, the main channel may be abandoned in favor of the auxiliary channel. This process may occur during a single season, particularly in braided streams with non-cohesive banks. Smith (1980) suggests that icing induced channel abandonment may be responsible for the maintenance of a braided channel at slopes below the thresholds of braided-single thread channels proposed by Leopold and Wolman (1957) and Schumm and Kahn (1972). This has not been field tested however. Controversy also exists as to what occurs beneath a channel icing. Ackerman (1983) identified mid-channel step-like structures on several icing affected channels and attributed this to the prevention of scour beneath portions of channel icings. Conversely, Carlson (1979) has hypothesized that scour may be encouraged beneath channel icings. Where icings block only a portion of the channel flow, redirection and locally increased velocities may result in increased erosion on that portion of the channel not directly affected by the icing (Froelich and Slupik, 1983).

A number of minor features may also be produced as an indirect effect of channel icings including: pavements, nalidi hollows, (Ackerman, 1983); melt out depressions, (Froelich and Slupik, 1983). Naledi pavements consist of channel bed material which has pressed into the underlying sediment by the weight of the overlying icing. Thus the icing contributes to bed consolidation during the winter. As mentioned earlier icings also affect the morphology of riparian vegetation and therefore impact upon the potential for erosion of stream banks.

One final geomorphic effect of channel icings, and indeed all river ice, is its potential for protecting the river banks and bed from erosion during the snowmelt flood. It has been suggested (Kellerhals and Church, 1979) that ice near shore during ice drives may act as a buffer preventing erosion of the banks by ice drives. Froelich and Slupik (1983) noted that where channel icings thermally eroded in channel centers during breakup, the remaining bank fast icings protected the channel banks during rising discharges.

2.10 SUMMARY

The study of river ice and in particular the geomorphic effects of river ice breakup, have only recently received the attention of a number of researchers. As a result, the significance of river ice breakup processes as geomorphic agents is quite controversial, and only one author has suggested that river ice has significantly altered the morphology of rivers affected by river ice. This controversy is in no small part due to the great variety of geologic, climatic, and topographic environments within which river ice and its associated processes have been studied. Thus, the successful synthesis of this information hinges upon the identification and study of gaps in the literature.

The preceding discussion has attempted to highlight the nature of river ice processes giving particular attention to channel icings and the geomorphic effects of river ice breakup as these are aspects which have been overlooked in research. The preceding discussion should serve as a solid background against which the results of this study can be discussed.

Chapter III

METHODS AND OBSERVATIONS

This chapter will focus upon a description of the study area, the methodology employed in data collection and analysis, and observations made during the field seasons of 1981, 1982 and 1983.

3.1 STUDY AREA SELECTION

The study area is located on Gravel Creek in the south-central ($61^{0}18'$ Lat.; $132^{0}57'$ Long.) Yukon Territory (Fig. 3.1). Gravel Creek was selected because it satisfied a number of criteria identified as necessary for studying ice breakup effects. Firstly, the literature review indicated that studies of ice breakup on smaller rivers and streams in the sub-Arctic were generally lacking. Secondly, it was necessary that the study stream undergo breakup after the winter academic term. Thirdly, the study area had to be accessible by automobile, while at the same time isolated enough to prevent human disturbance of the site for ten months of the year. Fourthly, the study stream had to be of sufficient size that flow occurred throughout the year, yet not so large as to prevent channel survey. Finally, some funding was made available by the University of Manitoba

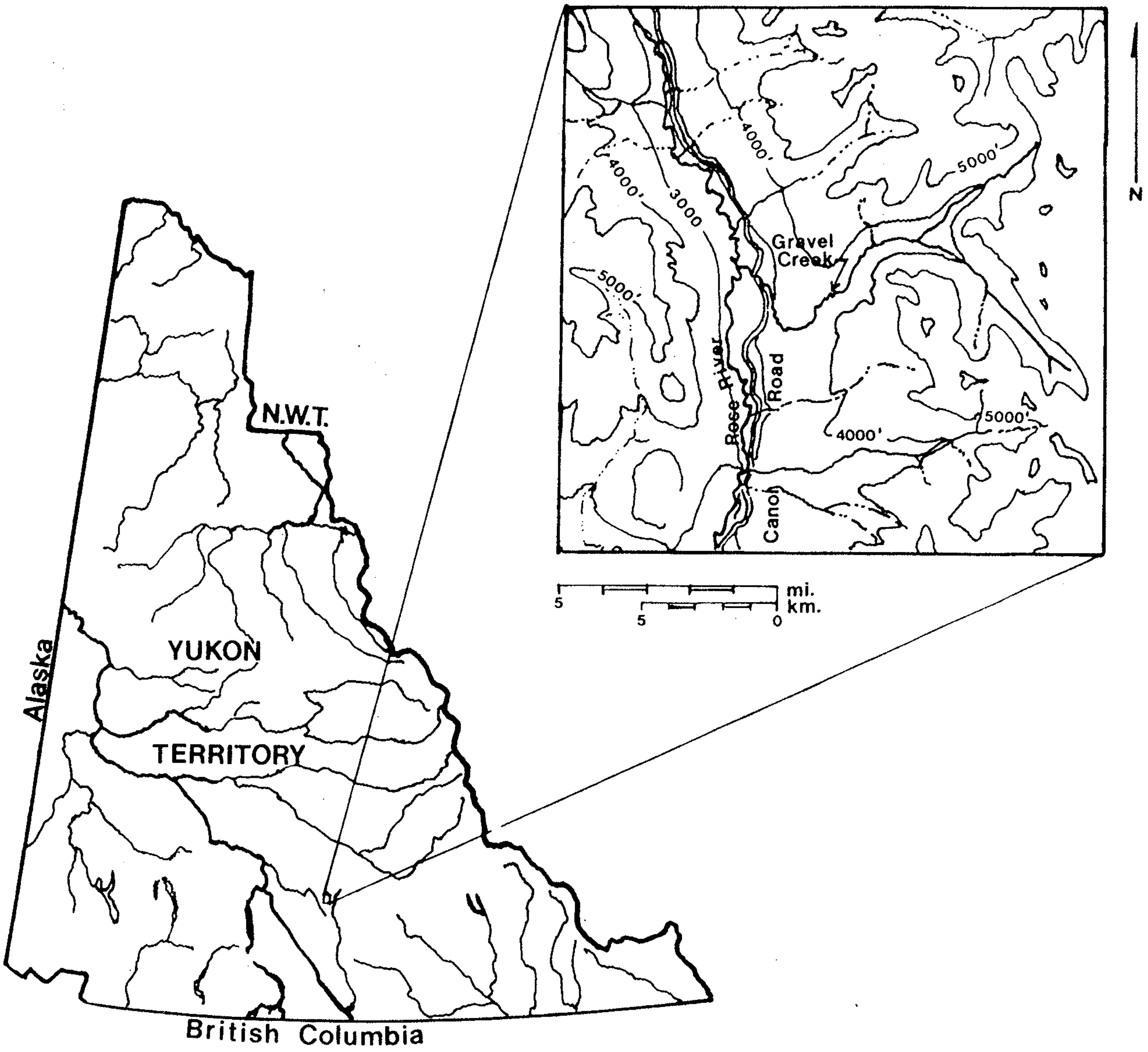


FIGURE 3.1 The Study Area

Northern Studies Committee for scientific research north of 60^0 latitude. Thus, the study area had to be located within either the Yukon Territory or Northwest Territories. The Canol Road presented an ideal area as the road is only open to traffic during the summer, thus reducing the possibility of site disturbance during long absences. Gravel Creek was finally selected as the study stream during the 1981 field season when it was discovered that most other streams along the Canol Road had recently had channel crossings converted from bridges to culverts. It was felt that this could have an impact upon the channel and as such, any channel changes measured at such sites might have been responses to the effect of culvert emplacement and not other processes. Finally icing control measures (steaming) are employed at culvert sites and as such interfere with natural breakup processes. Ironically, one other factor leading to the selection of Gravel Creek was the lack of evidence of icing on the channel at breakup in 1981. Therefore, the discovery of a significant overbank channel icing in 1982 was both surprising and, in the long run, fortuitous.

3.2 THE STUDY AREA

Gravel Creek is located at kilometer 120 on the Canol Road between Johnson's Crossing and Ross River. The Canol Road connects with the Alaska Highway at Johnson's Crossing, 120 kilometers southeast of Whitehorse, and extends in a northeasterly direction to Camp Canol, opposite Norman Wells, N.W.T. on the Mackenzie River. The Canol Road was completed in 1942, to service the pumping stations along the Canol pipeline from Norman Wells to Whitehorse. The pipeline was dismantled shortly after the second world war, and the Canol Road is now maintained for summer traffic only.

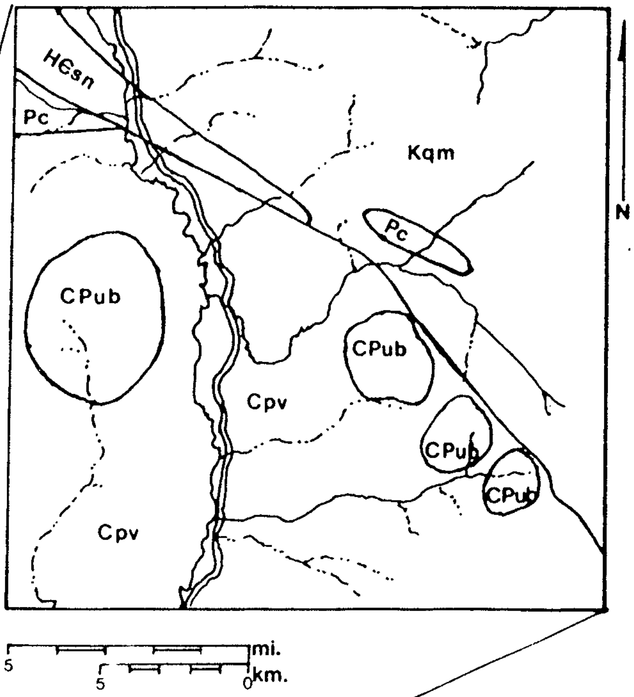
3.3 TOPOGRAPHY

The study area is located within the Pelly Mountains of the southern Yukon Plateau (Fig. 3.2). The St. Cyr Range forms the main unit of the Pelly Mountains, and in the northwest approaches elevations of 2500 m. In the immediate area of Gravel Creek local relief is on the order of 1000 m. The mountains to the north and west display the effects of alpine glaciation with numerous abandoned cirques, aretes, and horns. To the southeast mountain peaks are glacially scoured and smoothed, and granite erratics lie upon greenstone and schist (Bostock, 1948; Kindle, 1945). Large U-shaped valleys dissect all ranges of the Pelly Mountains. From Quiet Lake to Ross River the Canol Road follows one such valley now occupied by the Rose and Lapie Rivers. Glacio-fluvial deposits dominate the valley floors and consist of pitted and unpitted outwash, eskers, and kame deposits. Terracing of these deposits is common and lacustrine deposits of various lake levels are also common.

FIGURE 3.2 Physiography of the Study Area

FIGURE 3.3 Geology of the Study Area

FIGURE 3.3 Geology of the Study Area
(Source: Gabrielse et al.,1980.)



Key

Kqm - Cretaceous – quartz monzonite, granidiorite.

CPub – Carboniferous-Permian – serpentinite, diorite, pyroxinite, peridotite.

CPv – Carboniferous-Permian – andesite, basalt, chert, tuff.

Pc – Paleozoic – limestone, marble.

HЄsn – Handrian and Cambrian – schist, gneiss, quartzite.

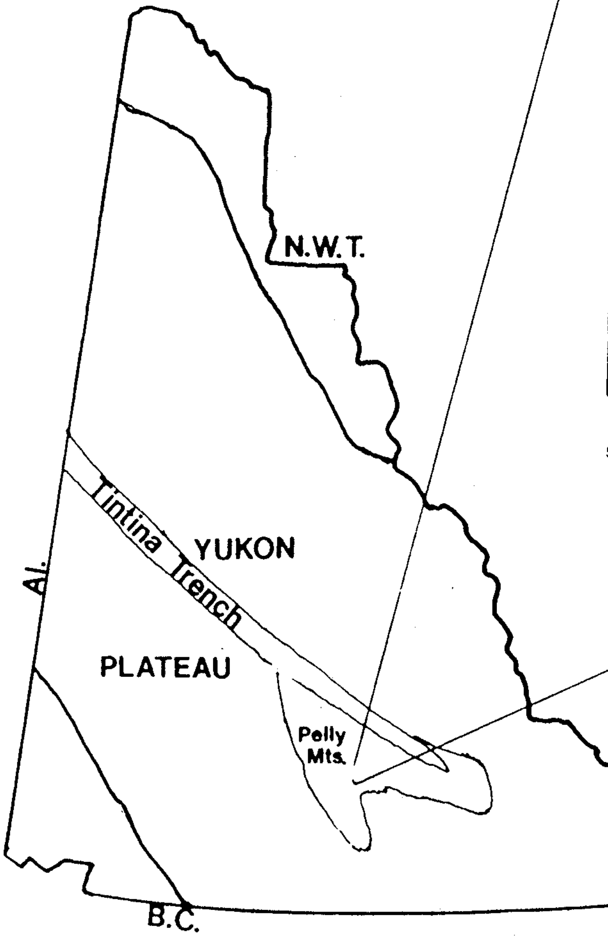


FIGURE 3.2 Physiography of the Studv Area
(Source: Bostock,1948.)

Mountain slopes are mantled with till. The general ice-flow direction during the last glaciation was to the northwest. In the southeast ice caps covered the mountain tops and flowed down large U-shaped valleys to the main ice body moving northwest down the Tintina Trench. In the northwest alpine glacier coalesced with the main ice body.

3.4 GEOLOGY

In general rocks of the Pre-Cambrian (?) Yukon group, consisting primarily of mica schists, micaceous quartzites, slates, marble, greywacke, greenstone, and andesite, intrusive stocks and batholitic masses of granite and grandiorite dominate the lithology in the region of the south Canol Road (Kindle, 1945). A belt of Paleozoics, 25 km wide, chiefly dolomites, limestone and shale, trends northwest across the Canol Road between kilometers 185 and 211. Steeply dipping, northwest trending faults are common. Within the drainage basin of Gravel Creek, Paleozoics dominate, though Gravel Creeks headwaters rise from an area of mid-Cretaceous quartz-monzonite plutons which post date regional metamorphism and deformation attributed to the Early Colombian Orogeny (Gabrielse et al.,)(Fig.3.3)

3.5 CLIMATE

The climate of the southern Yukon Territory may be classified as continental sub-arctic, and experiences extremely marked variability in both temperature and precipitation on a day to day and year to year basis. Winters are long and cold while summers are short and cool (Table 3.1). The Yukon Territory is located at the interface of Arctic anticyclones and subtropical Pacific westerlies, ensuring that changing weather systems dominate the area.

TABLE 3.1

Mean Monthly Temperatures, Amounts of Precipitation and Snowfall for Whitehorse

Whitehorse

	JAN	FEB	MAR	APR	MAY	JUNE
Temperature °C	-20.7	-13.2	-8.2	0.3	6.7	12.0
Precipitation mm	17.7	13.3	13.5	9.5	12.9	30.7
Snowfall cm	21.3	15.2	16.4	10.5	2.9	0.9

	JULY	AUG	SEPT	OCT	NOV	DEC
Temperature	14.1	12.5	7.5	0.6	-8.8	-16.6
Precipitation	33.9	37.9	30.3	21.5	19.8	20.2
Snowfall	0	0.8	4.5	16.1	23.8	24.2

Precipitation in the study area averages between 300-500 mm/yr. and decreases to the east. However, the dissected terrain greatly effects precipitation, and extreme local variability may result. Thus data from nearby class A weather station at Teslin and Whitehorse are not necessarily representative of conditions in the study area, particularly with reference to precipitation. Burn (1984) examined the correlation of temperature and precipitation records from a number of Yukon weather stations, using principal components analysis. The results indicated that temperatures correlate very well between groups of stations. However, precipitation showed no significant correlation.

The study area falls within the zone of discontinuous permafrost. The distribution of permafrost is affected by a number of factors including climate, elevation, aspect, vegetation cover, physical properties of sediments, surface water and groundwater. Permafrost extent increases from small isolated patches near the southern Yukon border to widespread continuous permafrost in the north (Brown, 1974). Permafrost may have a variety of effects upon the regions' streams including: increasing the proportion of surface flow to total runoff; retarding bank erosion in spring; and adding to the relative importance of block slumping of banks as a channel forming process. Observations made in the field through digging test pits did not indicate the presence of permafrost in the study area.

The Treeline generally occurs around 1200 m but varies due to local climate, slope, aspect, etc. Vegetation consists of whitespruce, lodgepole pine and aspen in well drained areas, and willow, black spruce and alder in those areas less well drained.

3.6 CORRELATION OF TEMPERATURE

The nearest weather station to the study area is located at the Quiet Lake maintenance yard 12 km south of Gravel Creek. The Quiet Lake station begins operation on April 19 each year and continues throughout the summer, although missing data are a frequent problem from this station. For this reason a surrogate measure of Quiet Lake temperature during the breakup season was required. Mean daily temperature as recorded at Quiet Lake was correlated with mean daily temperatures recorded at the Whitehorse and Ross River Class A weather stations. Data used in the analysis were those of of April, May, and June for 1981 and 1982. The results indicated a marginally better correlation between Quiet Lake and Whitehorse temperatures than between Quiet Lake and Ross River. Furthermore, there are no missing data in the Whitehorse A record, while Ross River A is missing data for the same periods in which Quiet Lake data is missing. Therefore, Whitehorse A data were used to estimate mean daily temperature at Quiet Lake when data were missing.

Correlation of mean daily temperatures at Quiet Lake and Whitehorse A yielded an R^2 of 0.827 at the 0.0001 level of significance. Thus, reasonable accuracy can be attributed to the Quiet Lake temperatures calculated through the derived equation:

$$Y = -1.76 + 0.98 X$$

where: X = mean daily temperature Whitehorse A.

Derived and measured temperatures are presented along with precipitation data for the breakup periods of 1981, 1982, and 1983 in Figure 4.1.

3.7 HYDROLOGY

Gravel Creek flows via the Rose, Nisutlin, and Teslin Rivers to the Yukon River. The flow regime of streams in the south-central Yukon are characterized by an annual spring flood created by snowmelt. Streamflows decline progressively throughout the summer, punctuated by occasional rain-storm flood events. In general, however, the spring freshet is the major hydrological event of the year (Verschuren and Bristol, 1974; Halket, 1985). Thus the significance of ice breakup as a geomorphic agent should be related to the time of its occurrence relative to the timing of the snowmelt flood.

3.8 THE STUDY SITE

Gravel Creek drains an area of 21.7 km^2 rising from two large U-shaped valleys trending NE-SW and SE-NW respectively. The greater portion of the study area is rugged and mountainous, and 57 % of the drainage basin lies above 4500 ft.

Two study reaches were identified: B-reach, a meandering reach of approximately 120 m length encompassing one full meander (Fig. 3.4); and A-reach, a relatively straight reach of approximately 90 m length encompassing three distinct pools and riffles (Fig. 3.5). Figure 3.6 displays the spatial relationship between the two reaches.

The straight reach is characterized by bank vegetation consisting almost entirely of willow and alder, whereas, vegetation on B-reach consists largely of blackspruce and some willow. It is possible that repeated occurrences of icing formation on A-reach has inhibited the growth of white and black spruce at this location.

The bed of both reaches of Gravel Creek consists of coarse gravel with a mean intermediate axial size of 55.9 mm. The entire area is underlain by glaciofluvial gravels and numerous abandoned late-glacial and Holocene channels were observed well above present stream level, suggesting that groundwater may be the water source of the icing. The banks of the channel are composed of fine-grained rich organic soil. The lower reaches of Gravel Creek, including the study site, are swampy suggesting the existence of an impermeable layer near the surface and/or a high water table.

Figure 3.4: B-Reach Configuration from the June 1981 Survey

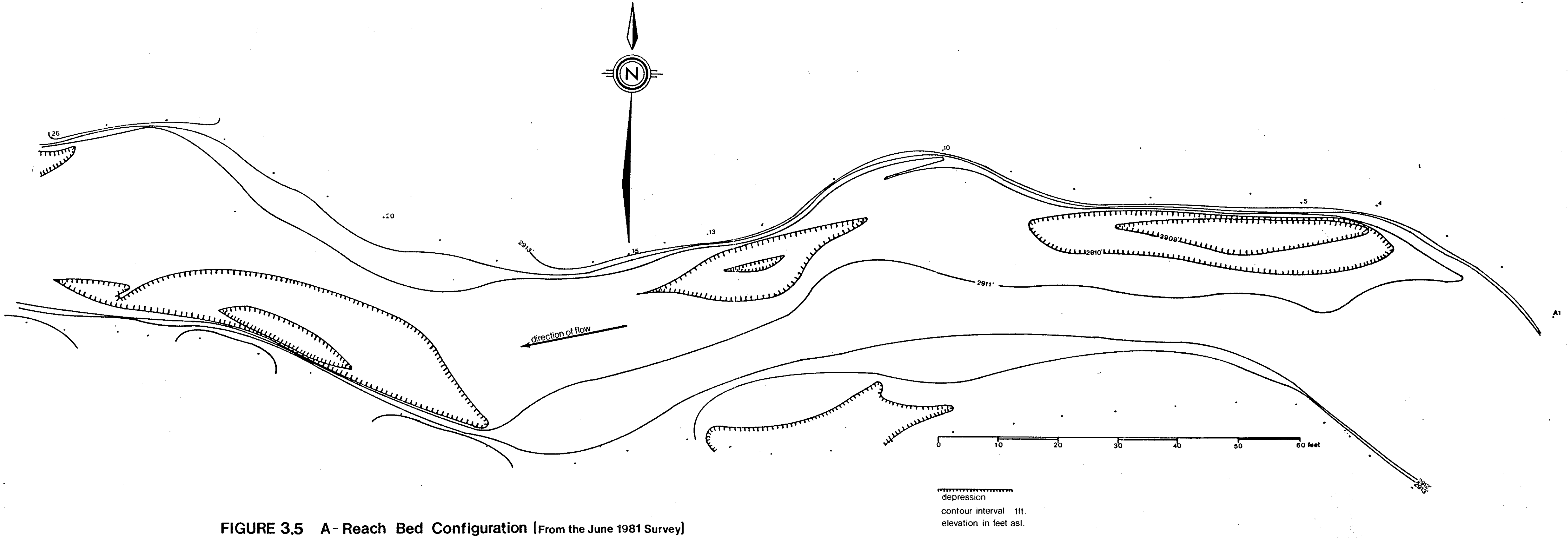


FIGURE 3.5 A-Reach Bed Configuration [From the June 1981 Survey]

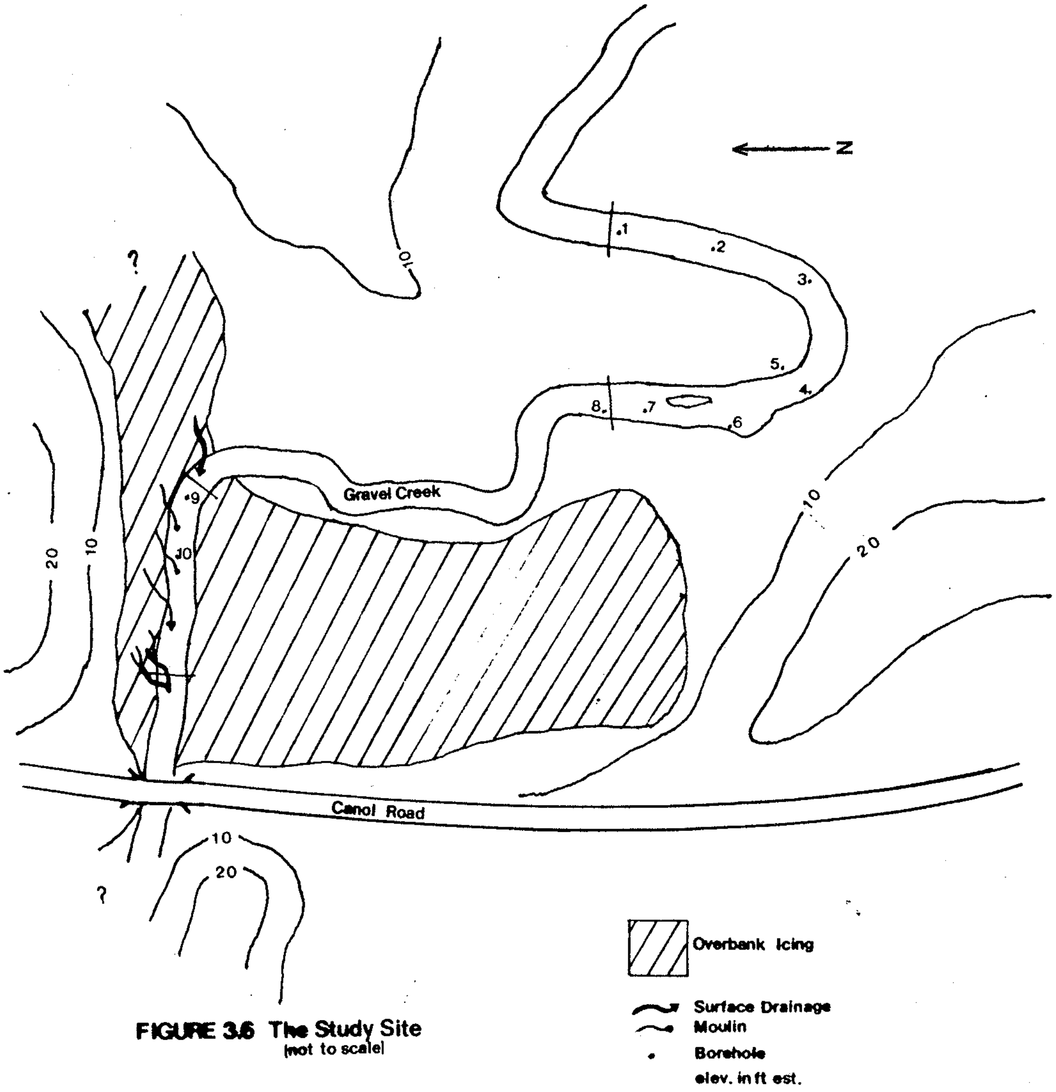


FIGURE 3.6 The Study Site
(not to scale)

3.9 FIELD METHODOLOGY

The most significant methodology employed in the study was the level survey conducted on the study reaches. During the field season of 1981 the study reaches were identified on Gravel Creek. Cross-sections were established upon both reaches at 10-15 ft intervals and benchmarks emplaced. Benchmark positions were surveyed using a Kern DKM1 theodolite. Individual cross-sections were then surveyed at one foot intervals. Using the information gathered through the channel surveys of 1981, base maps were constructed at a scale of 1:120, and later contour maps were constructed with a contour interval of 1 foot. Contour maps and surveyed cross-sections were to provide the bulk of the data collected. Surveys were conducted on both reaches again in 1982, and in 1983 B-reach alone was surveyed. During the 1982 field season surveys were conducted throughout the breakup period (B-reach only) in order to determine the bed configuration immediately after ice breakup and again after the waning of the snowmelt flood.

Prior to the breakup in 1982 it was noted that an extensive channel icing had developed on Gravel Creek and the adjoining valley flats. Boreholes were drilled through the ice to determine ice thickness, the presence of water, and whether or not water was flowing beneath the ice.

Bed material was sampled according to the methods described by Wolman (1959). A, B, and C-axes were measured and roundness determined. The individual particles were painted with a non-lead based paint, labelled as to cross-section, and replaced in the stream for tracer study.

Staff gauges were emplaced in a number of locations along the channel. As an automatic stage recorder was not available gauges were constructed to record instantaneous peak stage. The inner walls of hollow plastic tubes were coated with a thin water soluble paint, and affixed to staffs marked in inches and placed in protected locations along the stream. Thus, instantaneous peak stage was recorded by the removal of water soluble paint from the tube. Instantaneous stage was also recorded on a near daily basis during the snowmelt flood.

3.10 OBSERVATIONS

The breakup periods of 1981, 1982, and 1983 were spent in the field observing ice breakup and collecting data. During the field season of 1981 final site selection was conducted. As noted previously, observations of breakup on Gravel Creek prior to site selection indicated that the channel was not affected by icing. Breakup in 1983 preceded the field season, and upon arrival at the site on May 17 the channel was entirely free of ice and discharge was very low. The field season of 1982 (May 8 to June 28) however, presented an excellent opportunity to observe the entire breakup period, and ice breakup processes associated with it. The following, then, is an account of observations made during the 1982 breakup season.

The field season of 1982 began on May 8, and at this time the entire channel at both A and B reaches was covered with ice. Ice covered the adjoining valley flats in the vicinity of A-reach to a depth of 0.8 m. It was quite evident that the extent and thickness of the ice cover was not simply due to normal (primary) ice formation, but in addition that of channel icing development. The supposition that an icing had formed on Gravel Creek was confirmed on the evening of May 8. At approximately 8:00 p.m. a loud cracking of ice was heard in the vicinity of A-reach. Upon investigation, water was found to be fountaining through a crack in the ice cover near a surface drainage moulin. The event lasted only a few minutes, with water fountaining ten feet above the ice surface accompanied by the sound of air and water being released under pressure.

The extent and thickness of the ice cover was such that it was virtually impossible to locate the cross-sectional benchmarks emplaced along the two study reaches in 1981, and as a result attention was turned to the observation of the channel and surrounding areas.

It was noted that a small channel had formed 5 meters above A-reach on the right bank and was delivering water to the channel at a rate of approximately 5 cfs (Fig.3.6). The water had cut a channel in the ice surface for a distance of two feet and there descended through an ice tunnel to, what is suspected, the channel proper.

Downstream, near cross-section A-18, several small rivulets were flowing from the right bank area, across the ice surface, and into two moulins in the ice surface. The discolored ice surrounding these moulins was greater than one meter in thickness and the sound of running water could be heard from them, indicating that water was flowing within or beneath the ice cover (Fig. 3.7).

Upstream 400 meters from the top of A-reach, B-reach exhibited markedly less icing development. However, icing had developed within the channel to near the level of the channel banks. On the bar at cross section B-18-1 the icing was measured and found to be 50 cm thick. Boreholes drilled at various locations along the channel indicated ice thicknesses from 43 to 89 cm on B-reach, and greater than 1.1 m (the limit of the auger) on A-reach. Figure 3.6 displays borehole locations and Figure 4.4 exhibits ice thickness along B-reach.

As one progressed upstream from B-reach evidence of channel icing development became less apparent, and approximately 200 m upstream open water was first observed.

Figure 3.7: Surface Flow Draining into Moulin, A-Reach, May 9, 1982

From the initial point of open water, ice thicknesses were noticeably thinner (<50 cm) than those downstream, and open water stretches were encountered with increasing frequency. This trend continued until the entire channel was free of ice at a distance of approximately 1.5 km upstream of B-reach. Observations made upstream of B-reach indicated that riffle sections were the first areas of the channel, in a given reach, to open up. This was later confirmed on both A and B reaches.

Investigation downstream of the study sites revealed a continuation of the trends observed upstream. Downstream 40 m from A-reach a bridge of the Canol Road crosses Gravel Creek. At the bridge water was flowing on top of the channel icing and appeared to drain under the ice along the edge of the bridge structure. Water could also be heard flowing under the ice as well. Below the bridge the left bank of the channel abutted against an esker for a distance of 100 m. The valley flats along the right bank widened progressively from 2 m in width to tens of meters 100 m downstream. Approximately 300 m downstream from the bridge Gravel Creek entered the Rose River. The entire valley flat from the bridge to the confluence with the Rose River was covered in ice of undetermined thickness. However, observations made during breakup suggested ice thickness over the channel in excess of 1.5 m. Figure 3.8 displays the thickness of ice immediately downstream from the bridge.

Figure 3.8: View of Bankfast Ice Downstream from Bridge, June 5, 1985 (note layers)

Upstream on B-reach the pre-breakup period lasted only until May 10. A-reach, however, did not begin to break its ice cover until May 28. Prior to initiation of breakup B-reach displayed a slight subsidence of channel ice along its length. As well a large bowl-shaped depression began to develop in the vicinity of cross section B-7 on May 9 (Fig. 3.9). On May 9 the ice at the center of the depression was of sufficient thickness to allow a borehole to be drilled. Measurement through the borehole indicated ice thickness to be 58 cm with 22 cm of rapidly flowing water beneath the ice. A 10 cm air space separated the water surface from the

Figure 3.9: Sequence of Breakup at B-7, Depression May 10,1982

base of the ice. Semi-circular cracks marked the transition from the level ice surface to depression. By mid-day of May 10 the ice thickness at the center of the depression had been reduced to 43 cm, no air space existed, and water levels had risen to 23 cm. The base of the depression was now 67 cm below the level of the surrounding ice. The semi-circular cracks had expanded and new cracks had developed marking the zone where upper layers of the icing had separated from underlying ice strata. On May 11, another depression developed in the vicinity of cross-section B34. Both cross-sections B-34 and B-7 occur at

Figure 3.10: May 14

channel riffle sections. This observation suggested that the initiation of breakup resulted largely from the thermal erosion of the basal ice surface in zones of energy loss from the stream. By 7 pm of May 11 the depression at B-7 had collapsed considerably and a 1.2 m by 0.7 m patch of open water was present. Figures 3.9-3.13 display the sequence of breakup at this location from May 10 to May 27. Initially, the ice cover collapses into a bowl-shaped depression surrounded by roughly concentric semi-circular cracks. With increasing depression and/or increasing water levels the base of the depression erodes away, breaching the ice cover. The initial opening continues to enlarge through

Figure 3.11: Sequence of Breakup. Depression, May 10

the thermal erosion of ice by flowing water until all the ice of the initial depression has been removed. As can be seen in Figure 3.12, the ice surrounding the depression fails in the manner of a beam along the concentric cracks. When the ice of several depressions have been removed, a series of ice bridges remain separating the open water reaches. The ice bridges tended to fail parallel to the channel, again with beam failure of the ice, resulting in a vertical sheet of ice laying against the channel banks in these areas (Fig. 3.14).

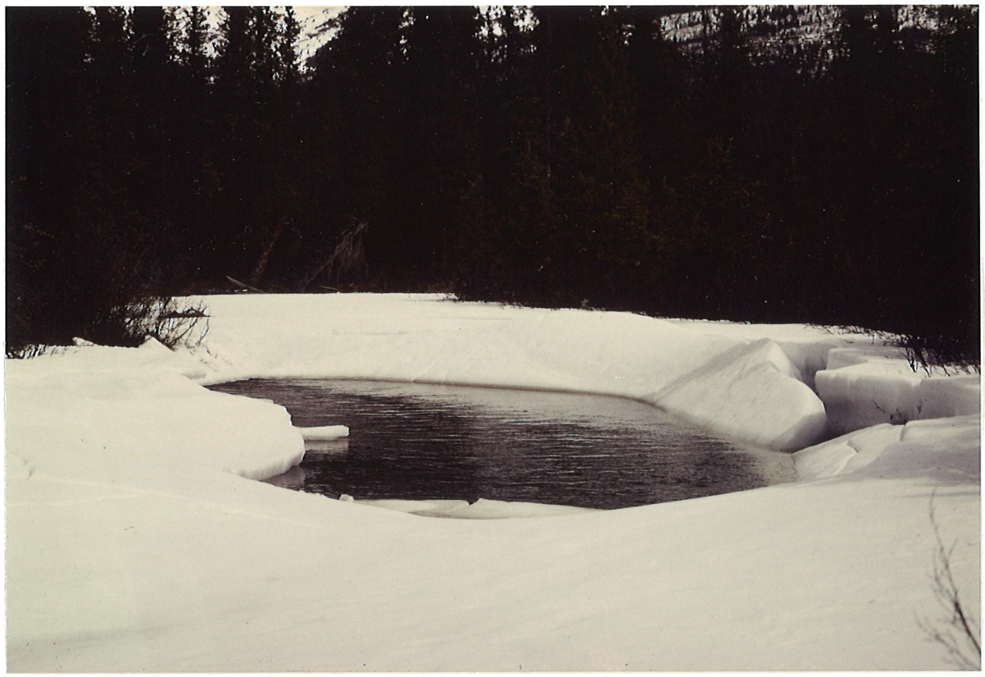


Figure 3.12: May 20

The initial depression at B-2 was entirely free of ice by May 27. Subsequent depressions at B-32, B-14, and B-25 opened and became free of ice as indicated in Table 3.2

While the breakup period on B-reach proceeded slowly, breakup was not initiated on A-reach until May 27 and then proceeded at a very rapid rate. Observations on A-reach from May 9 to May 27 suggested, on the surface, that little change was taking place. On May 13 it was noted that surface flow on A-reach had decreased and had virtually stopped by May 20.

Figure 3.13: May 27

By May 25 the ice surface of A-reach had been reduced by 0.3 m and on May 26 the first depression developed on A-reach at A1-1. Depressions developed on A-reach had generally steeper slopes and were V-shaped as opposed to the smooth bowl-shaped depressions of B-reach. By May 28 the depression at A-1 was open and a new depression had developed rapidly near A-24-26; the sound of the ice surface collapse could be heard 300 m away on B-reach at 2:45 p.m. Upon investigation the ice in the vicinity of A-24-26 was found to have dropped more than 1 m. Figures 3.15-3.18 display the sequence of breakup at this location and Table 3.2 documents the A-reach breakup season.

Figure 3.14: Ice Protecting Channel Banks

TABLE 3.2

Chronology of Breakup, 1982

	B-Reach	A-Reach
May 8	Both reaches ice covered	
May 9	Depression develops near B-7	
May 11	Depression develops near B-32, B-7 open	
May 12	Depression develops near B-15	
May14	Depression at B-7 enlarged to B12	Flow on ice surface noticeably reduced
May 19	Depression at B=32 open	
May 15	Depression at B-15 open	
May 23	Open water from B-1 to B15 Depression develops near B-25	
May 24	B-reach open from B-1 to B-16 and B-31 to B-24	
May 26	Continued erosion of ice bridges	Depression develops near A-1
May 28		A-1 open, depression at A-10 opens
May 29		Rapid depression near A-25 opens at 2:55 pm
May 30	B-reach free of ice	
June 2		A-reach free of ice

Figure 3.15: May 29, 2:55 pm (Sequence at A-24-26)

Figure 3.16: May 29, 4:00 pm

Figure 3.17: May 30

Complete opening of the channel on B-reach occurred on May 30 and A-reach on June 2. At this point open water existed along both study reaches. However, a significant amount of ice remained fixed to the channel bank as illustrated in Figure 3.18.

Figure 3.18: June 2

3.11 OBSERVATIONS ON ICE EFFECTS

The geomorphic effects of ice breakup observed during the 1982 field season consisted of both direct and indirect effects. Direct effects were most evident on A-reach where ice breakup proceeded at a much more rapid rate.

The most significant direct effect of ice observed was the beam failure of bank materials frozen fast to the channel ice. On B-reach thin veneers of organic material were observed frozen to bank ice that had pulled away from the bank well after failure (Figure 3.19). However, on A-reach, rapid ice failure along the channel banks incorporated large slabs (20 cm x 2 m) of bank material at cross-sections A-4 and A-13. Figure 3.20 and 3.21 display the mode of ice failure (beam) and the resultant bank material removed. It is possible that this effect of greater magnitude on A-reach, is the result of icing formation. This will be one focus of the following chapter.

As noted previously the breakup season on B-reach spanned a much longer period of time than breakup on A-reach. As a result, bank fast ice on B-reach generally slowly melted away. This was not without possible effects, however. The ice on B-reach resting vertically against the channel banks may have protected the banks as discharge increased (Fig. 3.15). Furthermore, ice blocks occasionally broke free and floated gently downstream until grounding in the shallow riffle zone of B-23. Figures 3.22 a and b display one such event. In the photographs the hydraulic head is evident between the downstream flow and upstream dammed flow. Also visible are small standing waves downstream and to the right of the obstruction. Observations at the site include scour upstream of the obstruction and on one occasion a cobble of 8 cm imtermediate axial size rolled over 1 m through the channel of the locally increased velocity.

Observation at the confluence of Gravel Creek and the Rose River on May 29 indicated that a large mass of ice was blocking the entire depth and breadth of the channel at the mouth. This resulted in the ponding of backwater on the

Figure 3.19: Veneer of Organic Material Pulled From Bank By Ice at B-16

Figure 3.20: Failed Ice Slab with Bank Material (A-4-right bank)

Figure 3.21: Material Removed as a Result of Failure shown in 3.20

valley flats to the right of the channel. The ponded water had eroded two deep, narrow channels to the Rose River which terminated in small unstable Gilbert-type deltas. No flow was visible at all within the main channel. Subsequent investigation of this site during the field season of 1983 indicated that all flow was delivered to the Rose River through the main channel and that the base levels of the auxiliary channels were well above that of the main channel of Gravel Creek.

Water levels rose throughout the breakup period and continued to rise until they peaked on June 8, 1982. This,

Figure 3.22: Grounded Ice Pan B-22

Figure 3.25: Flood Stage 1982

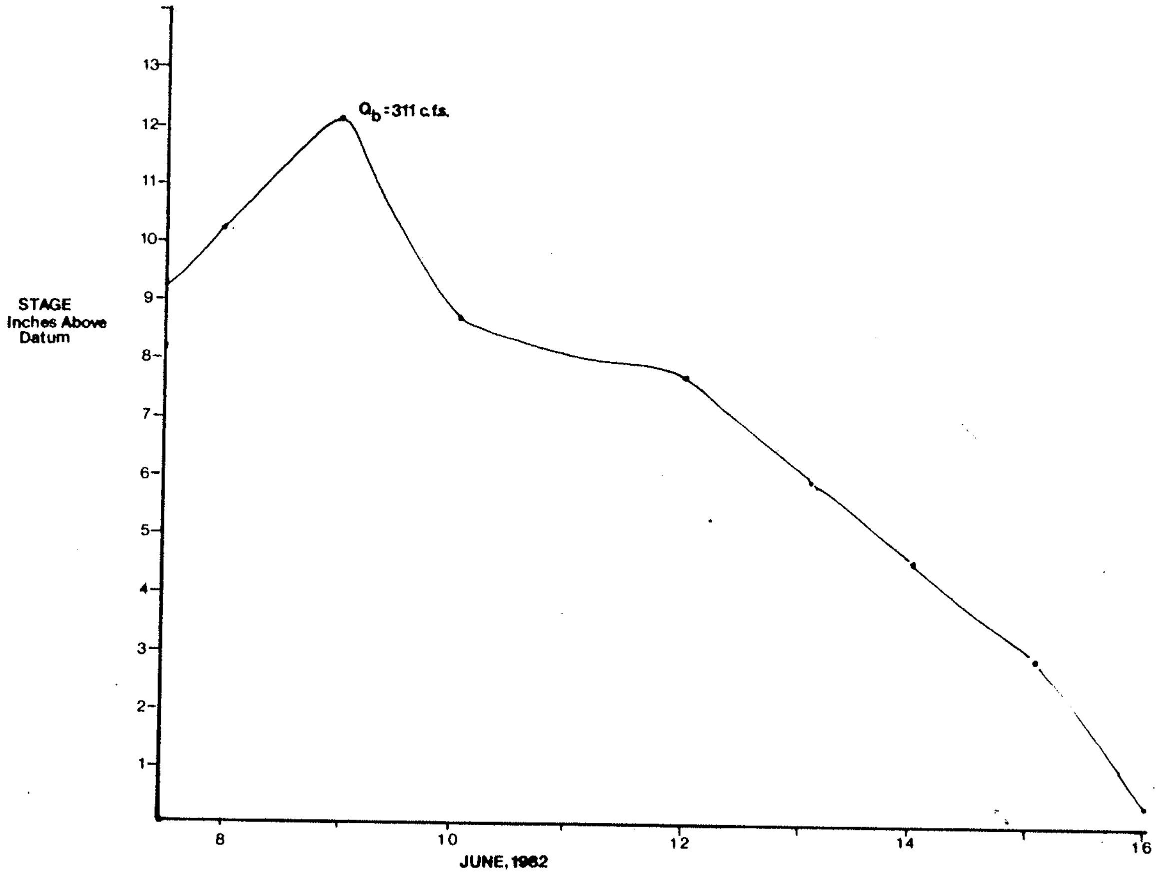


FIGURE 3.23 Flood Stage 1982

Figure 3.24: Near Bankfull Flows, June 9, 1982

Figure 3.25: Low Flows, May 22, 1983

3.12 SUMMARY

The field season of 1982 provided the only real opportunity to observe the ice-breakup processes on Gravel Creek. The extreme variability of Yukon weather and therefore, the accompanying variability of icing formation on Gravel Creek contributed to the complete mistiming of the 1983 field season. Furthermore, a marked reduction in research funds seriously curtailed the length of the study season, thus reducing the margin for error in research timing. Thus, the 1983 season was almost a complete loss.

During the 1982 field season breakup and breakup effects were observed to be markedly different on the two study reaches. B-reach began to break up much earlier than A-reach and as a result the breakup phase on B-reach covered a span of 19 days. A-reach however underwent a delayed rapid breakup spanning only five days. The observable effects of breakup on B-reach were by and large minor and in the majority consisted of ice protecting the channel banks from erosion, whereas the observable effects on A-reach were greater.

At this point in the discussion, considering only the observations made in the field it would appear that the delay in the breakup of A-reach was largely due to the vertical extent of icing development on that reach, and that the rapidity of ice failure that resulted was responsible for the more striking ice effects on A-reach.

The importance of channel form (i.e. straight, meandering) in terms of the above is indeterminate at this point.

3.13 POST FIELD METHODOLOGY

The data collected during the field season of 1981, 1982, and 1983 were analyzed both cartographically and statistically. By and large survey data were analyzed cartographically, while tracer rock data were analyzed statistically. The following discussion outlines the methodology employed in all phases of the analysis and concludes with a short discussion of sources of error.

3.14 CARTOGRAPHIC ANALYSIS

Data collected from the initial survey was used to produce working base maps at a scale of 1:120. Elevations in feet above sea level were calculated for all survey points and transferred to the base maps. Contour maps were then constructed at a contour interval of one foot. Cross-section diagrams were then produced for all surveys of both reaches using the Sasgraph plot procedure (Appendix A). Differences in bed elevation between the two cross-section surveys were calculated such that the signs "+" and "-" indicated deposition or erosion, respectively, at survey points. These were then used in constructing cross-sections of change, again using the Sasgraph plot procedure (Appendix B). From these cross-sections it appeared that the direction of change (i.e. erosion/deposition) at a point or over a series of points was spatially homogeneous. Contours of the amounts of change at intervals of 0.15 feet were constructed. Figure 4.9 displays the amount and location of erosion and deposition that occurred between the original survey of 1981 and the post-breakup survey of May 28 1982 at B-reach. Figure 4.10 shows the record of erosion and deposition between the post-breakup survey of May 28 1982 and the post-flood survey of June 22 1982; and Figure 4.11 shows the record for the period between the post-flood survey of 1982 and the only survey of 1983. Only two surveys were conducted on A-reach, (1981-1982), and therefore only one measure of change is available, (Figure 4.12). From the four contour maps describing net changes of erosion and deposition along the two reaches, volumes of material eroded and deposited were calculated.

3.15 STATISTICAL ANALYSIS

The movement of tracer rocks was analyzed using stepwise multiple regression in order to determine if particle movement was significantly related to selected particle and flow characteristics. As no measure of initiation of motion was available, distance travelled was used as the dependent variable. (See Fig. 3.26). Independent variables included the particle parameters of maximum intercept sphericity, flatness, roundness, and b-axis diameter and the flow parameters of critical dimensionless shear stress and flow depth. Independent variables are described in Table 3.3

For the regression analysis 150 bed particles from B-reach cross-sections 1 through 8 were used. These particles were chosen for the following reasons. First, they display great variation in distance travelled. Second cross-sections B1-B8 represents a straight reach with relatively constant cross-sectional area and shape, thus

Figure 3.26: Plan View of Paths and Distances of Tracer Particle Movement

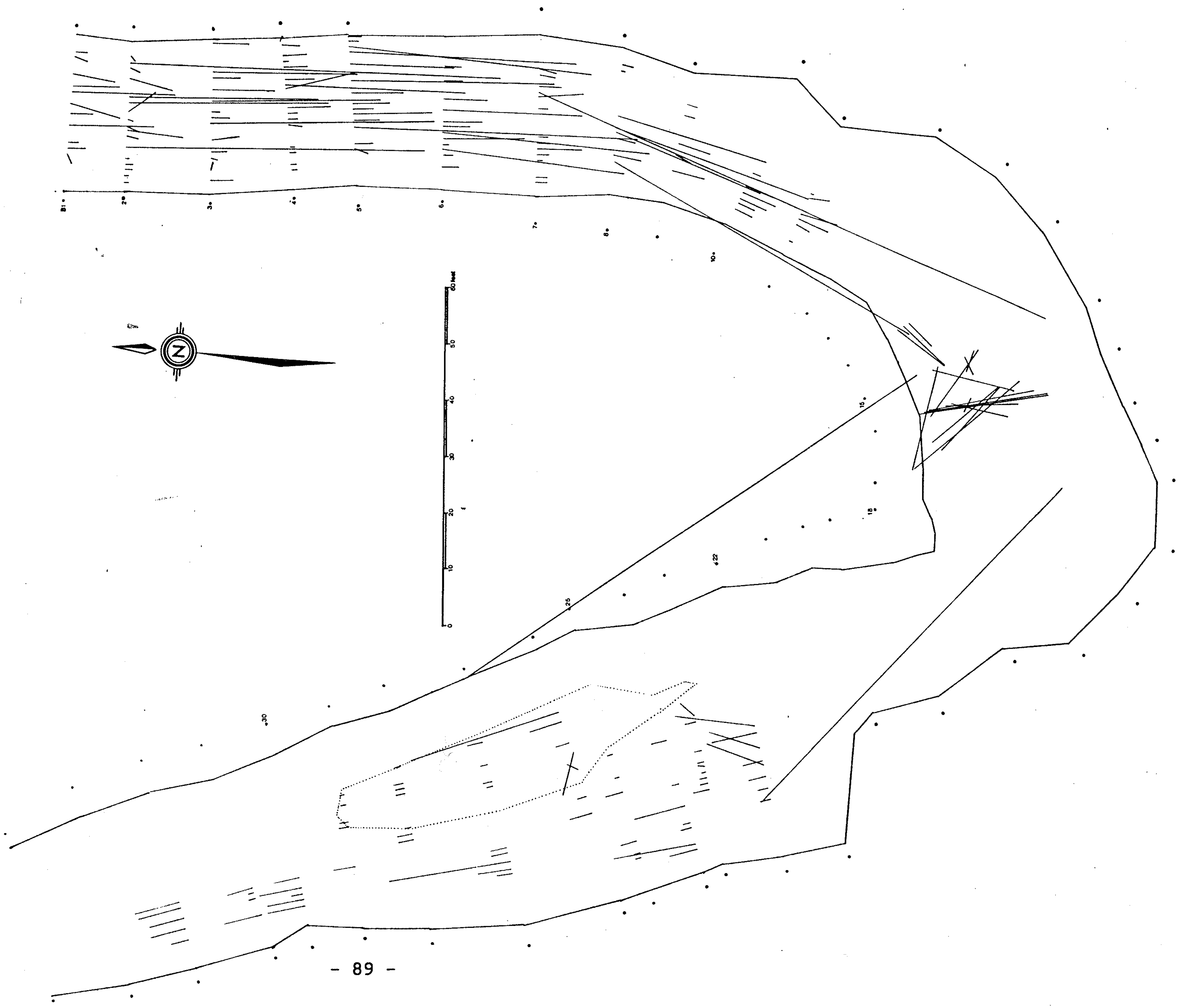


TABLE 3.3

Independent Variables Entered in Tracer Analysis

Variable	Symbol	Unit	Means of Calculation	
Independent Intercept Sphericity	SPH	Dimensionless	$\sqrt[3]{\frac{bc}{a^2}}$	Krumbein (1941)
Flatness	F	Dimensionless	$\frac{a+b}{2c}$	Wentworth (1922
Roundness	R	Dimensionless	Krumbeins's (1941) chart	
Intermediate axial length	b	L, mm		
Critical Dimensionless shear stress			$\tau_i/\{(\gamma_s-\gamma_f)d_i\}$	Andrews (1983)
Depth	D	L, mm	Field Measurement	

reducing any possible effects due to channel assymmetry. Finally, staff gauges located at cross sections B1 and B8 allowed for the accurate determination of water surface slope.

3.16 CALCULATION OF DISCHARGE

Bankfull discharge was calculated using the Manning-Limerinos formulae to determine velocity.

$$V = \frac{1.49}{n} R^{067} * S^{05}$$

$$n = \frac{.113\ R^{0167}}{1.16 + 2.0 \text{ Log } (R/D_{84})}$$

where: R = hydraulic radius (ft)

$S =$ water surface slope (0.0037) (dimensionless)
$n =$ Manning roughness coefficient (dimensionless)
$D_{84} =$ characteristic bed particle size (ft) of the 84th percentile.

The value of D_{84} was calculated along with other descriptive statistics of particle characteristics and these are presented in Appendix D. B-reach cross-sections 1 through 8 were selected for discharge determination due to the fact that this reach is very straight and cross-section profiles are relatively constant. Cross-sectional areas were calculated for all eight cross-sections and the mean cross-sectional area determined (64.89 sq ft). While this reach does not satisfy all the criteria suggested for the estimation of discharge by the Manning-Limerinos equation, it was the most suitable reach on Gravel Creek during the snowmelt flood as it was completely free of ice.

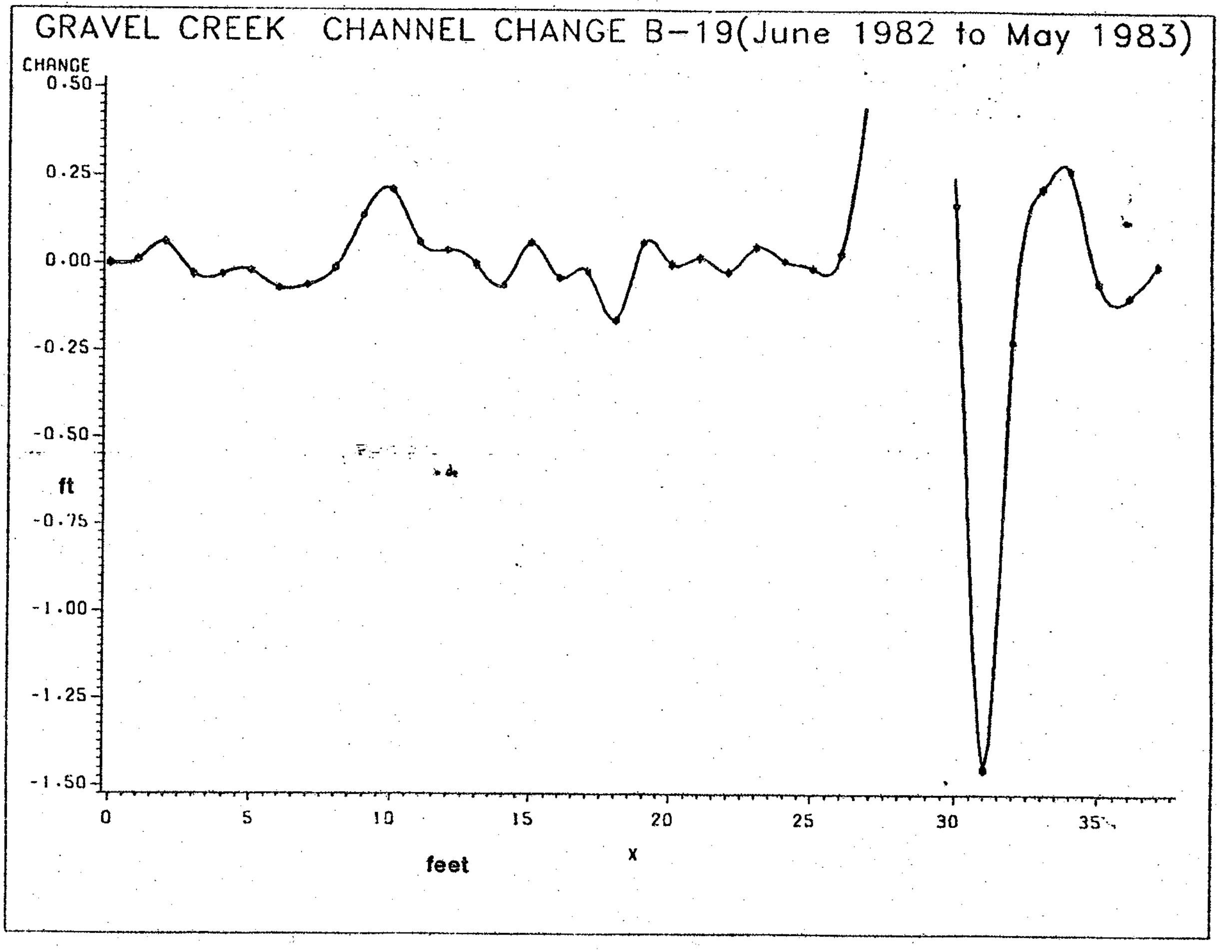
In addition to the Manning-Limerinos formula, surface floats were used to determine mean flow velocity. A series of float runs were timed over distances of 50 and 80 feet and a mean velocity was determined. Gardiner and Dackombe (1983) suggest that to determine mean velocity from surface floats a conversion factor of 0.8-1.0 be used, with higher values employed for smooth beds. As the float runs were conducted at near bankfull stage and flow was turbulent, a conversion factor of 0.8 was employed. Results of the converted float velocity runs compare very favorably with those of the Manning-Limerinos method, and exhibit less than one percent variation.

3.17 SOURCES OF ERROR

A number of error sources were identified during the course of the study, the most significant of which involve the level survey. In order to control for variation of instrument height, cross-sectional benchmarks were assumed to be constant. Thus, all surveyed points along a cross-section were measured relative to the position of the benchmarks. This was particularly important during the post-breakup survey of 1982 on B-reach which was conducted over a period of ten days. With the instrument situated at one location over such a long period of time, particularly during the melt season, it was inevitable that some settling occur. As a result continuous leveling of the instrument was required, thus greatly increasing the time required to survey the reach. However, the identification of benchmarks as constant should effectively remove any error due to instrument settling.

During the course of the level survey, positioning of the rod along the cross-section displayed the potential for significant error near vertical banks. While great care was taken in positioning the rod at the appropriate point along the cross-section, results of the between survey changes indicated great variation in measured elevations near vertical banks. Figure 3.27 displays an example of this effect, which is by no means unique. Examination of the cross-section diagrams in Appendices A and B clearly display

Figure 3.27: Example of Measurement Error Near Vertical Bank



the changes in measured elevations on steep and vertical channel banks. This problem was further compounded on A-reach, when the tape connecting paired benchmarks stretched, further altering the position of the rod when readings were taken. As such, measured elevation near vertical banks on A-reach display even greater variation than those on B-reach. As a result of this particular problem, readers should be cautioned against attaching any significance to elevation changes measured near steep or vertical banks. During construction of the contour maps of change, values of change measured near vertical banks were ignored. As such, the survey results measure bed changes only. This is unfortunate, as it results in the loss of important data concerning bank erosion particularly on A-reach where significant bank failure occurred.

Finally, some error was introduced to the survey simply as a result of the interaction of flowing water and the mechanics of conducting channel bed surveys. The placement of the survey rod on the channel in some cases initiated scour through flow separation, resulting in higher than actual readings, and hence lower elevations. Observations in the field indicated this was not a frequent occurrence and every attempt was made to prevent this from occurring. When it did occur, scour was generally limited to 0.1 ft.. To account for this and minor variations in rod placement a contour interval of 0.15 ft. (approximately equivalent to the mean c-axis size of bed particles) was used for all contour maps of change, and variations in bed elevation between 0.15 and -0.15 are not included in the analysis.

Chapter IV

RESULTS AND DISCUSSION

4.1 PREAMBLE

The thesis to this point has outlined the nature of river ice processes, the gaps in current knowledge, and the methodology employed in this study. The following discussion will present the results of this study, and then discuss their merits in light of previous research.

4.2 RESULTS OF LEVEL SURVEY

Results of the level survey are presented graphically in cross-sectional diagrams and cross-sectional change in Appendices A and B. Table 4.1 displays the measured volumes of bed material eroded and deposited between surveys and the net change incurred. Table 4.2 displays the channel morphological characteristics necessary for discharge determination.

TABLE 4.1

Volumes of Material Eroded and Deposited (in cu. ft)

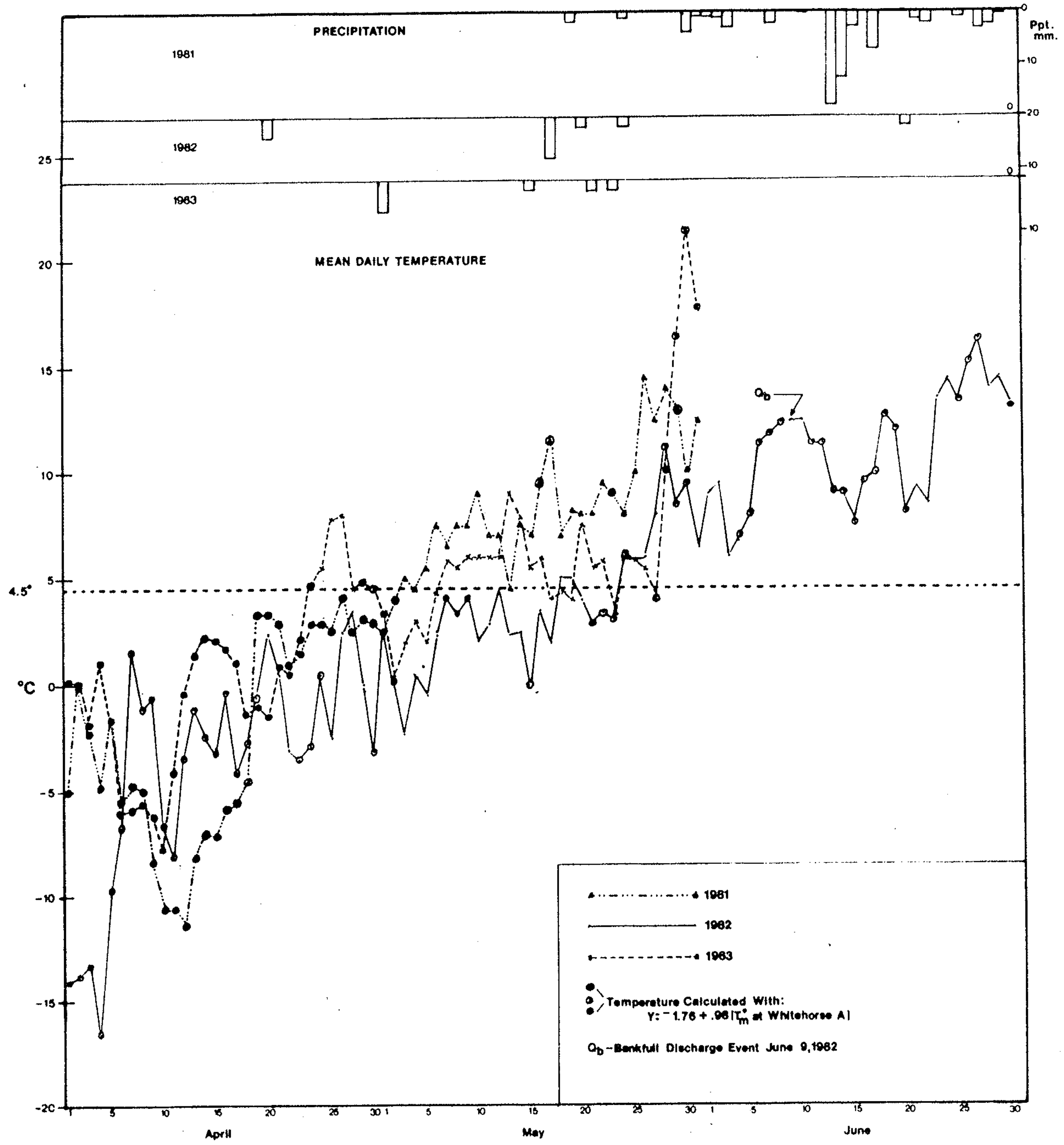
Surveys	Erosion	Deposition	Total	Net
May 1982	406.95	360.60	767.55	-46.35
June 1982	239.25	523.05	762.30	283.80
May 1983	201.45	170.55	372.00	-30.90
June 1982 A-Reach	338.70	228.00	556.70	-110.70

TABLE 4.2

Characteristics Used in Discharge Determination

CROSS SECTIONAL AREA ft^3		AVERAGE	SLOPE B1-B8	VELOCITY ft/sec	Q cfs
B1	67.30			4.84 – floats	314.07
B2	62.75	64.89	0.0037		
B3	67.93				
B4	64.51			4.80 – Manning	311.47
B5	63.15				
B6	57.30				
B7	67.38				
B8	68.80				

FIGURE 4.1 Quiet Lake Mean Daily Temperature and Precipitation 1981,1982,1983.



4.3 TRACER ROCKS

Figure 4.2 displays the paths and distances of tracer rock movement initiated by the near bankfull flood event of 1982. Results of the regression analysis of dependent variable distance travelled and independent variables maximum projection sphericity, flatness, roundness, b-axis size, critical dimension-less shear stress, and depth yielded an R^2 value of only 0.076, significant at only the 0.15 level of significance. These results were not however unexpected, as Neill and van der Giessen note: "In any channel a wide range of combinations of depth and mean velocity is possible, all producing the same mean bed shear stress (tractive force)"(1966,p.285). The calculation of critical dimensionless shear stress (Andrews, 1983) used in this study is a function of shear stress as calculated using mean water surface slope. Observation of turbulent flow indicates that a variety of slopes exist within the flow, reflecting local variations in velocity and depth. These local variations are, more than likely, responsible for initiation of local particle movement. Furthermore, Reid et al. (1985) note that the threshold of initial motion occurs at levels of bed shear stress three times those of final motion. Thus, no clear relationship between distance travelled and the independent variables describing particle characteristics can be expected. This lack of applicability of bedload equations in current use to gravel bedded streams

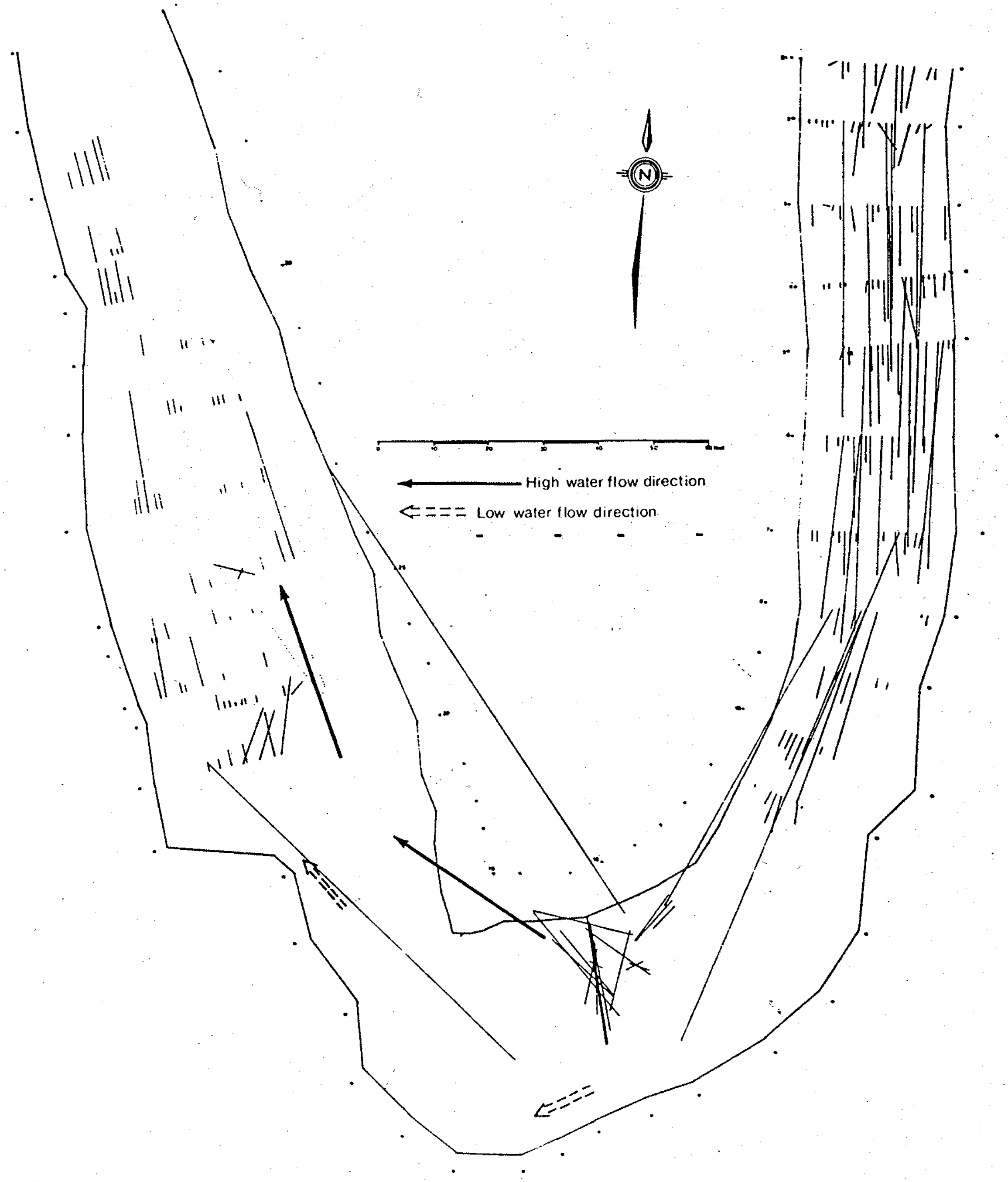


FIGURE 4.2 Plan View of Paths and Distances of Tracer Particle Movement [in response to Bankfull Q June 9,1982.]

has prompted some researchers to suggest alternative solutions. Recently, Mosley (1978) and others have suggested that the bedload of steep gravel-bedded streams in New Zealand travels as a wave. In this case the sediment is supplied to the stream in episodic pulses following severe storms. Meade (1985) and Reid et al. (1985) also noted the wavelike pulses of sediment while studying streams in the U.S. and U.K., respectively. Their findings are presented in the following discussion and the results of the level survey discussed in light of this.

4.4 DISCUSSION

Observations made during the course of this study indicated that a significant channel and overbank icing had formed along A-reach on Gravel Creek during one year only (1982) of the three year study. Based upon observations of breakup and cartographic analysis of the surveys it is apparent that the presence or absence of a channel icing impacts significantly on the geomorphic effects of ice breakup on Gravel Creek.

It has been shown, through description of breakup in 1982, that presence of a channel icing delays the breakup process, and that the length of delay is related to icing thickness. The following discussion will focus on the manner in which the ice cover was removed from A- and B-reaches during 1982, with a view to explaining the observed and measured geomorphic effects.

4.5 BREAKUP

As noted previously, the initiation of ice cover destruction centered over riffle sections, and in general proceeded in a downstream direction. It has been hypothesized (Ashton, 1978) that a significant factor in the initiation of breakup is the loss of stream energy as heat in areas of turbulent flow. Furthermore , and perhaps more importantly the transfer of stream heat is most rapid in areas of turbulent flow. As the snowmelt progresses warmer groundwater enters the stream more rapidly and increases the hydaulic head. Michel (1972) notes that increasing discharge is also a significant event in the initiation of river ice breakup. Therefore, as discharge increases and, consequently, stream energy, so should the accompanying loss of this energy as heat, thus increasing the rate of melt at the ice undersurface.

Figures 4.3 and 4.4 illustrate the longitudinal bed profiles of A and B reaches: indicating the points and dates of initiation of ice cover destruction; original ice thickness; water depth; and ice cover-water surface air space where measurements were possible.

The initiation of breakup in this manner produces a series of bowl shaped depressions centered over riffle sections separated by ice bridges of relatively uniform thickness. Similar observations of icing breakup have been reported by Froehlich and Slupik (1983) who attributed the melt at the ice undersurface to points of groundwater emergence, a feature which appears to be absent along

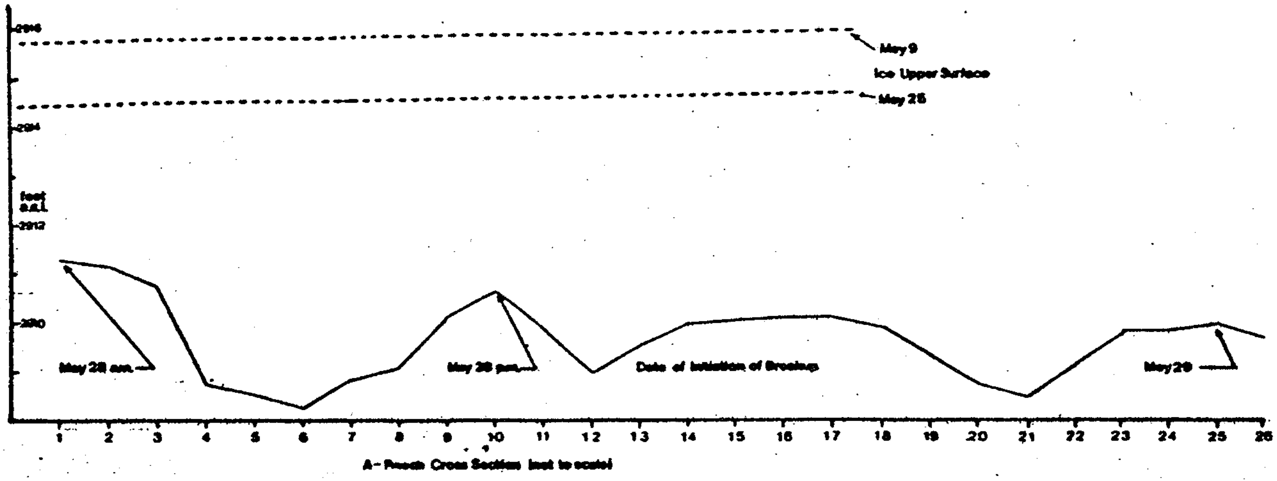


Figure 4.3: A-Reach Longitudinal Bed Profile (Showing date and point of iniation of breakup

reaches of Gravel Creek.

From the observations made in the field it is apparent that the rate of ice surface depression over riffles was significantly slower on B-reach than on A-reach, where depression was often almost instantaneous. In fact the initiation of ice cover destruction on A-reach resembled more a failure in the ice cover's ability to support its

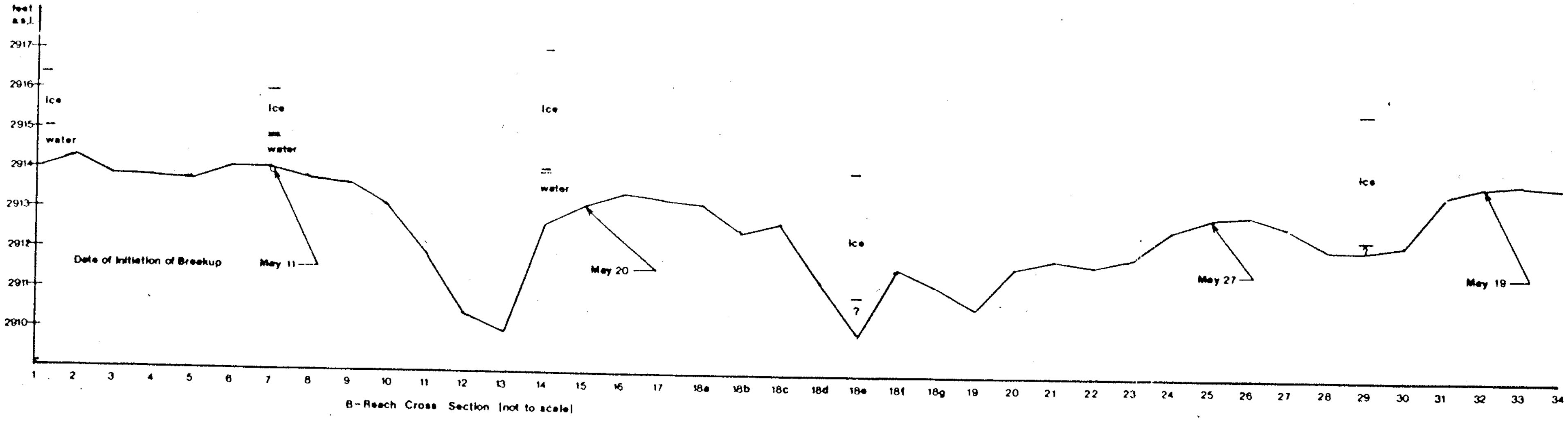
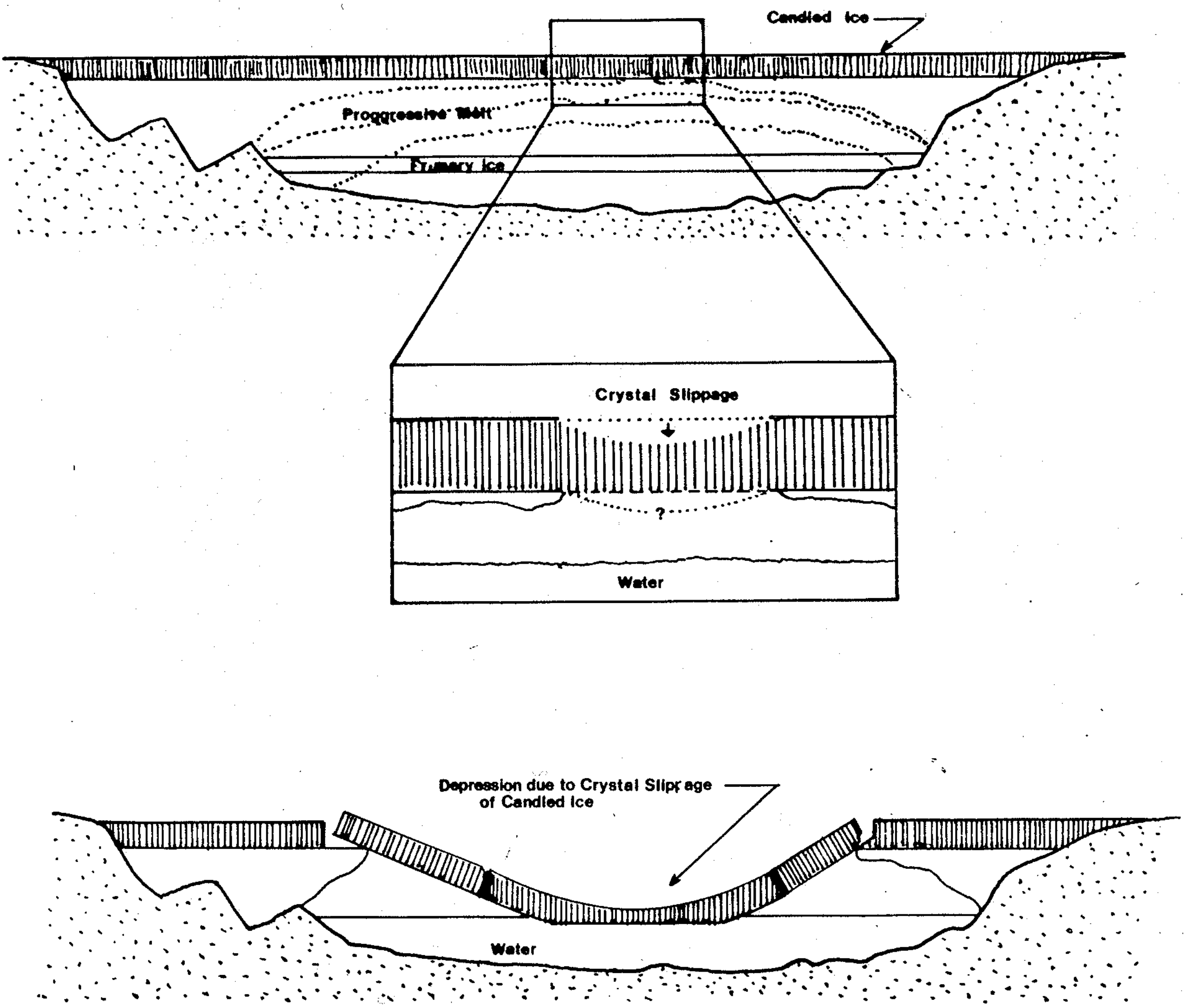


Figure 4.4: B-Reach Longitudinal Bed Profile (Showing date and point of initiation of breakup

weight rather than a slow depression. This can be explained in terms of the relationship between the respective melting rates of the upper and under surfaces of the ice cover. Observations and measurements made in the field indicated that melting of the upper ice surface was taking place, though much more slowly than at the under surface. The major effect of the surface melt was the gradual and uniform lowering of the upper ice surface. At the same time the under surface is melting at greater rates at riffle sections. Once the melting of the ice cover has begun on both surfaces the ice mass essentially becomes an isothermal slab making description of energy flow through the system very difficult (Ashton, 1978). While a discussion of this is beyond the scope of this study, the changes that occur to the ice cover at this point are considered by the author significant to depression formation. Once the isothermal condition exists the ice melts preferentially parallel to the c-axis of ice crystals, producing the effect known as candling. The process of candling, as observed on Gravel Creek, is somewhat complicated by the stratified structure of the channel icing, with decreasing degrees of candling being displayed in lower strata. Whether candling induced by under surface melt increases upwards in the ice cover was not observable.

It is hypothesized that the ice surface remains level until melt at the undersurface progresses to an ice state displaying an unknown critical amount of candling relative to the weight of the overlying ice. At this point minute slippages occur along the ice-crystal planes paralleling the c-axis. The sum of these slippages over time and space produces a depression at the upper surface, which is in effect a mirror image of the ice undersurface prior to slippage. Towards the periphery of the depression where melt at the ice undersurface is reduced, slippage does not occur. Rather the ice undergoes a beam failure as presented graphically in Fig. 4.5 The only alternative explanation for depression formation is the simple beam failure of an ice

FIGURE 4.5 Hypothesized Manner of B-Reach Breakup



cover no longer able to support its own weight. This cannot, however, explain the smooth bowl shaped depressions, and would in fact have produced steeply angled V-shaped depressions.

Significantly, depressions that developed on A-reach were steeply angled and often V-shaped (See Fig. 4.6) suggesting beam failure rather than crystal slippage as the operative

Figure 4.6: Depression at A-1-A-4 Displaying Sharp Angle of Ice Failure

depression forming process. It is suggested, in this case, that the critical degree of candling necessary to allow slippage to occur, lay in ice strata well above the minimum thickness at which the ice cover can support itself. Figure 4.7 displays the hypothesized manner of ice failure for A-reach.

To this point in the discussion no reference has been made to the effect of temperature on the breakup process. Figure 4.1 displays mean daily temperatures for the Quiet Lake station for the breakup periods of 1981, 1982, and 1983. From Figure 4.1 it can be seen that mean daily temperature began to rise above 4.5°C on May 24, 1982 and remained so for the duration of the field season. Sixteen days later peak flows occurred, after mean daily temperature rose above 11°C for four days in a row. During the period from May 16 to June 1 the surface of the ice at A-reach was reduced by 0.6 m. Breakup on A-reach began on May 26 and the entire length of the reach was open by June 2. From the preceding it is apparent that temperature plays a significant role in the initiation of ice breakup. However, this role involves more than the simple effect of melt of the surface ice cover.

Verschuren and Bristol (1974), from studies of snowmelt flooding on a series of small drainage basins near Watson Lake in the southern Yukon, found that peak flows are triggered by any period of three or four days in which the mean daily temperature rises above 4.5°C. Furthermore, they note that drainage basin elevation can significantly affect the timing of peak flows. This appears to be the case in

Gravel Creek, where 57% of the drainage basin lies above 1371 m(4500 ft) and 38% lies above 1524 m (5000 ft). The elevation of the study reaches is 889 m (2917 ft). The temperature decrease with elevation, as calculated using the average environmental lapse rate of 0.65°C/100 m, is 3.24°C at 1371 m and 4.13°C at 1524 m. From this it is suggested that temperature as measured at Quiet Lake must exceed 4.5°C by these amounts for three to four successive days in order to initiate significant melt at these elevations. Thus, in 1982 peak flows, which occurred after four successive days where mean daily temperature exceeded 10°C, appear to be the result of melt above 5000 ft.

While the snowmelt in areas above 5000 ft. appears responsible for the peak flow event, melt occurring at lower elevations and hence lower temperature appears to be responsible for breakup. The manner in which air temperature most significantly affects breakup is through the introduction of progressively greater amounts of heat to the ice undersurface in the form of meltwater.

To this point the discussion has focussed upon the breakup of Gravel Creek in 1982, during a period of rising temperatures and discharges. The relationships between temperature, discharge and breakup have been examined, and the two observed manners of breakup explained qualitatively in terms of these relationships. The discussion will now turn to the nature of the geomorphic effects of breakup on A and B reaches, and their relationship to the manner of ice breakup.

4.6 EFFECTS

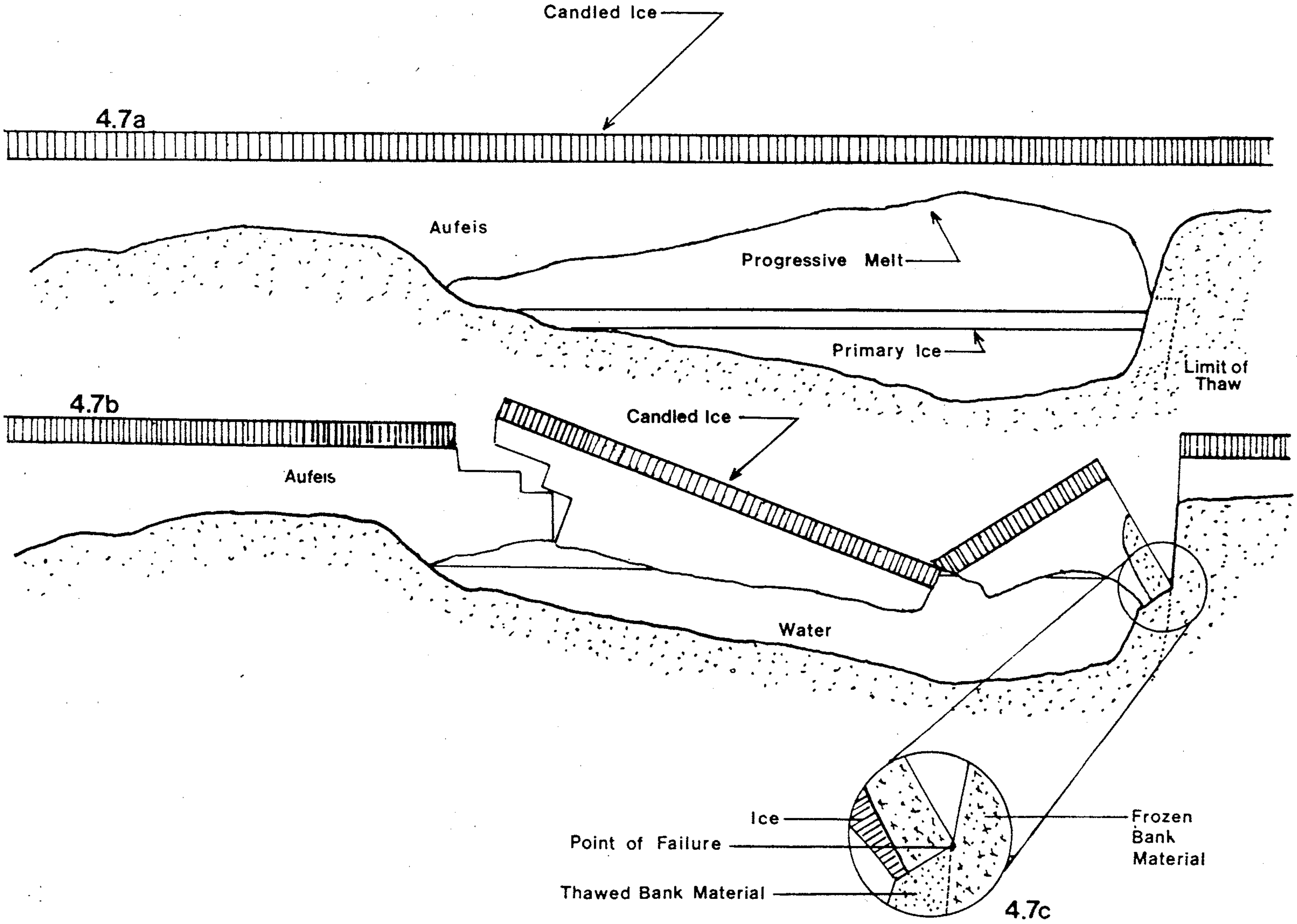
Observations presented earlier indicated that direct geomorphic effects of ice breakup on B-reach were essentially non-existent, whereas A-reach exhibited marked bank failure in two locations (A4 and A13). This can be directly attributed to the manner in which ice breakup occurred on the respective reaches, which is in turn determined by ice thickness. The gradual slippage that occurs paralleling ice crystal c-axes allows the ice undersurface to be supported and at the same time thermally eroded by water. As crystal slippage, once begun, appears to keep pace with melt at the undersurface, no significant failure can occur.

Conversely, the thick overbank icing development on A-reach resulted in the failure of the ice cover, which in turn resulted in the bank failure observed on the right bank at cross sections A-4 and A-13. Both these failures occurred in areas of vertical banks at the downstream end of depressions where depressions occurred very close (<4 ft.) to the right bank.

Essentially, the channel icing can be said to extend within the channel banks and is caused by bank saturation during icing events. During the breakup and pre-breakup period thawing of the channel banks can only occur from the underside, at a rate no faster than ice undersurface melt, due to the thick mass of icing overlying bank tops. The lateral penetration of thaw is not known. However, it is suggested that the point marked by the upper limit of thaw at its lateral limit of thaw is the point of failure of the overlying "icing" slab Fig.(4.7). At the moment the ice cover can no longer support its own weight, the weight is transferred to the thawed bank material directly under that slab. Being thawed and saturated the bank materials yield by compaction and slippage (Fig. 4.7c), placing the icing-bank material slab in the stress of tension centered at the point where the planes of thaw meet, thus producing the beam failure of the overlying icing-bank material slab (Fig. 3.20). The amount of material removed in failures of this type, is therefore directly related to the lateral and vertical progression of thaw.

The preceding discussion has presented the author's hypothesis of the manner in which the observed beam failure of bank material takes place. One alternative hypothesis is that of undercutting and subsequent failure in a manner similar to the above during breakup. However observations made in the field rule this out. Figure 4.8 clearly shows the step-like structure of the once vertical bank. Undercutting and subsequent failure would tend to produce a

FIGURE 4.7 Hypothesized Manner of A-Reach Breakup and Bank Failure



vertical bank whereas icing induced failure as described above would result in a step like bank profile (Note ice damage to cross-section peg).

The following discussion will focus on the changes of the channel bed as determined from the level surveys. Measured volumes of sediment eroded and deposited are presented in Table 4.1, which clearly indicates that the direction (i.e. erosion-deposition) of change incurred between surveys varies significantly. The measure of change between the initial B-reach survey of 1981 and the post-breakup survey of 1982 indicates that 46.35 cubic feet of bed material was removed from B-reach during that period, while between the post-breakup survey of 1982 and the post flood survey of 1982, 283.8 cubic feet of material was added to the reach. Examination of the spatial distribution of erosion and deposition, for these two periods (displayed in Figures 4.9 and 4.10) clearly indicates that erosion occurred in one survey where deposition occurred in the previous survey. In fact the observed reversal of depositional areas with those of erosion are nearly uniform from B-1 to B-24.

Figure 4.8: Step-Like Bank Produced by Failure at A-13

4.7 TEMPORAL AND SPATIAL VARIATION OF EROSION AND DEPOSITION

It is readily apparent from Figures 4.9 and 4.10 that deposition tends to occur as a series of wavelike sediment lobes along the channel bed. Zones of erosion are similarly discrete. More importantly, zones of erosion and deposition do not appear to be strongly related to locations of pools and riffles.

Using field survey techniques Meade (1985) studied the bed load transport of coarse sands and fine gravels on the East Fork River of Wyoming and found that bedload was transported in wavelike pulses of sediment that paralleled discharge pulses. During rising discharges bedload was scoured out of storage areas and transported onto and across riffles. As discharges waned, sediment was scoured off riffles and deposited in storage areas.

Similarly, Reid et al. (1985) noted pulses of medium to coarse grained gravel on a small stream in the U.K., and speculated that the pattern reflected the passage of kinematic waves of particles in a slow moving traction carpet. This was accomplished by the installation of a Birkbeck bedload sampler in the channel bed. They also noted however, that long periods of inactivity (low flow periods) led to some consolidation of the channel bed. As such, during the next flood event, bedload transport was largely confined to the recession limb of the flood wave.

Figure 4.9: Channel Change B-Reach June 1981 to the Post-Breakup Survey May 1982

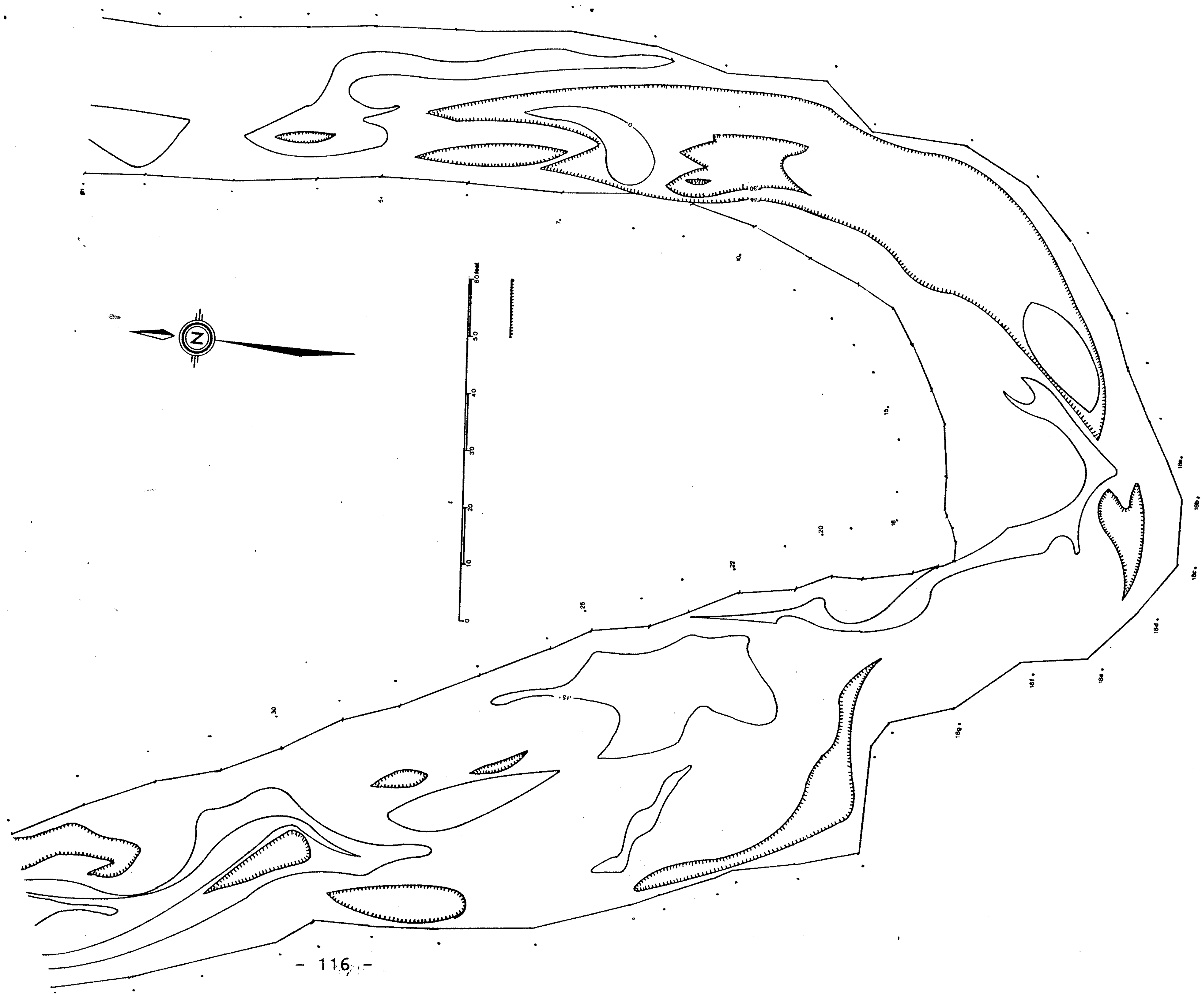
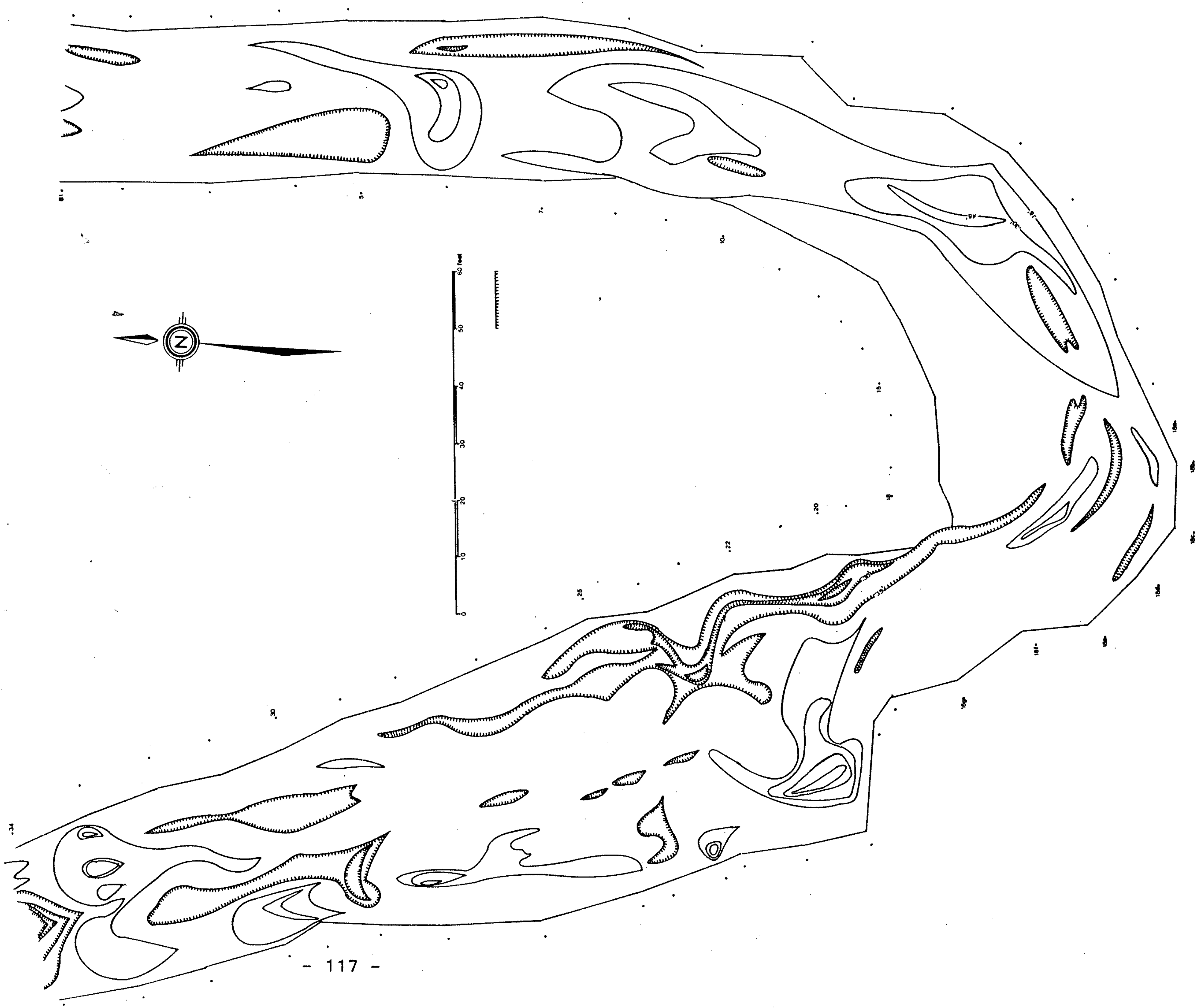


Figure 4.10: Channel Change B-Reach Post-Breakup to Post-Flood Survey 1982



When succeeding flood waves did not allow consolidation of the bed to occur, bedload transport occurred on the rising limb in mid-riffle zones, and the falling limb in pools.

Due to the lack of a continuous record of bed profiles along the study reaches, assessment of the measured changes on Gravel Creek in terms of the sediment pulse hypotheses presented above are not conclusive. However, some reasonable inferences can be made.

Firstly, it can be assumed that the bed profile as measured in the post-breakup survey is somewhat consolidated. Consolidation is brought about through low flows throughout the winter, and the effects of channel icing resting on the channel bed. From this it can possibly be assumed that bed transport during the snowmelt flood is confined to the falling limb of the flood wave. As the post flood survey was conducted well after the snowmelt flood had waned, the channel charges as displayed in Fig. 4.10 should represent the total amount of bed transport accomplished during the snowmelt flood. The pattern of erosion and deposition suggests sediment transport ceased at an intermediate stage between transport onto and across riffles, and scour of riffles and deposition in pools. Tracer particle movement (Figure 3.23) shows that the area of most concentrated movement occurs in the riffle section B1-B10. This area corresponds with the largest lobe of deposition. Meade (1985) suggests that zones of sediment storage represents the point at which bedload transport stopped during the preceding flood event.

Thus, on Gravel Creek B-reach, the pattern of deposition displayed after the snowmelt flood of 1982 suggests locations of sediment storage. In this case, sediment storage is not confined to pools as is suggested by Meade (1985), but because of consolidation during the long Yukon winter, is reflective of sediment transport during the falling limb of the flood wave only.

The results displayed in Figure 4.9 indicate bed changes from the initial survey in 1981 to the post-breakup survey of 1982. As the initial survey was conducted on June 22, 1981, well after the snowmelt flood, the bed configuration should be the result of that snowmelt flood. Thus changes in the bed measured by the post-breakup survey of 1982 must be interpreted as the result of the events which occurred since June 22, 1981. These changes may be the result of the effect of confined flow under an ice cover; indirect ice effects during breakup; or post June storm flow flood event. The indirect effects of ice during ice breakup can be ruled out on the basis of observations made during the breakup period. As noted previously, breakup on B-reach largely consisted of the ice melting in place. On only one occasion was ice observed to cause scour (B-21-31, ice grounded). The effect of confined flow under an ice cover is more difficult to rule out, and indeed cannot be conclusively rejected, for it has been hypothesized that scour may occur beneath channel icings (Carlson, 1979). However, the effect of an intervening storm flow flood event presents the most plausible cause of the changes. Table 4.3 shows rainfall as measured at Quiet Lake for the period of September 4-14, 1981 and represents the only continuous period of intense rainfall recorded during the two year study period. As the contour map of change for the period of 1982-1983 (Fig. 4.11) shows very little change over the reach and no major period of intense rainfall was measured during the intervening period, it would appear safe to assume that changes incurred between the 1981 survey and the 1982 post-breakup survey are the result of a stormflow flood event caused by the rainfall of September 4-14, 1981.

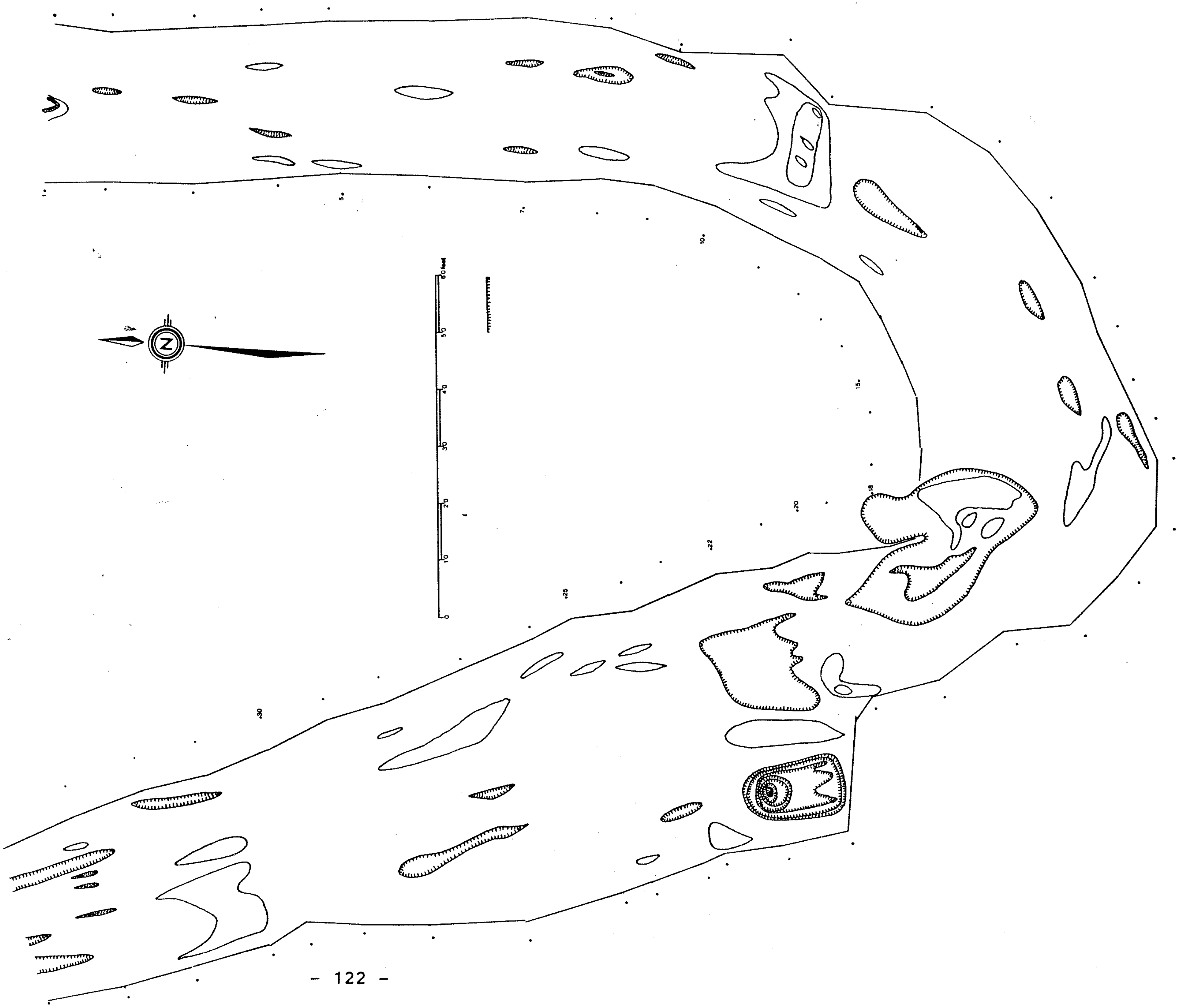
TABLE 4.3

Precipitation at Quiet Lake September 4-14, 1982

Sept.	4	5	6	7	8	9	10	11	12	13	14	30
ppt mm	C	C	C	25	9.1	5.0	13.0	C	C	4.2	16.2	16.3

While it is difficult to determine the peak flows resulting from a precipitation event on an ungauged basin, a number of studies have identified geomorphological factors which influence this response (Verschuren and Bristol, 1972; Anderson and Mackay, 1973; Jasper, 1973; Halket, 1985). Factors noted as important, that are considered here, include: basin area; basin relief and hypsometry; and basin aspect. Furthermore, Anderson and Mackay (1973), during hydrologic studies in the Mackenzie delta, noted that runoff increased noticeably in August following storms of a magnitude that brought little or no runoff response in June and July. It was hypothesized that this was primarily due to an increase in baseflow resulting from greater availability of soil moisture due to reduced rates of evapotranspiration. The rate of evapotranspiration is reduced by the trend toward cooler and wetter weather in the late summer and early fall. Examination of the hydrographs of the streams studied by Verschuren and Bristol (1972) indicated that this effect occurred in the southern Yukon as well, although it was not noted by the researchers. Two of the study streams investigated by Verschuren and Bristol (Moore Creek, Upper Tom Creek) display geomorphic characteristics similar to Gravel Creek. Upper Tom Creek, which varies from Gravel Creek only in elevation and relief displayed near maximum recorded discharge in response to small precipitation imputs (<1 inch) in August of 1972, and little or no response to similar inputs in June and July. It is therefore reasonable to assume that the precipitation event of September 1981 could have produced streamflows capable of initiating bed transport on Gravel Creek. Basin relief and elevation would further intensify the precipitation event through orographic effects. The intervening period of four months between the two flood events of 1981 would allow for bed sediment to

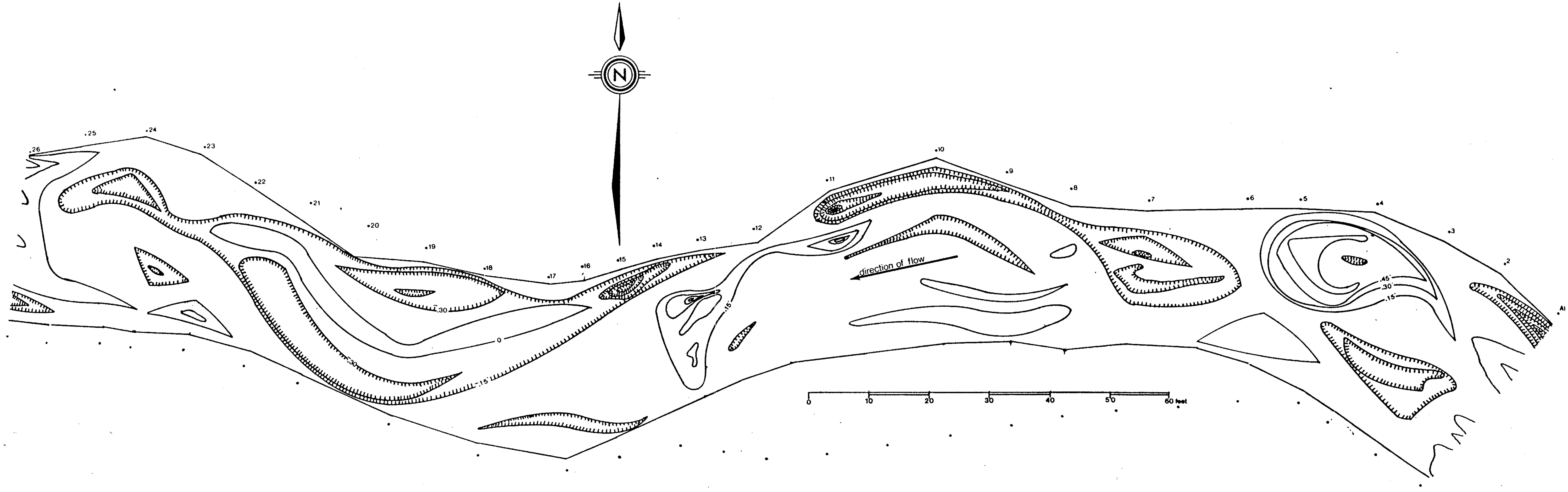
Figure 4.11: Channel Change B-Reach Post-Flood Survey 1982 to May 1983



reconsolidate, thus only one transport event would occur during the flood, and this on the recession limb of the flood wave. The fact that the changes displayed in Figures 4.9 and 4.10 are near mirror images of one another suggests the flood event of September, 1981 removed stored sediment in B-reach while the snowmelt flood of 1982 restored sediment to the reach. Thus it appears reasonable to assume that sediment pulses occur within Gravel Creek in response to flood pulses. Furthermore, as the dominant flood event of Yukon streams is the snowmelt flood (Vershuren and Bristol, 19874), consolidation of bed material between these events should lead to bed transport occurring on the falling limb only. Therefore, assuming no intervening flood, bed changes as measured after succeeding snowmelt floods should alternate on a yearly basis. The influence of intervening stormflow events would tend to complicate this in the manner described above, depending upon whether or not sufficient time exists between floods allow for bed consolidation. In general, however, the effects of bankfull flows produced by snowmelt should dominate the system, thus the alternation of sediment supply to and removal from the reach occurs over two years.

Results of the surveys of A-reach, when mapped as channel change, (Fig. 4.12) displays the lobe-like structure of deposition as observed in B-reach. Erosion, however, generally follows a pattern of linear scour paralleling the channel banks, which, it is suspected, reflects the indirect effects of ice breakup. As was the case on B-reach, zones of erosion and deposition are not related to channel configuration in terms of pools and riffles. Furthermore, they reflect bed changes produced over the period of June 8, 1981 to June 16, 1982, and therefore both surveys represent bed configuration after the snowmelt flood. The lack of an intervening survey prohibits discussion of A-reach changes in terms of the effect of the September, 1981 flood and accompanying and subsequent channel changes. However, the linear scour pattern does suggest indirect ice effects. During breakup of A-reach failed slabs of ice were often observed protruding into the flow (Fig. 4.6) and the resulting flow separation could be expected to produce severe scour in the bed directly under the failed slab. The one observation of scour around flow obstructed by grounded ice on B-reach (B-22-31) suggests that the effect of bed consolidation over a long period of inactivity may be insignificant where severe flow separation occurs. In fact the linear scours on A-reach reflect very closely locations of ice failure. In particular, the parallel linear scours between A-8 and A-11 reflect failure near the right bank at this location as noted earlier. Also the scour pattern between A-17 and A-22 is reflective of failure at this location. While the preceding evidence is hardly conclusive, it strongly suggests an indirect effect of ice breakup during a period of rising discharges. Furthermore,

Figure 4.12: Channel Change A-Reach Post-Flood 1981 to Post-Flood 1982



if the indirect effects described above did indeed occur, then the effects of bed consolidation should have been eliminated by these indirect effects of ice. Therefore, it is reasonable to assume that bedload transport occurred during both the rising and falling limbs of the snowmelt floodwave of 1982. Thus, the changes in the bed of A-reach measured during the post-flood survey reflect the results of at least three separate bedload transport events.

4.8 SUMMARY

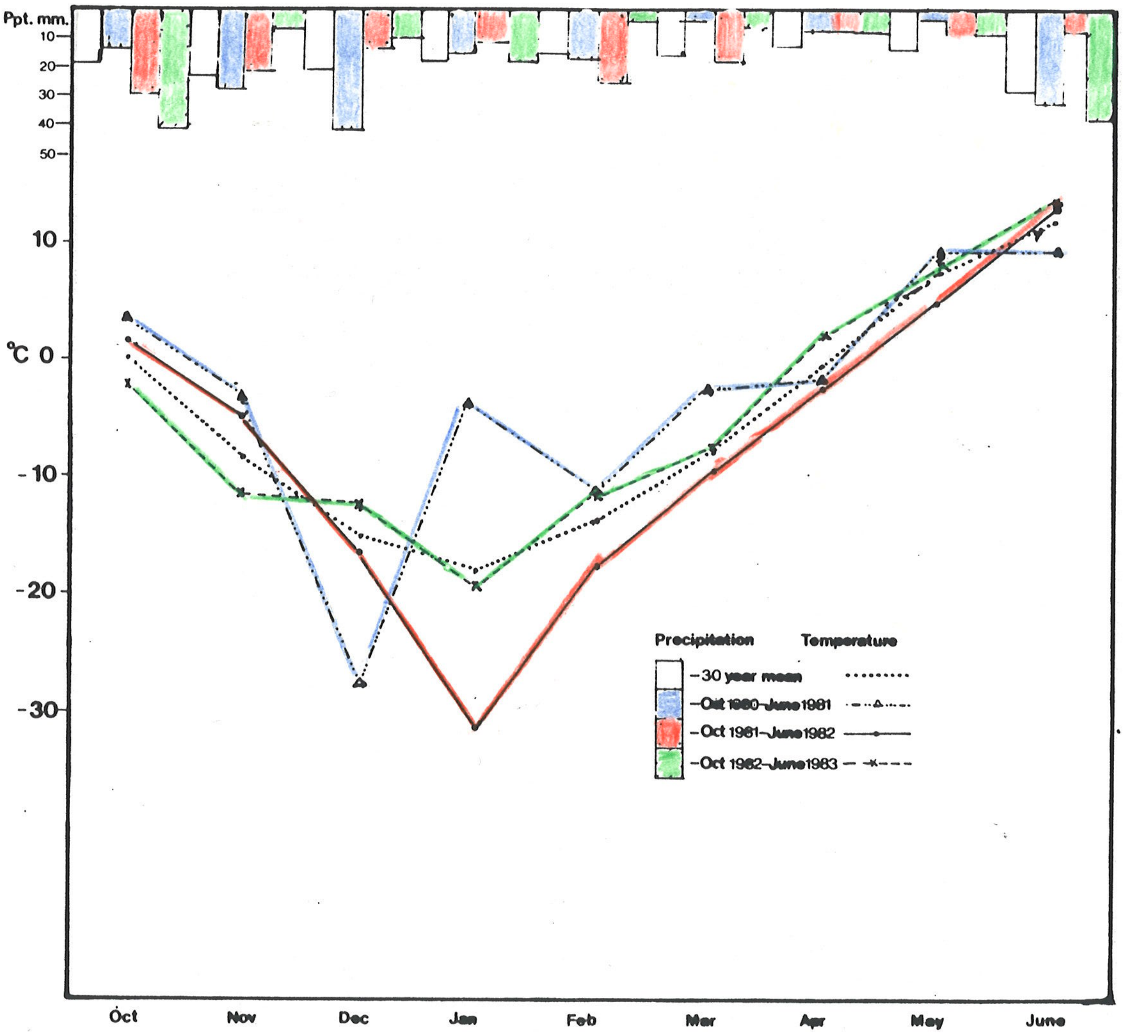
The preceding discussion has attempted to explain observed and measured changes along Gravel Creek over a two year period. Results of the level survey are inconclusive, due largely to the lack of information regarding events that may have occurred between surveys. A pre-freezover survey during the fall of 1981 would have produced valuable information regarding bed configuration at this time for comparison with the post-breakup surveys. However financial and academic constraints would not permit this.

While still speculative in nature, the discussion of measured changes on A-reach suggests indirect effects of ice breakup which cannot be wholly discounted. The observed bank failure on A-reach can, with reasonable certainty, be ascribed to the effect of the manner of ice breakup experienced on this reach, which is in turn due to the development of a thick overbank icing during the winter of

1982. The fact that this effect has not been documented in the literature is most likely due to the fact that previous research on channel icings has tended to concentrate on streams in which icings form every year. In general streams of this type have non-cohesive banks and tend toward braiding. The continued bank failure as described above could conceivably lead to channel widening, which in turn would favor annual icing formation. At present icing formation on Gravel Creek appears to be controlled by climatic factors. Figure 4.13 displays mean monthly temperature and precipitation as measured at Whitehorse for the winters 1981-1983. As noted previously, precipitation correlates poorly from station to station in the Yukon and extreme local variability is the rule. Therefore, precipitation values for Whitehorse do not necessarily reflect conditions at the study site. However, Burn (1983) did note that in general winter precipitation increases with increasing temperature. From Figure 4.13 it is evident that winter temperatures during of 1981-1982 were colder than average and colder than those experienced during the other two years of the study. Furthermore the intense period of precipitation of September 4-14, 1981 would substantially increase groundwater recharge. Thus a general picture of the conditions leading to icing formation on Gravel Creek during the winter of 1982-1982 is presented. Given that an icing formed on Gravel Creek in only one of three years, it is not likely that the observed bank failure on A-reach would significantly effect channel morphology at the present rate of bank failure. However, future alterations to the site (eg. culvert emplacement) could significantly alter local factors, and as such result in annual icing formation, which should in turn increase the rate of bank failure. The channel would widen and consequently result in greater icing effects and therefore problems at the highway crossing.

Results of the level surveys of B-reach are suggestive of the pulse-like movement of sediment waves through the reach. The detailed nature of the level survey clearly displays lobes of sediment and areas of scour on the bed of Gravel Creek. However, detailed bed surveys of this type necessarily limits the length of reach that can be surveyed within a given time frame. Thus, while the level surveys of A and B reaches accurately depicted changing bed configuration, the locations of sediment storage cannot be accurately assessed in terms of the entire channel. Alternatively, and not necessarily contrarily, sediment storage and removal may not be strictly controlled with respect to riffles and pools. Rather, the apparently alternating relationships between erosion and deposition may reflect the fact that competence to transport bed material is achieved only after the effect of bed consolidation is overcome. At this point bedload transport begins and continues until such time as the flow is no longer competent to maintain particle motion which is usually 1/3 that of

FIGURE 4.13 Monthly Precipitation and Mean Monthly Temperature, Whitehorse 1981-83.



initiation competence (Reid et al., 1981). For Yukon streams this suggests a general two year cycle of erosion and deposition for any given reach, as the snowmelt flood is, in general, the dominant hydrologic event of the year.

Chapter V

CONCLUSION

5.1 CONCLUSIONS

A review of the literature revealed that the geomorphic effects of ice breakup on small streams had been largely ignored, and were in general considered to be insignificant (Kellerhals and Church, 1979). In view of the recent controversy over the significance of the geomorphic effects of ice breakup on larger rivers, this study was undertaken to determine the geomorphic effects along a small gravel bedded stream. Upon arrival at the site in 1982 it was apparent that significant channel icing had developed on A-reach. Observations made during the course of this study indicated that the presence of a significant (overbank) channel icing impacts significantly upon the geomorphic effects of ice breakup on Gravel Creek. Where only minor or no channel icing existed breakup consisted of ice melting in place producing no geomorphic effects. Conversely, where overbank icings existed, breakup was rapid and dramatic, producing significant bank failure and possibly significant bed scour. These effects were explained in terms of the ice breakup process. It was shown that ice breakup is initiated through melt at the ice undersurface (thermal erosion) in areas of turbulent flow where stream energy is lost as heat and the transfer of stream heat is most rapid Melt at the ice upper surface progresses at a relatively constant rate along the channel, but at a much slower rate than melt at the undersurface. Thus the ice cover is significantly thinner over riffle zones than pools prior to breakup. Where ice is thinnest, candling is insufficient to penetrate through the thick ice cover. the ice cover. At this point minute slippages occur along the ice crystal planes paralleling the c-axis, gradually lowering the ice cover to the water surface, creating a smooth bowl-shaped depression. Where the ice cover is thicker, candling is only present in the upper layers. Due to the delayed breakup, ice retreat at the undersurface occurs more and more rapidly due to increased discharges as snowmelt progresses. The melt at the undersurface reaches a point where the ice cover can no longer support itself, yet crystal slippage cannot occur, and consequently the cover fails rapidly in a beam-type failure. This rapid failure causes bank materials still frozen fast to the icing slab to fail at that point marked by the bank material and vertical and lateral limits of thaw. Indirectly, the failure of the ice cover in this manner (beam failure) may cause severe scour of the channel bed through flow separation. Linear scours on A-reach reflected very closely those locations at which ice cover failure occurred.

Thus it can be concluded that the development of an overbank channel icing significantly alters the geomorphic effects of breakup on a stream in which channel icings do not form in every year. Results of the level survey, though not conclusive, suggest that bedload transport takes place as pulse-like waves of sediment moving through the reaches. In general, long periods of inactivity between peak flow events allow for some consolidation of the bed to occur. Thus, during the rising limb of the succeeding peak flow bed consolidation is overcome, and bedload transport is confined to the falling limb of the flood wave. Given that the dominant hydrologic event of the Yukon year is the snowmelt flood, this suggests that, in general, the cycle of erosion and deposition along a given reach takes place over a two year period. This inferred pulse-like movement is displayed in the spatial arrangement of deposition as distinct lobes of bed sediment. However, further research is required in order to state conclusively that the apparent pulse-like movement of bed sediment in fact occurs. Furthermore, it has been suggested that the indirect effects of ice breakup in concert with near peak flow may initiate bed scour through separation around failed ice cover beams protruding into the flow. As a consequence, bed consolidation may be rapidly overcome allowing the initiation of bed load transport to occur on the rising limb of the flood wave, thus altering the apparent two year cycle of erosion and deposition. The lack of a pre-freezeover survey in 1981, and post-breakup survey in 1982 seriously hampered interpretation of survey results.

Thus, it was not possible to conclusively determine what, if any, effects were the result of sub-icing scour, and the inferred indirect effects of ice breakup are deduced by inference. Finally, observations made in the field indicated that ice slabs laying against the channel banks after breakup may prevent the erosion of the channel banks during the snowmelt flood event.

5.2 SUGGESTION FOR FUTURE RESEARCH

The observed bank failure due to icing breakup has not previously been identified in the literature. Therefore, it is suggested that further research on the effects of channel icing at breakup be conducted on streams in which icings do not form every year. In this manner the significance of the failures observed on Gravel Creek may be determined, as well as the geomorphic significance of icings in general under these circumstances. The nature and causes of icing formation on streams in which icings do not form in every year may also be determined, and hence prediction of icing formation at specific sites may be possible. This would, by its nature, require a long period of study, as determined by the frequency of icing formation in response to climatological variation. This should not deter research however, for if it is determined that bank failure due to icing formation and breakup is significant, then human activity, which enhances icing formation, may result in channel widening thus increasing icing control problems. In the long-term, then, it should be less costly to prevent the problem from occurring than attempting to rectify it once it has occurred. This is particularly important in view of continued northern development.

The suggestion of a two-year cycle of sediment supply and removal from a reach is not conclusive, and further research could proceed with a view to examining this particular hypothesis. The survey techniques as used in this study should comprise just one segment of such a research project, and will provide a detailed view of bed configuration before and after flood events. In concert with a less detailed survey of a greater length of channel, and the installation of Birkbeck type bedload samplers, an accurate picture of the time of initiation of particle motion, the duration of particle movement, and zones of sediment storage and removal could be developed for a significant length of channel, thus leading to the acceptance or rejection of the hypothesis.

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Appendix A

GRAVEL CREEK CROSS SECTIONS

A-Reach 1981, 1982

B-Reach 1981, 1982, 1982, 1983

KEY TO APPENDICES A+B

All units in feet

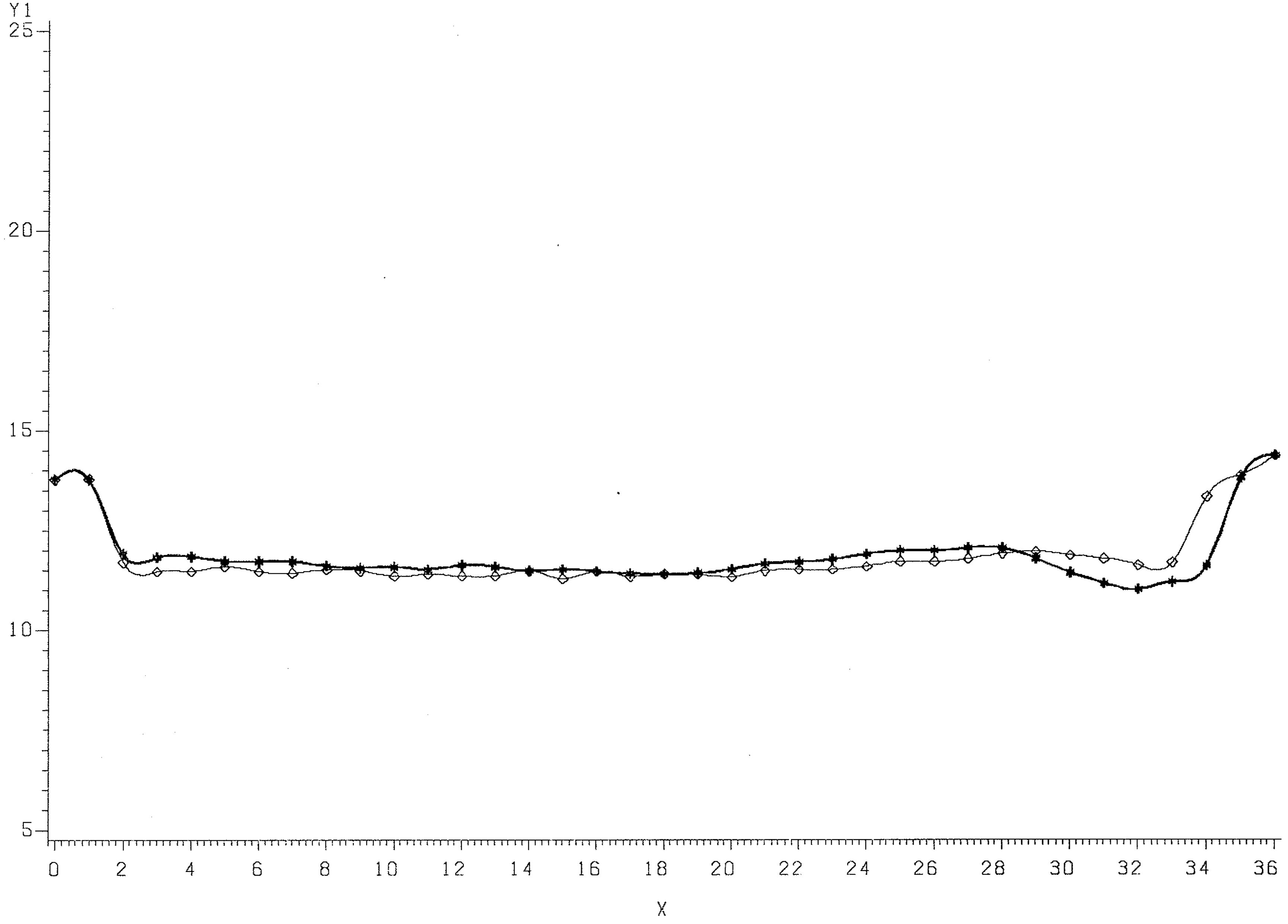
◇ 1981

▲ 1982 pre-flood

✱ 1982 post-flood

□ 1983

GRAVEL CREEK CROSS SECTION (A-1 post-flood 1981 and post-flood 1982)



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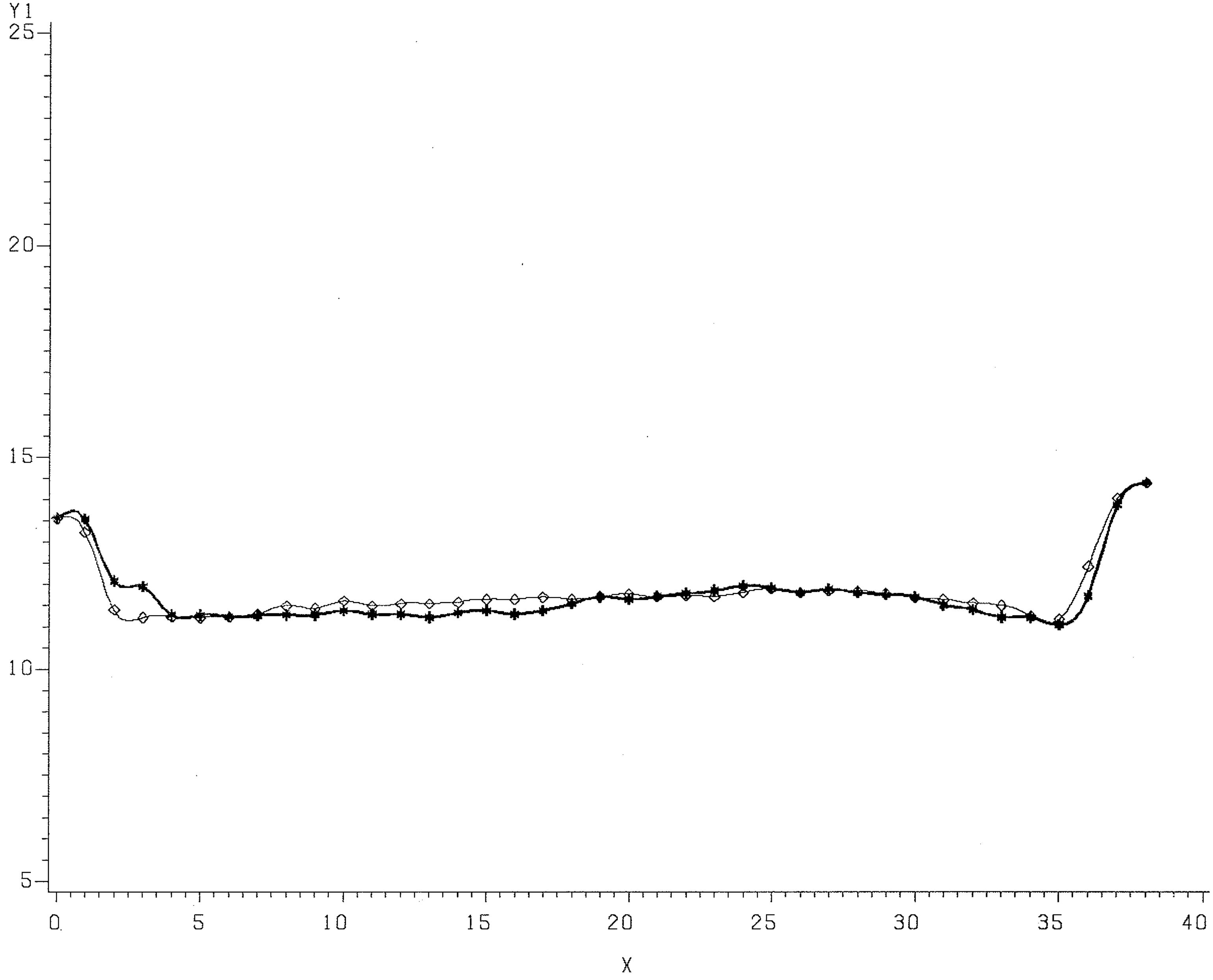

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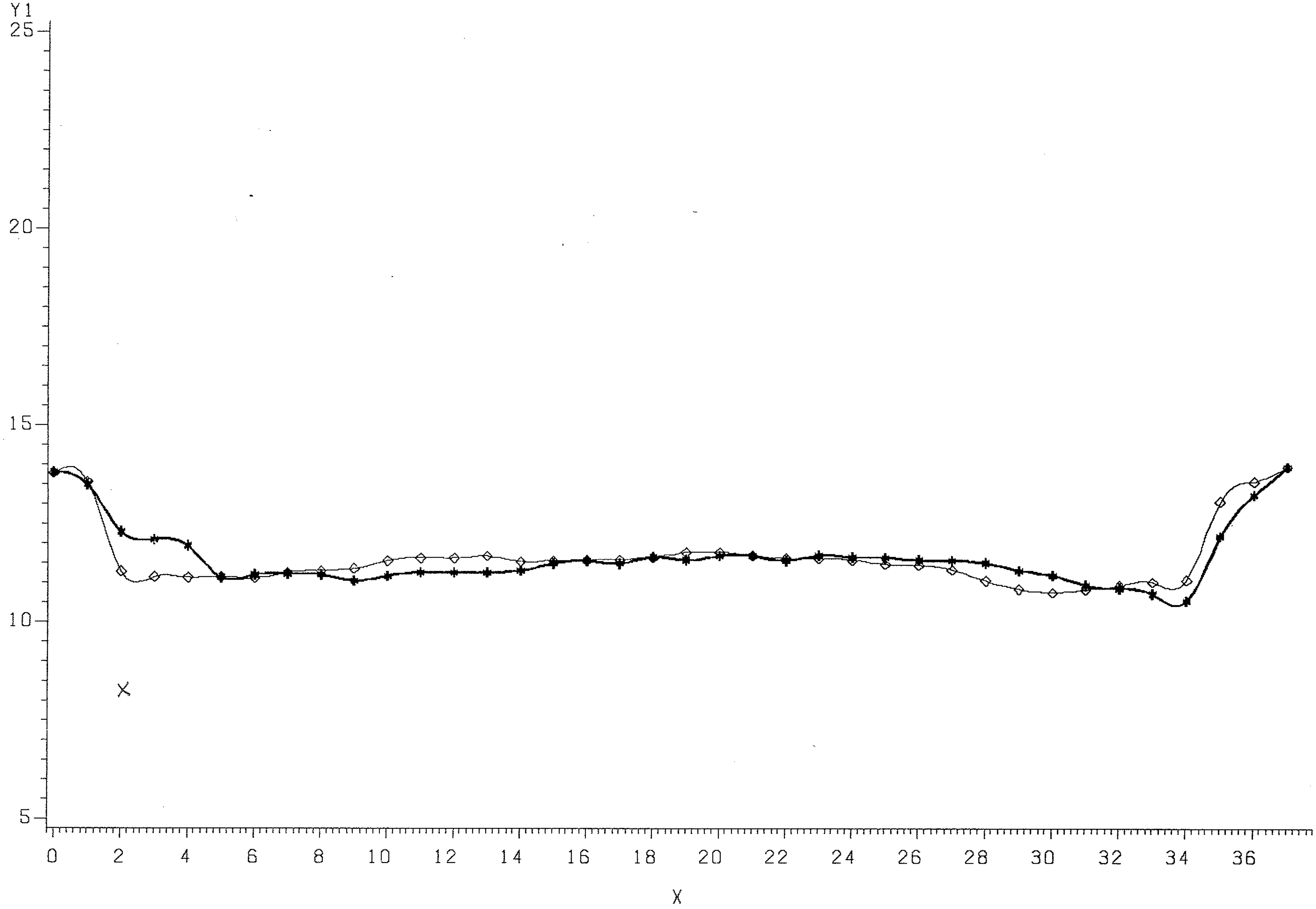

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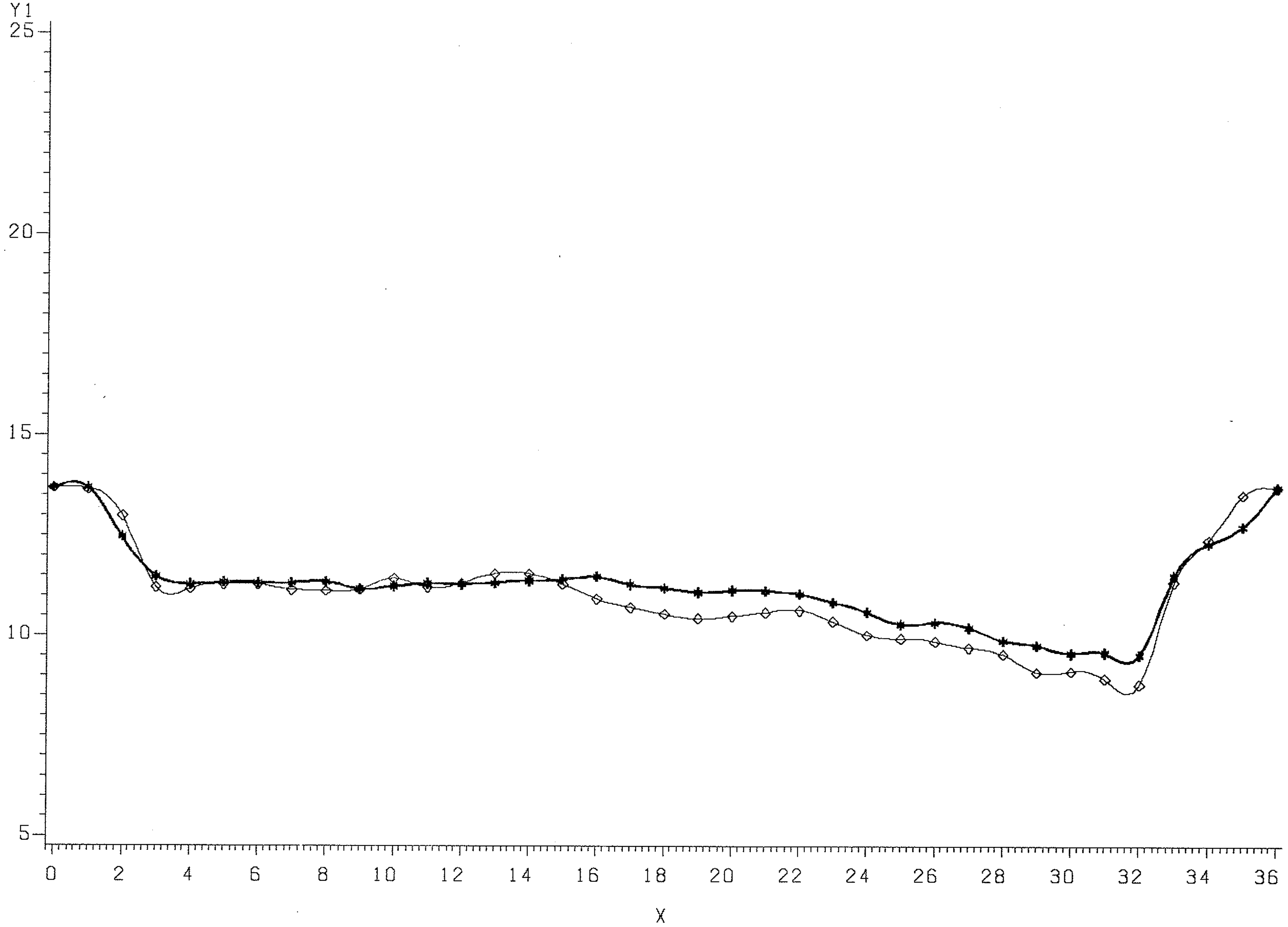

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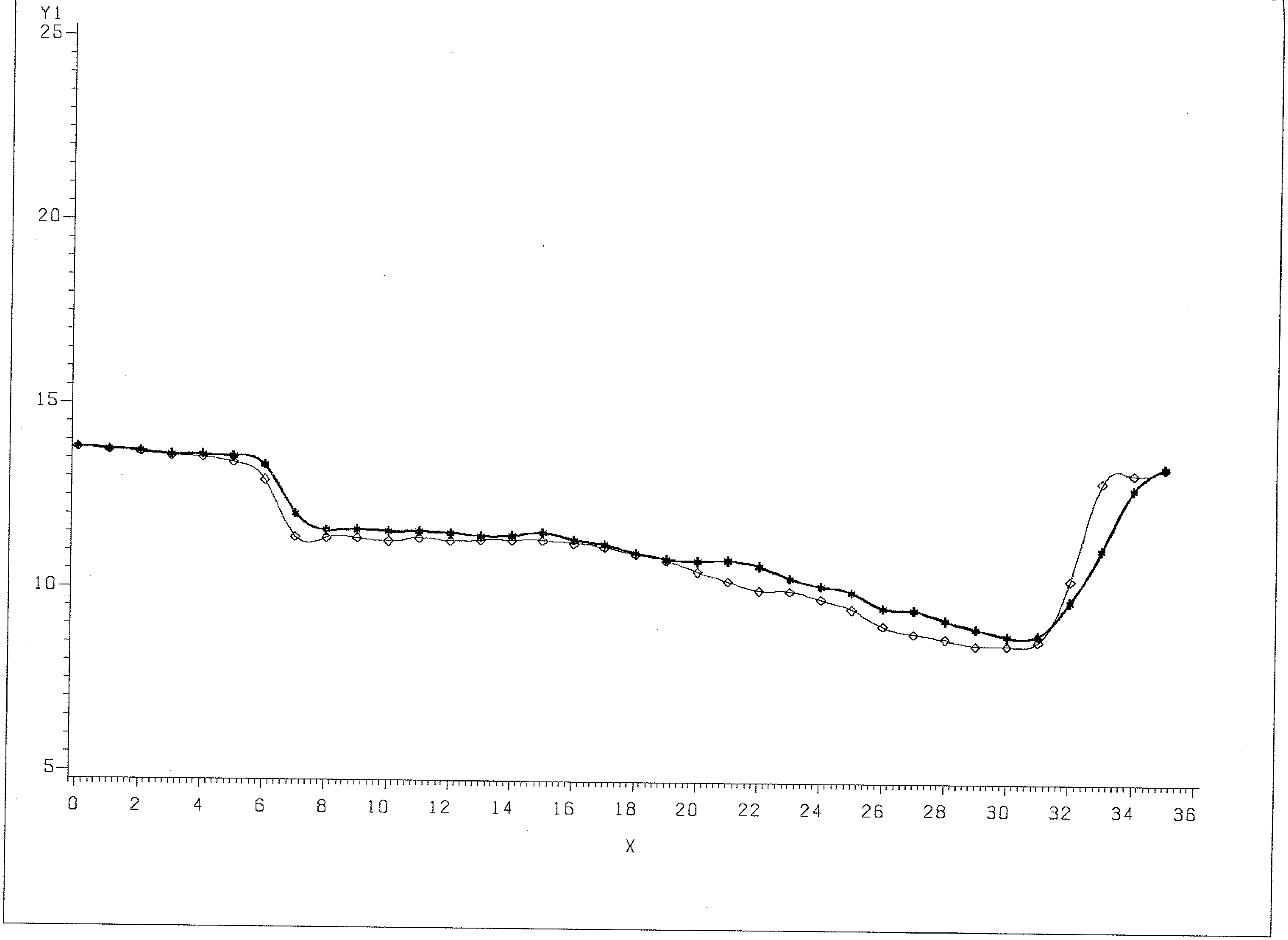

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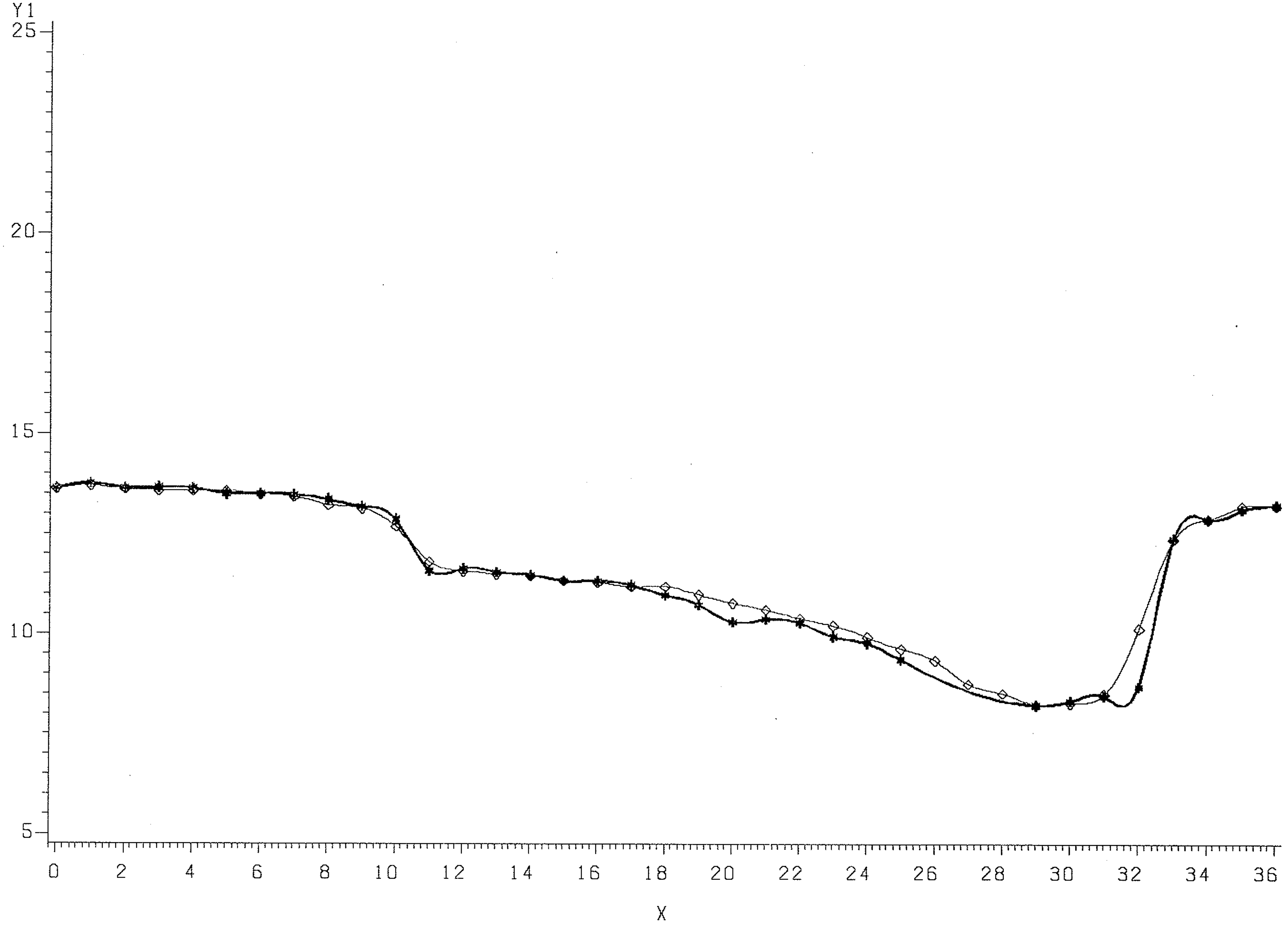

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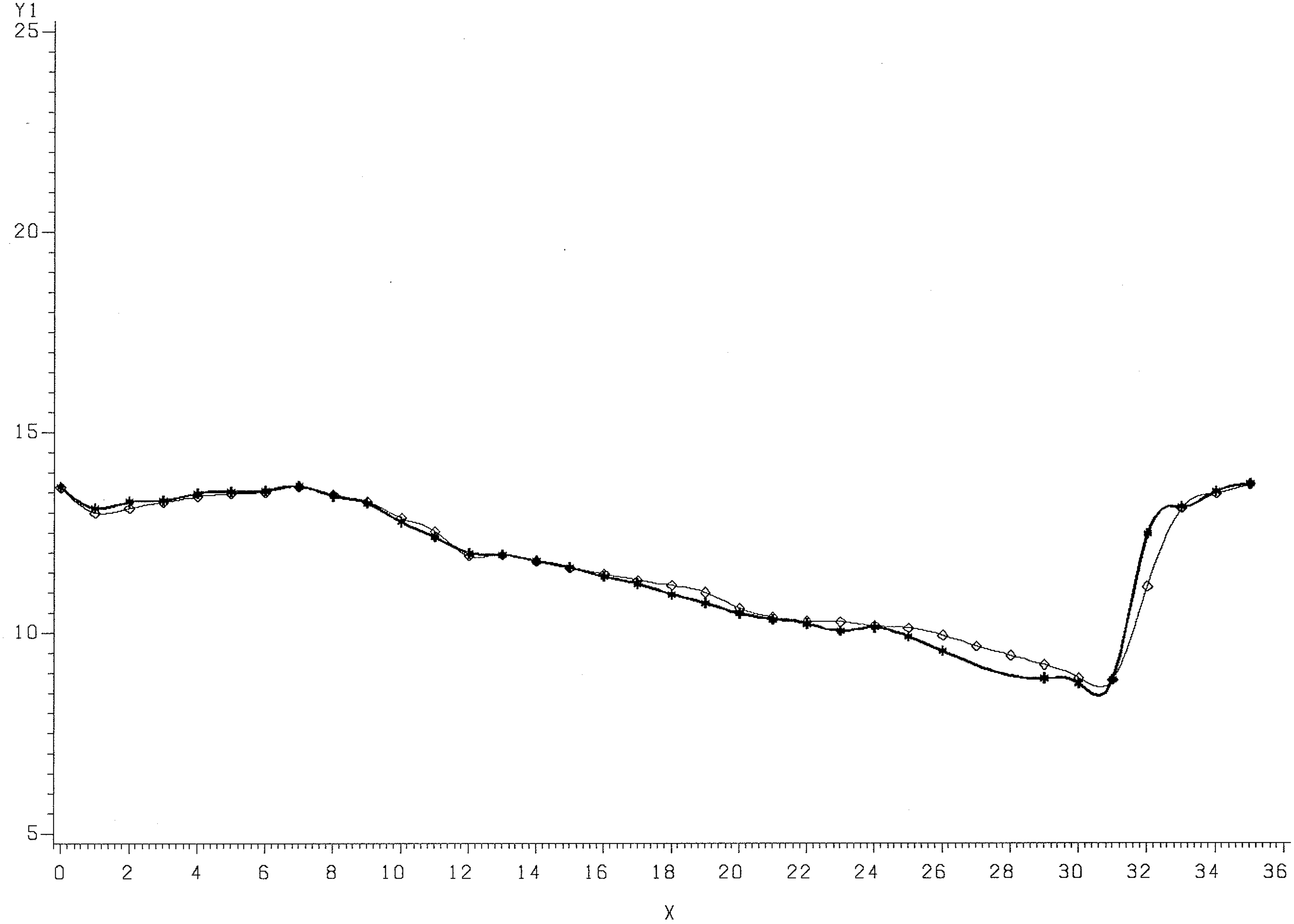
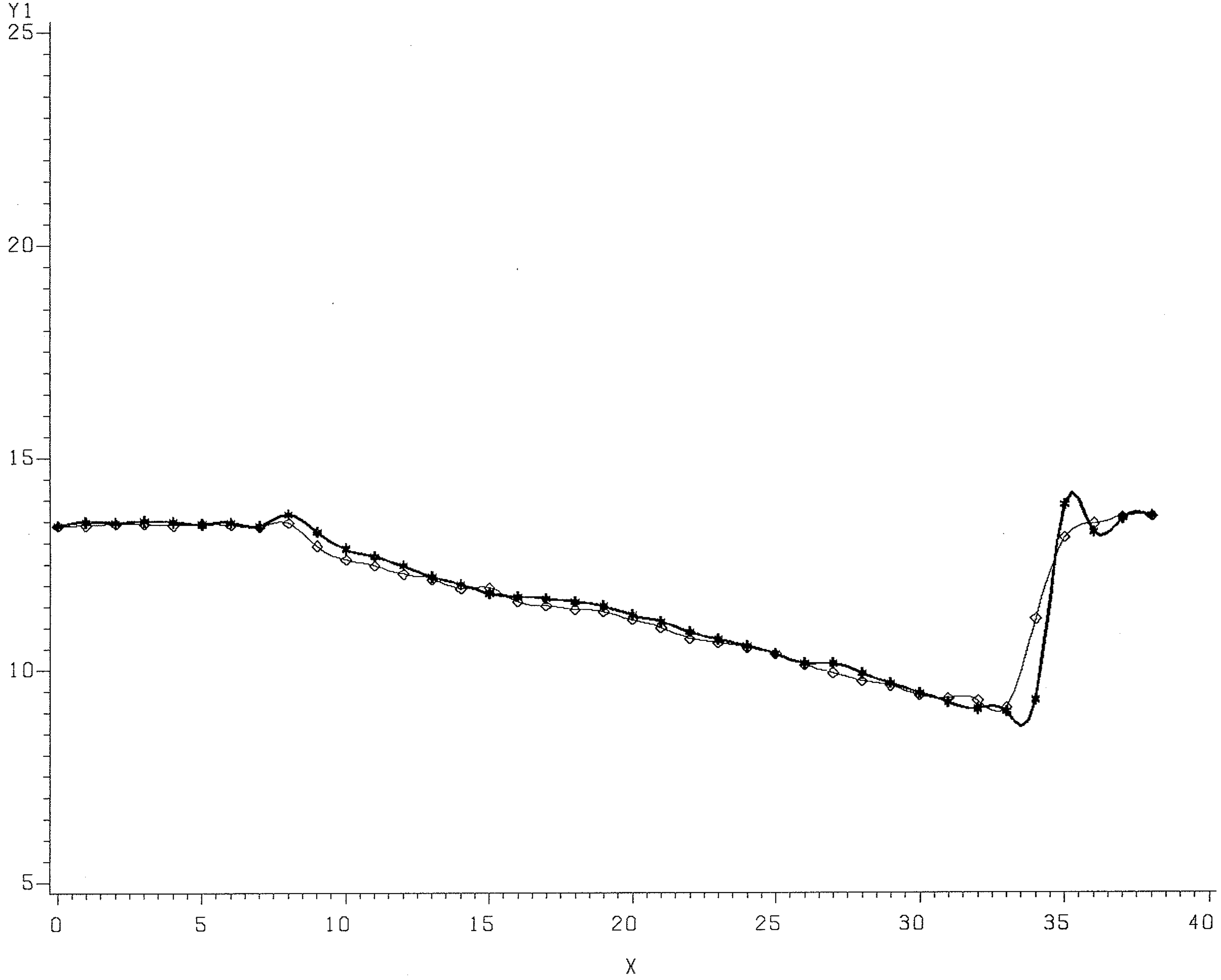


GRAVEL CREEK CROSS SECTION (A-8 post-flood 1981 and post-flood 1982)



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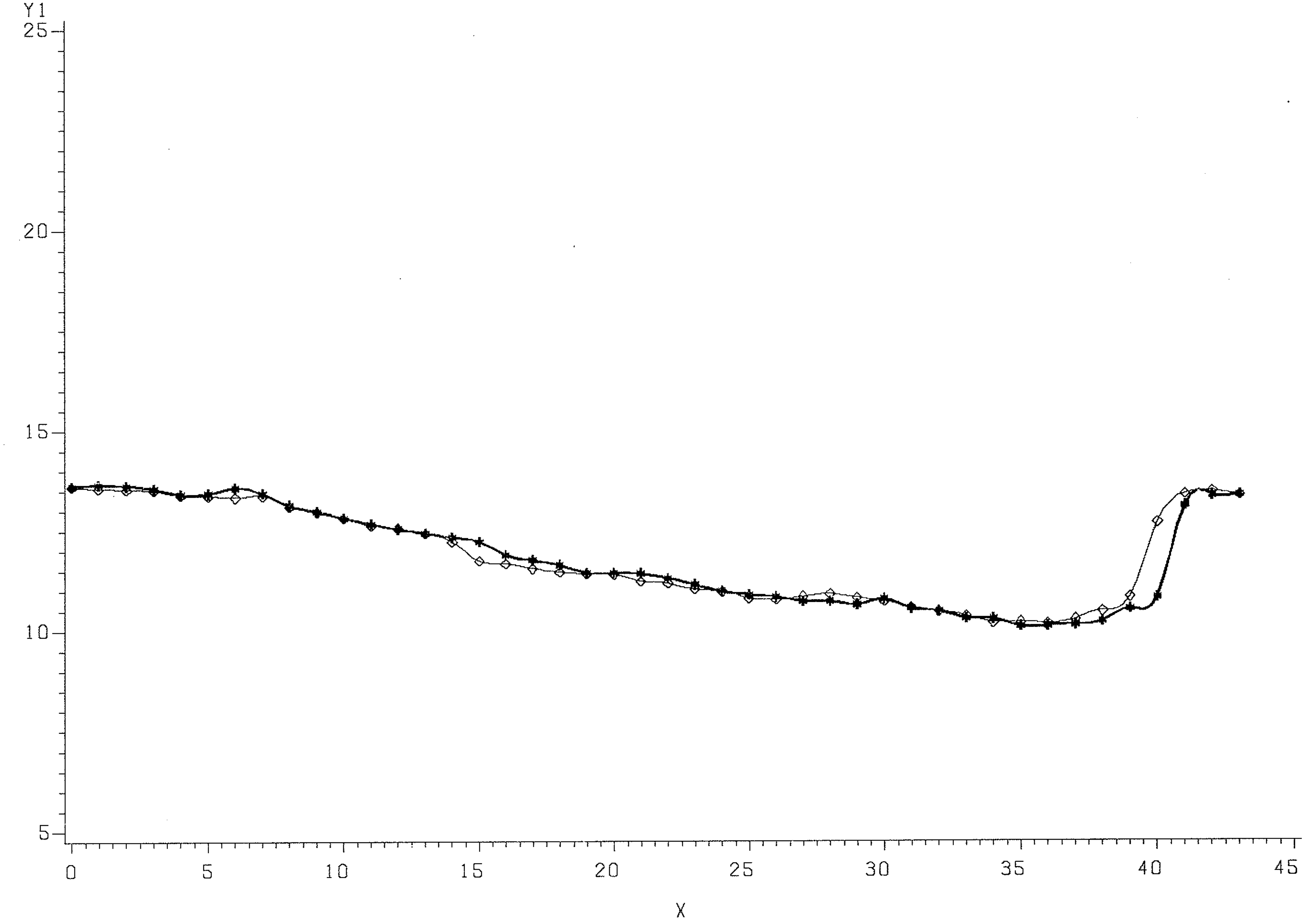

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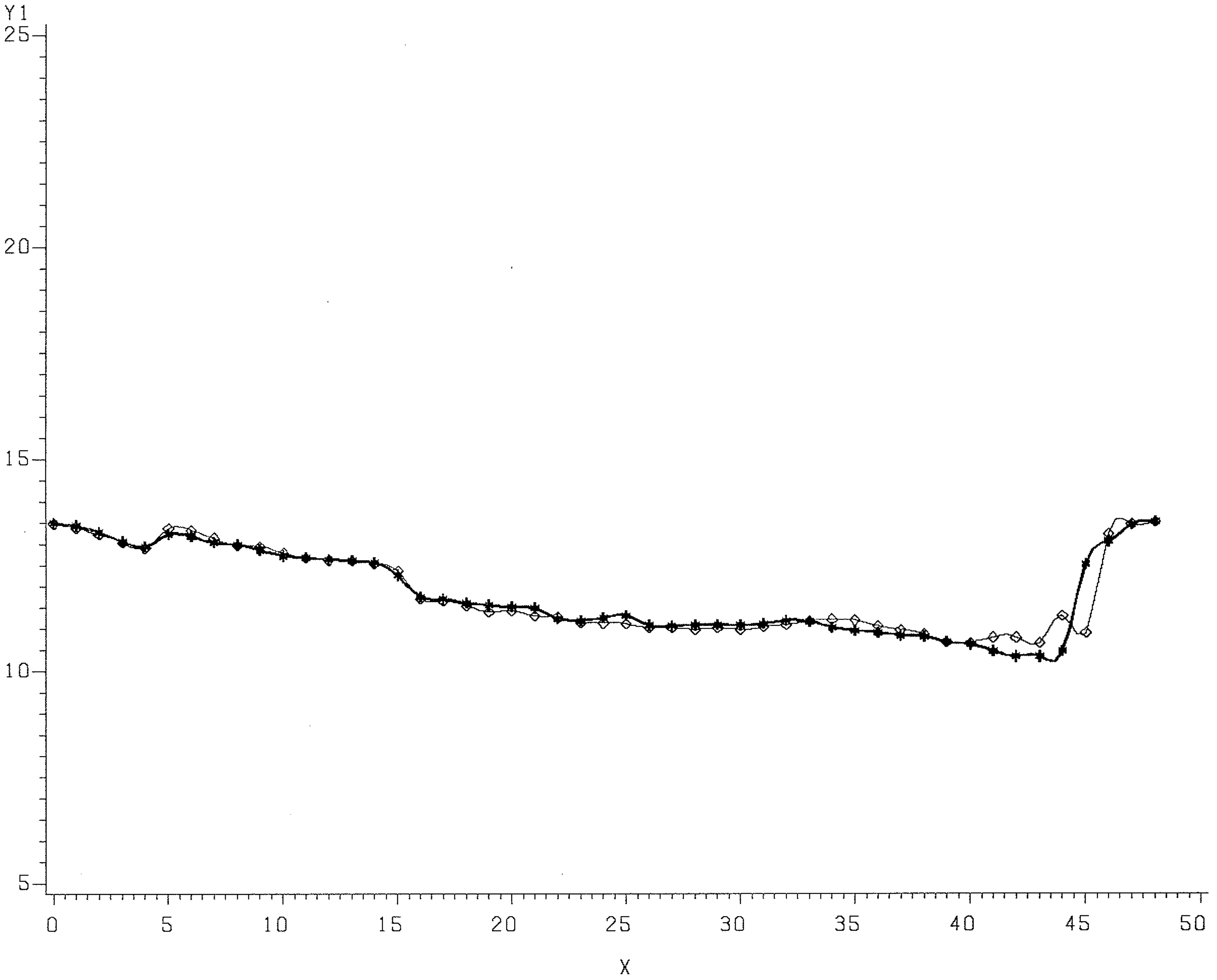

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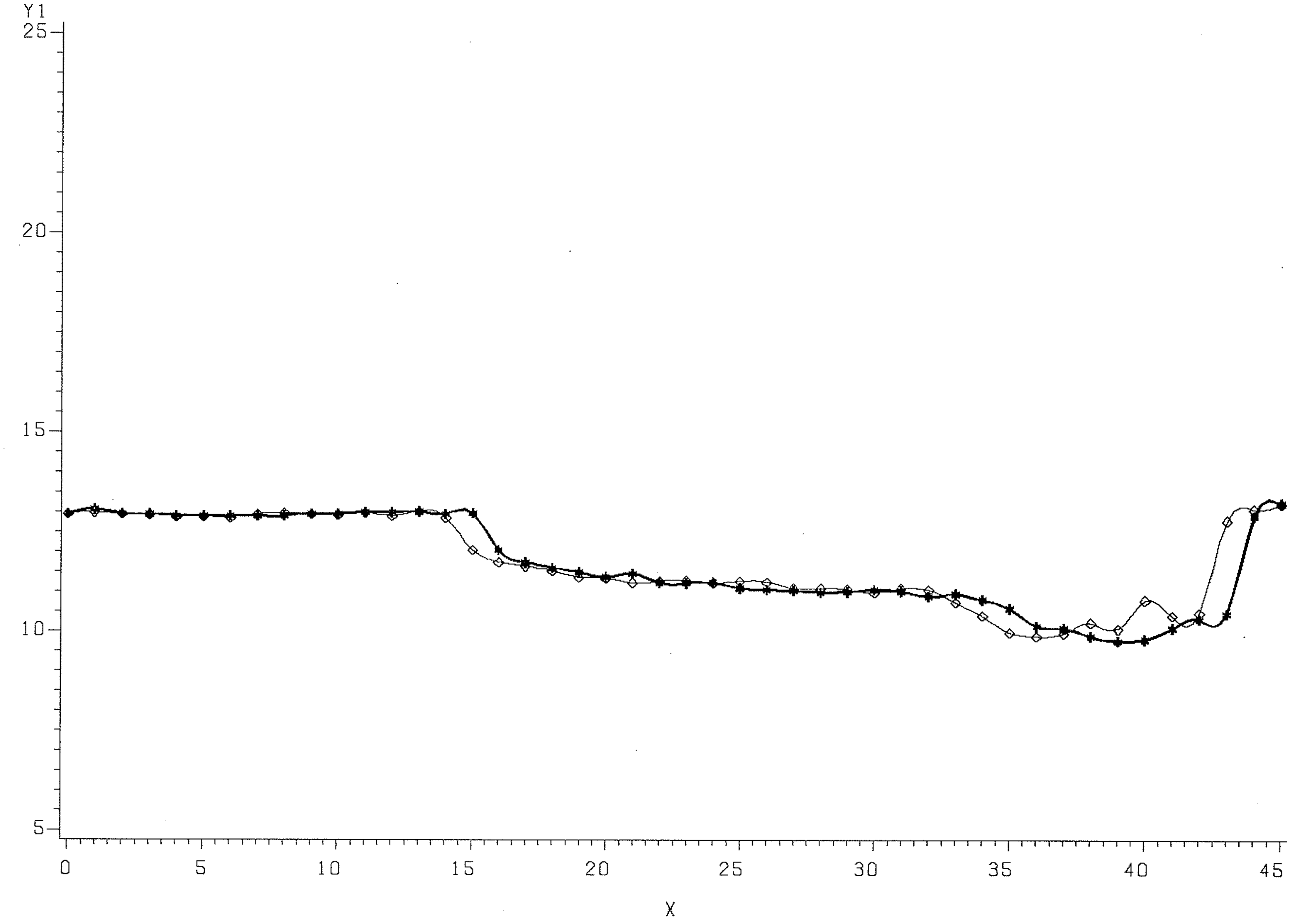

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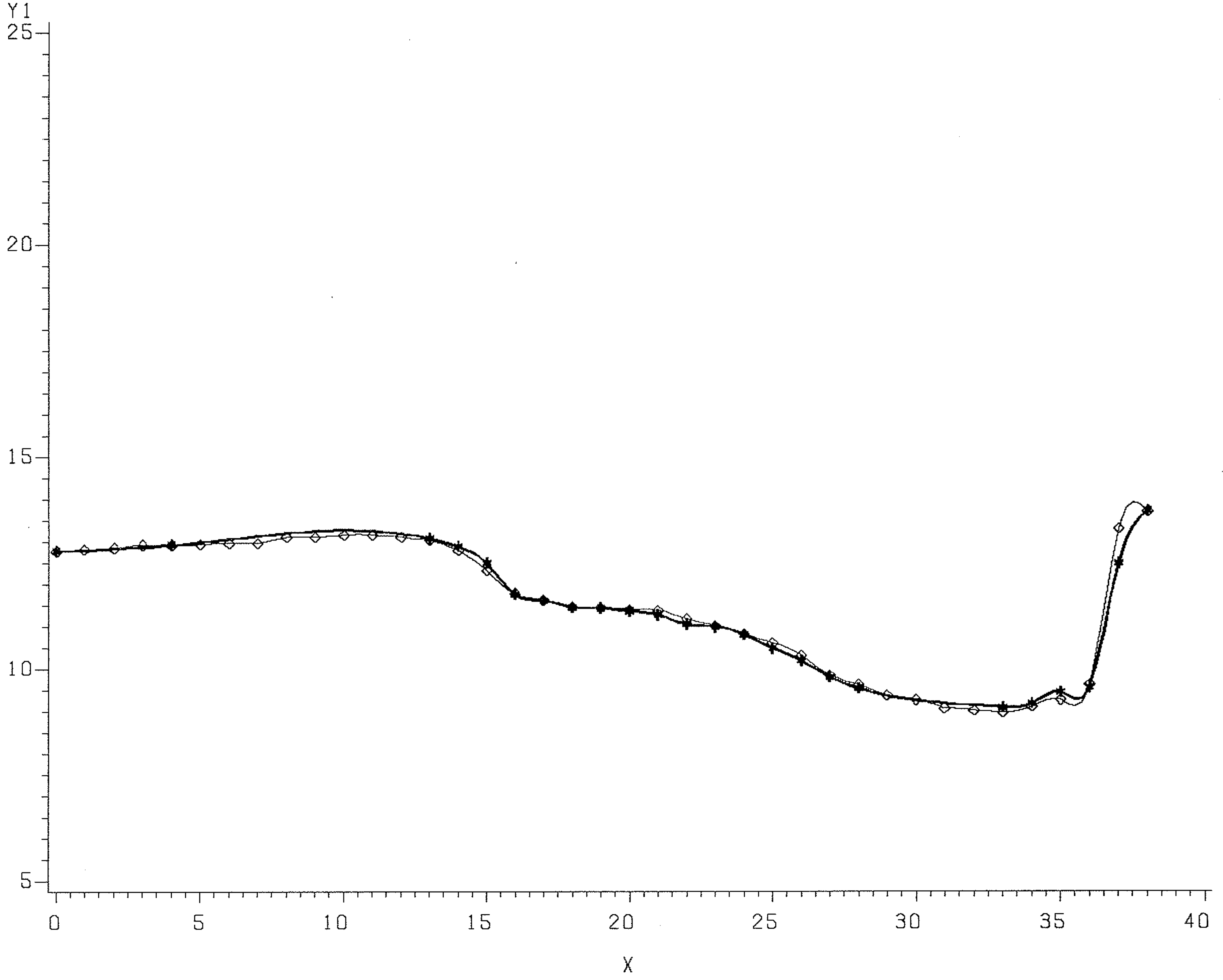

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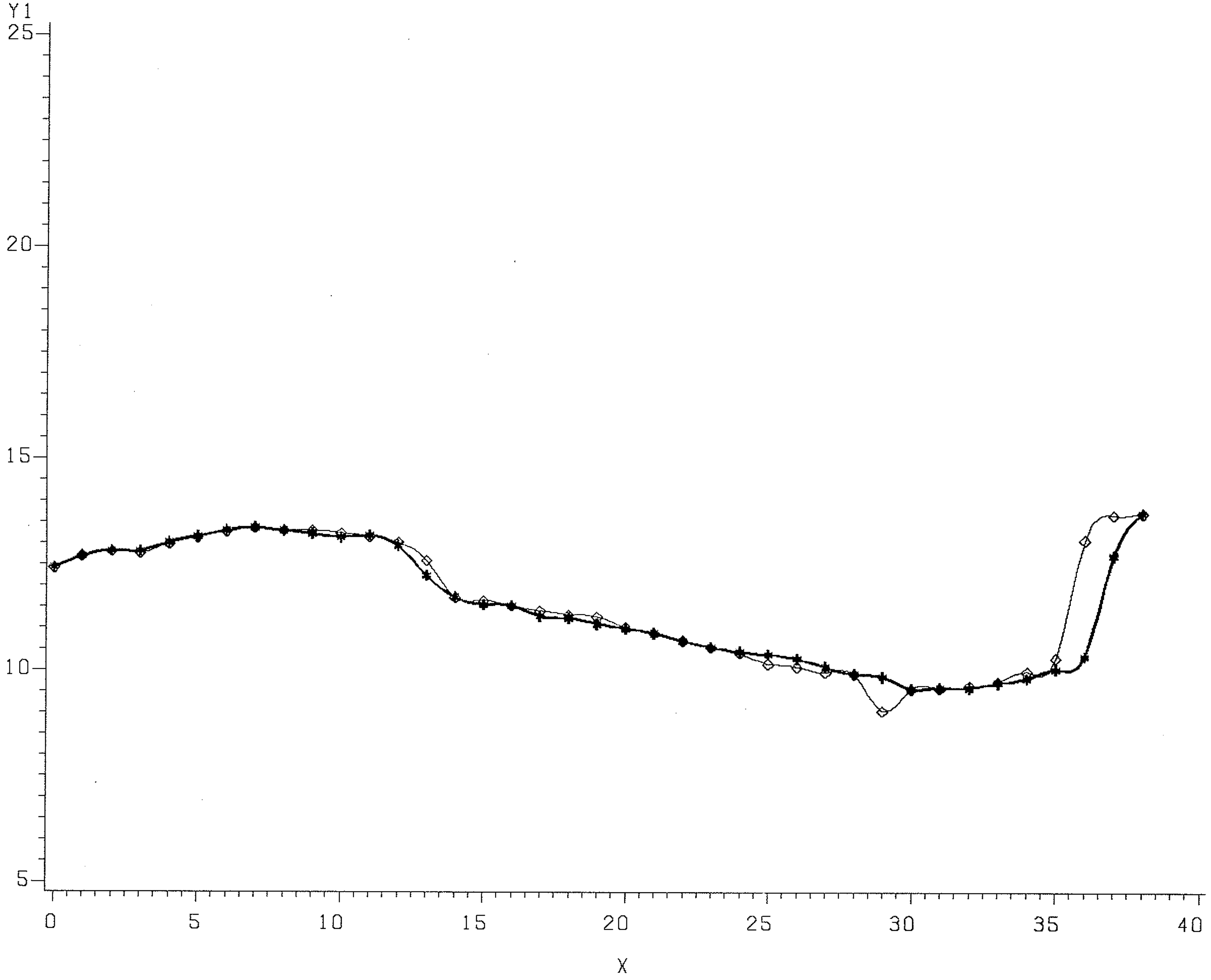

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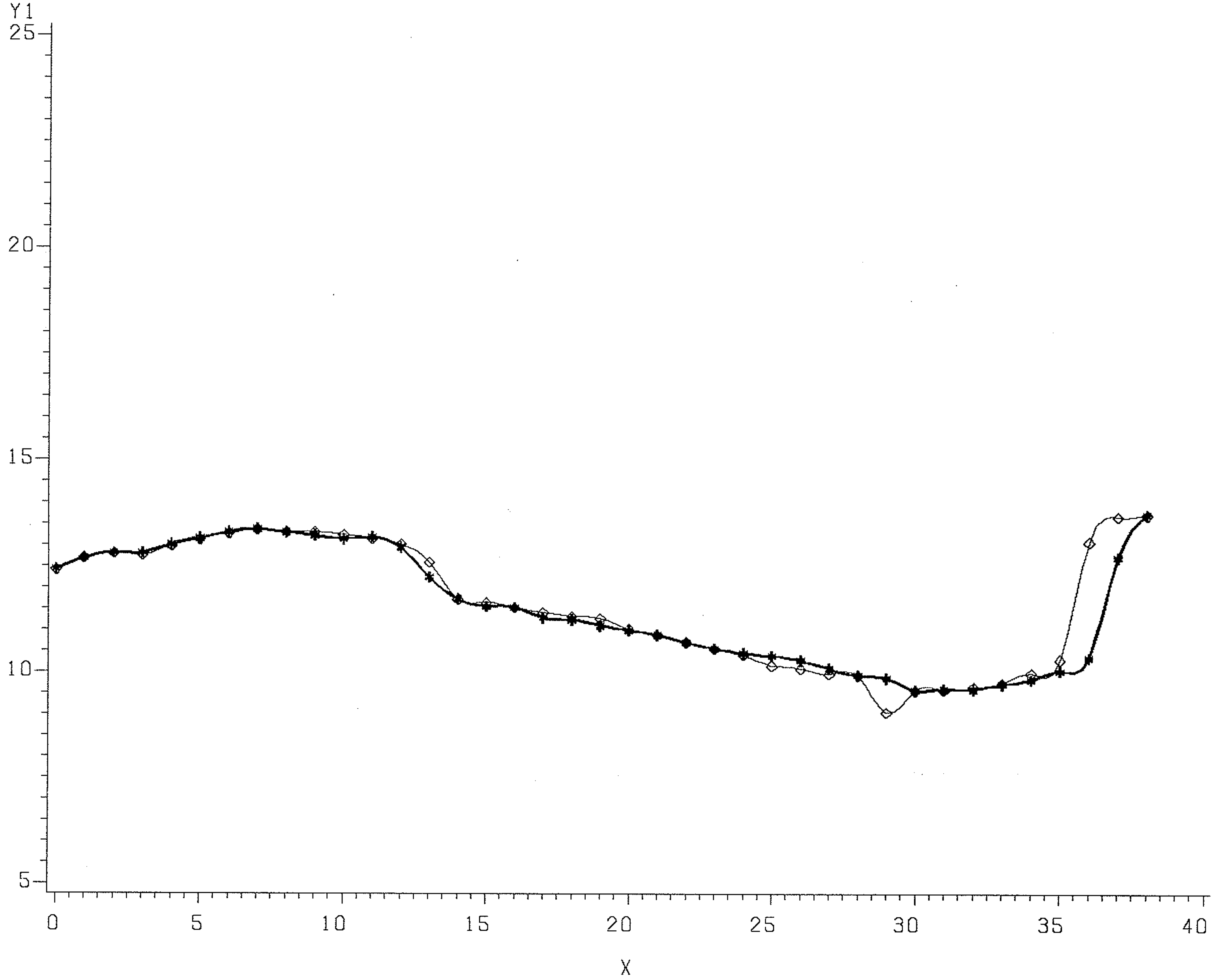

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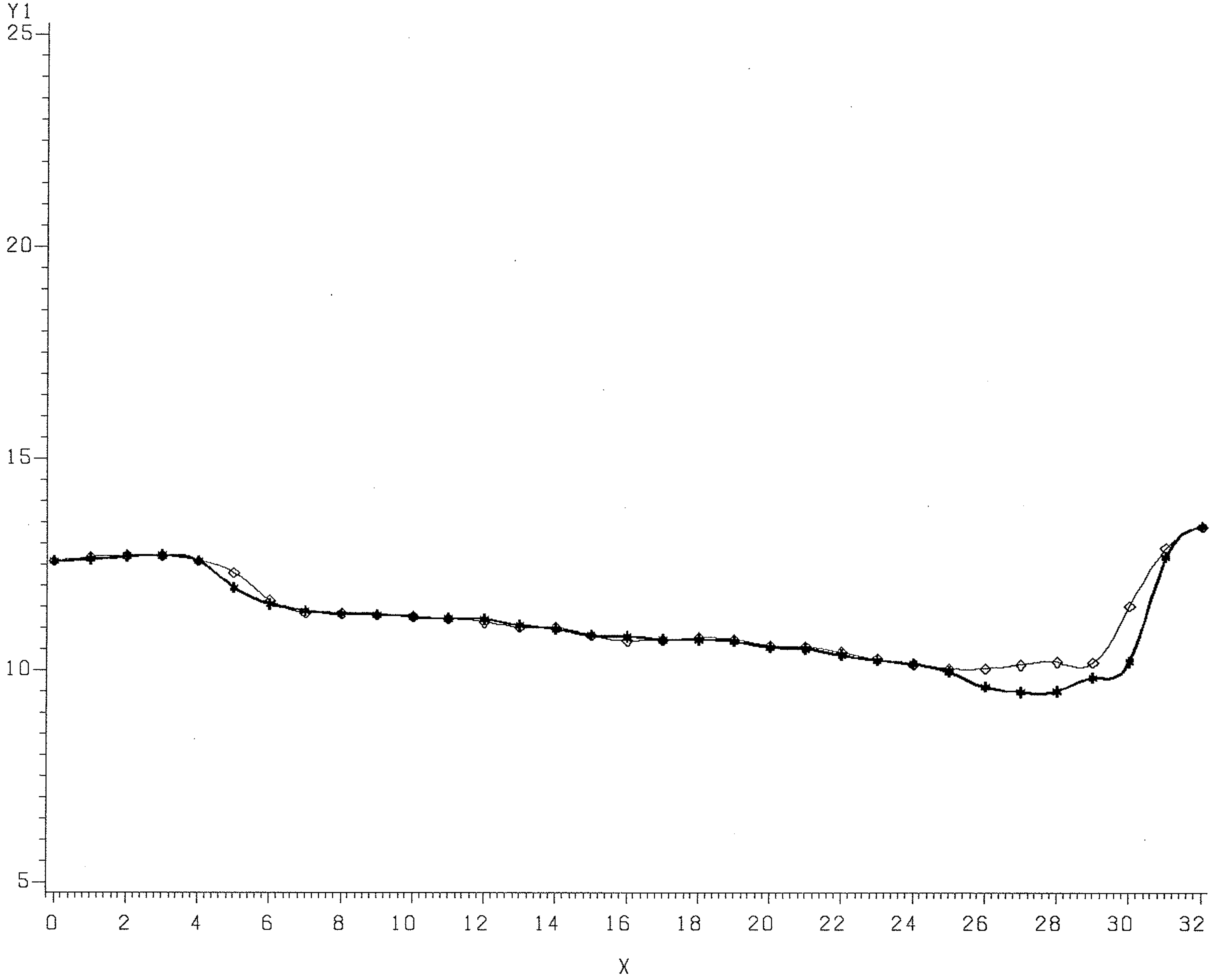

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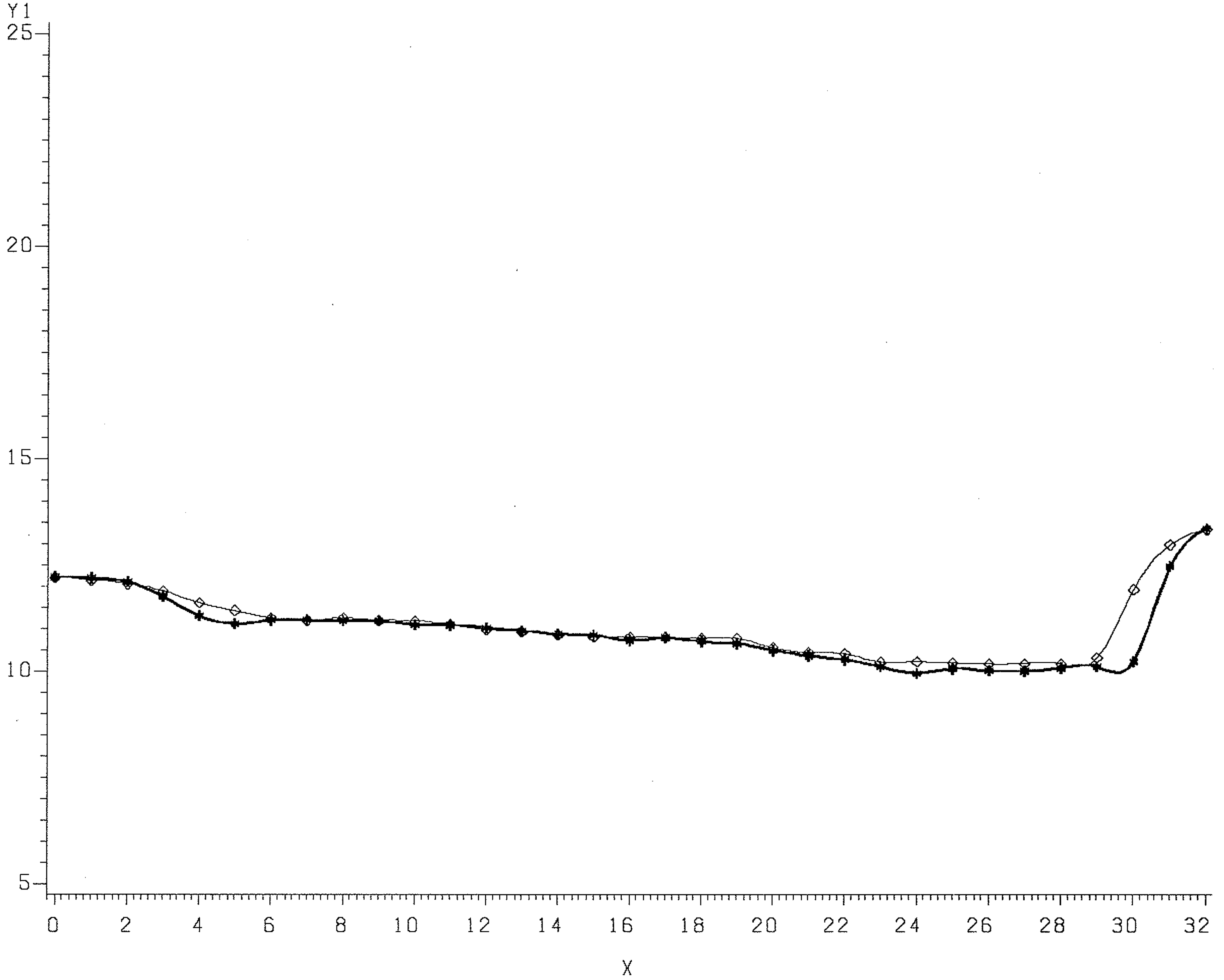

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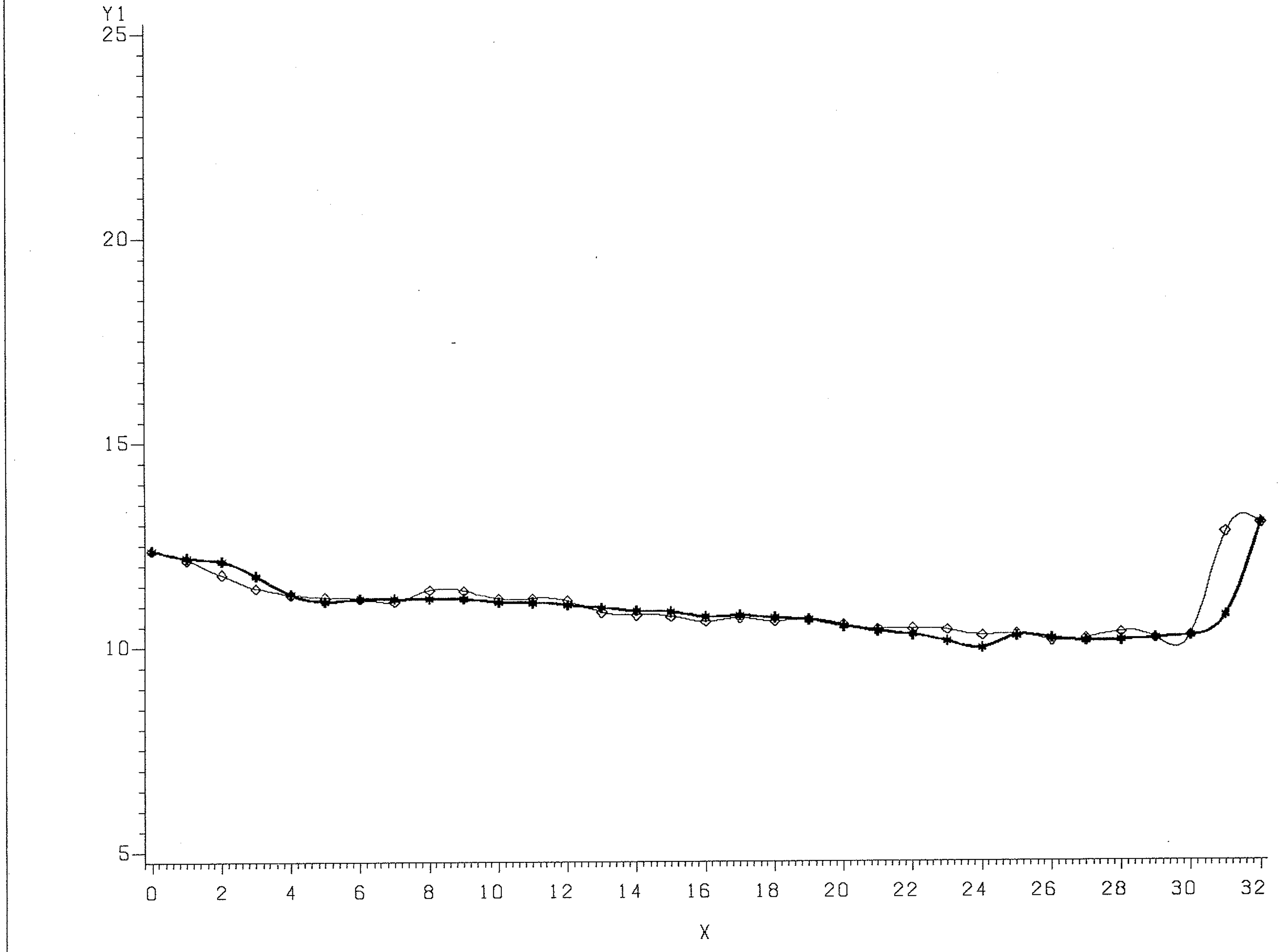

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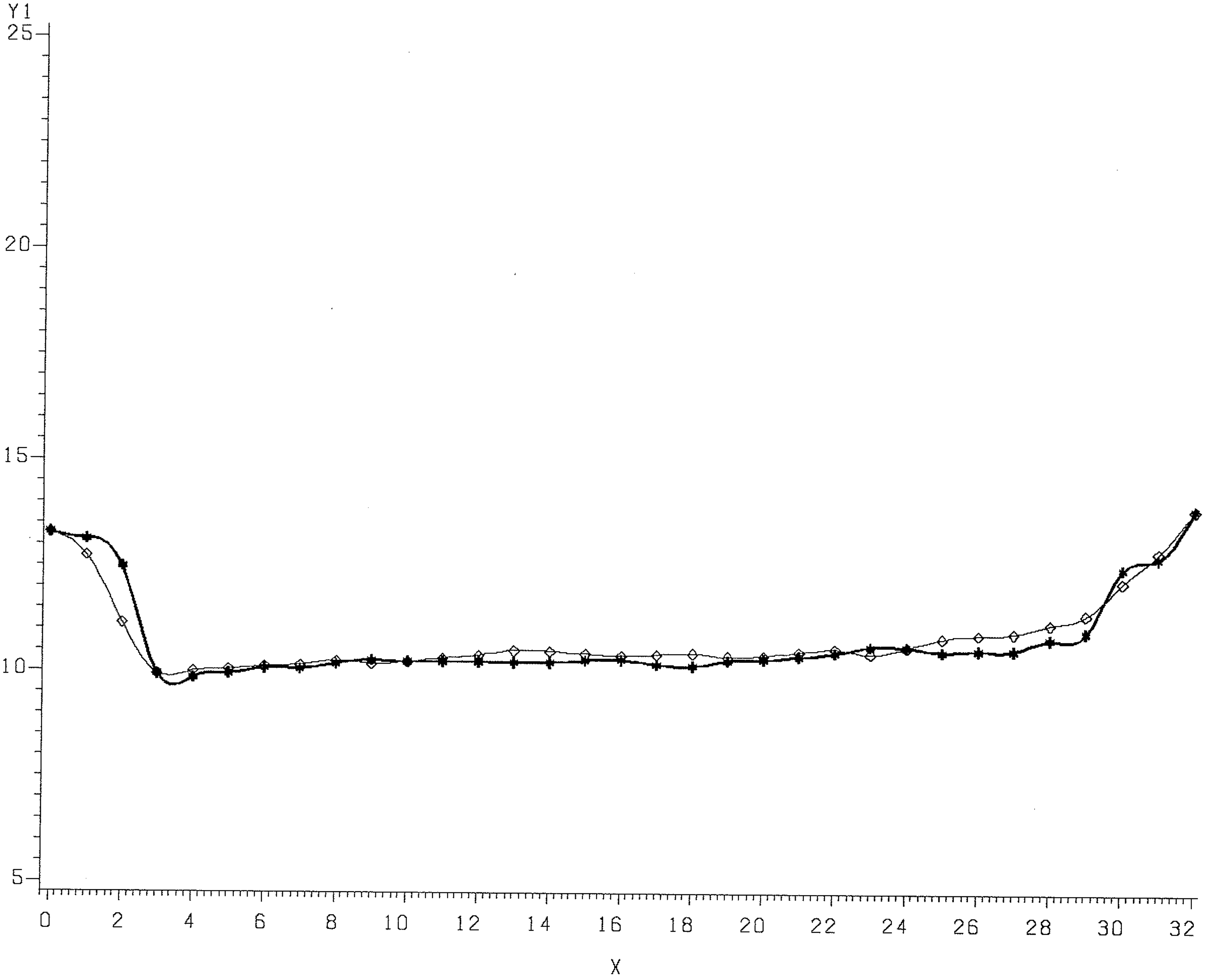
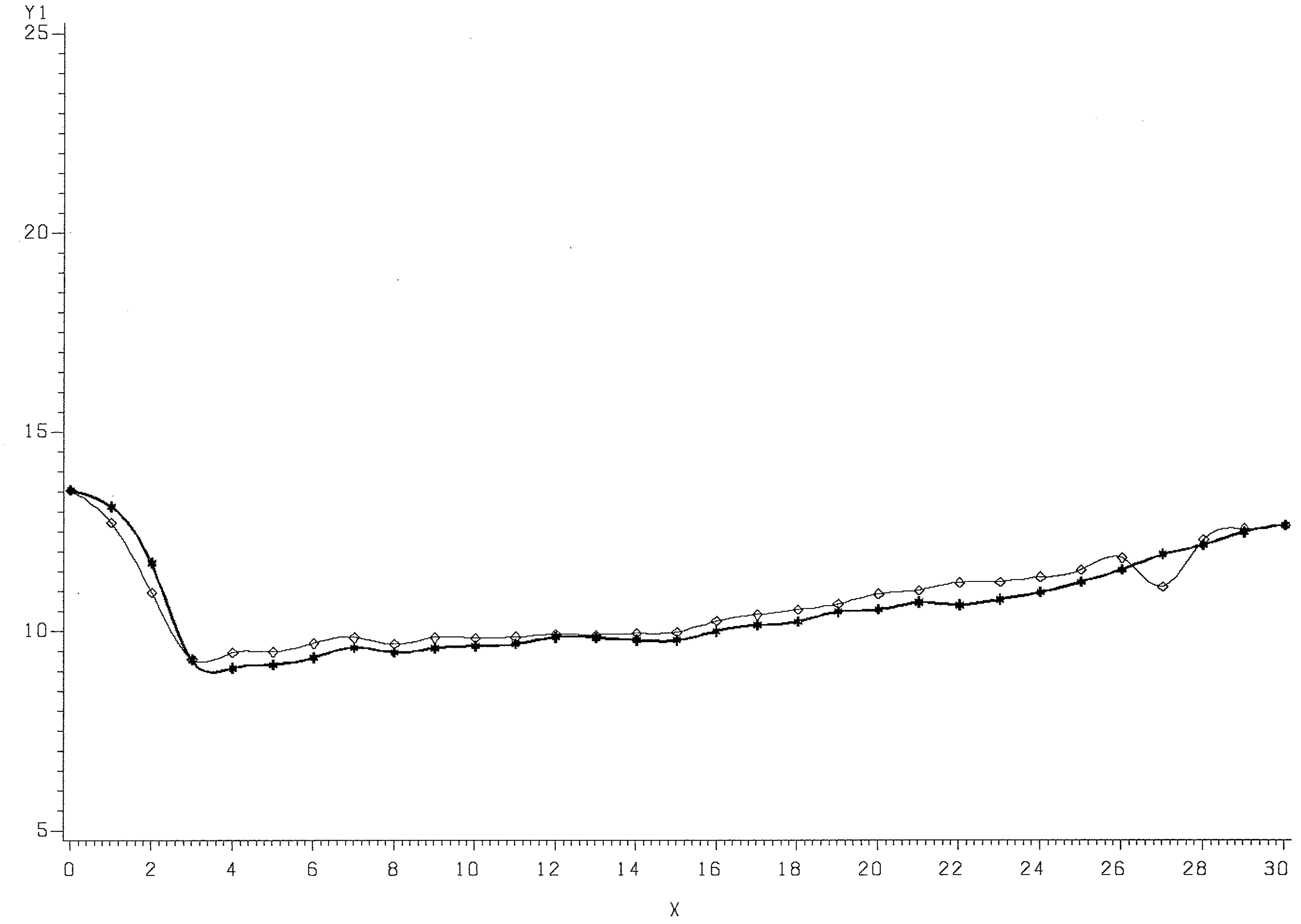
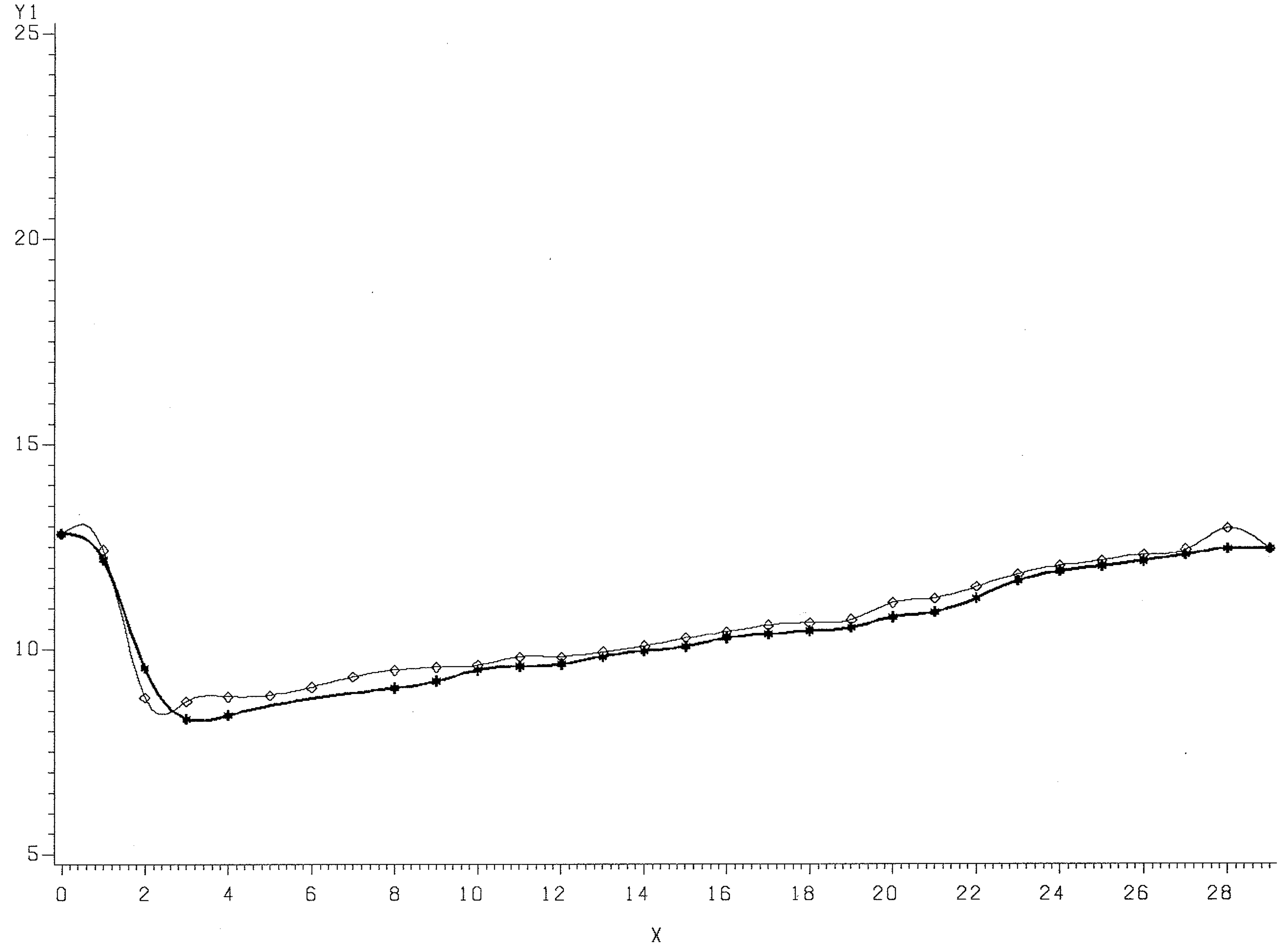



GRAVEL CREEK CROSS SECTION (A-19 post-flood 1981 and post-flood 1982)

GRAVEL CREEK CROSS SECTION (A-20 post-flood 1981 and post-flood 1982)



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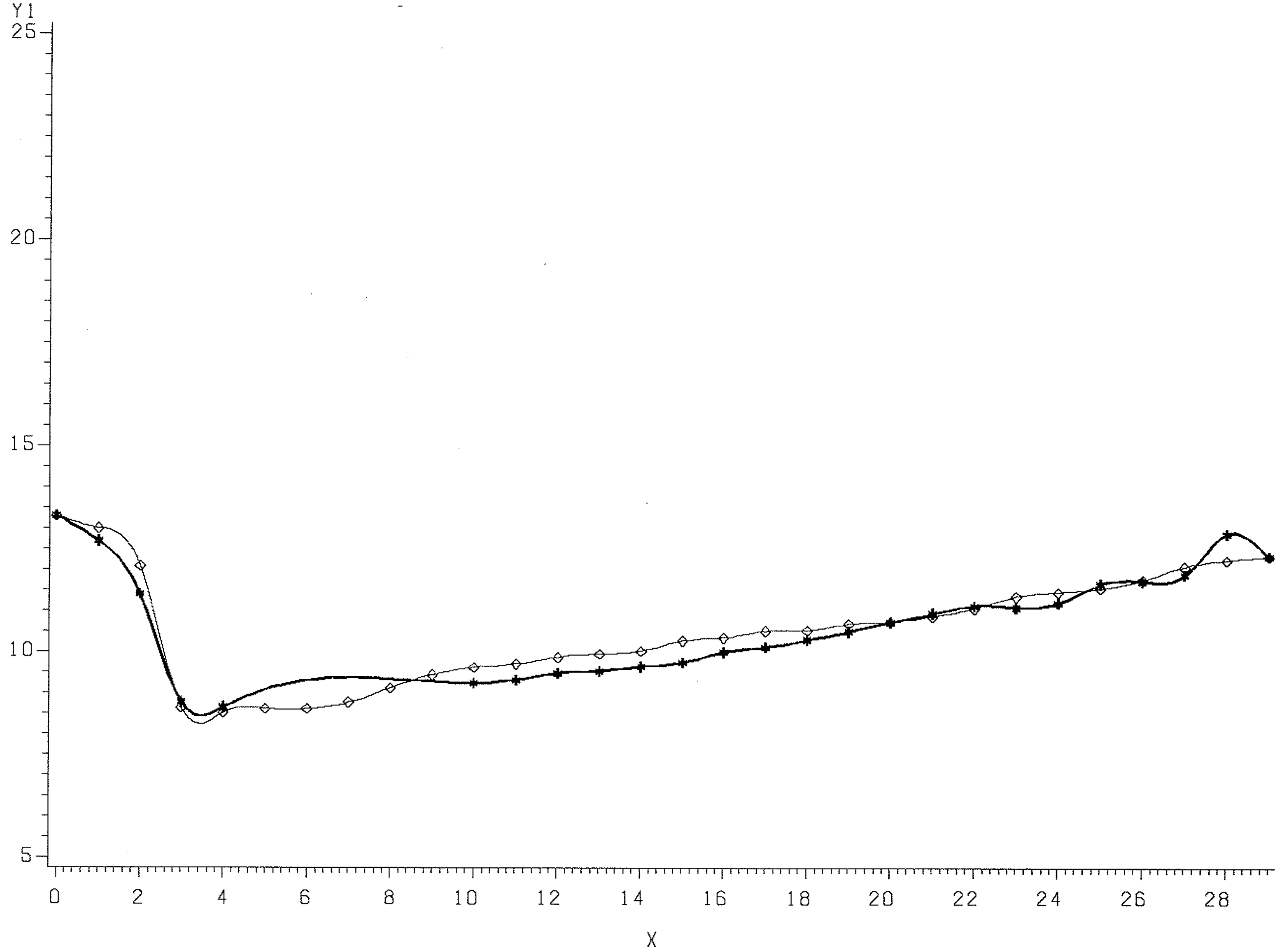

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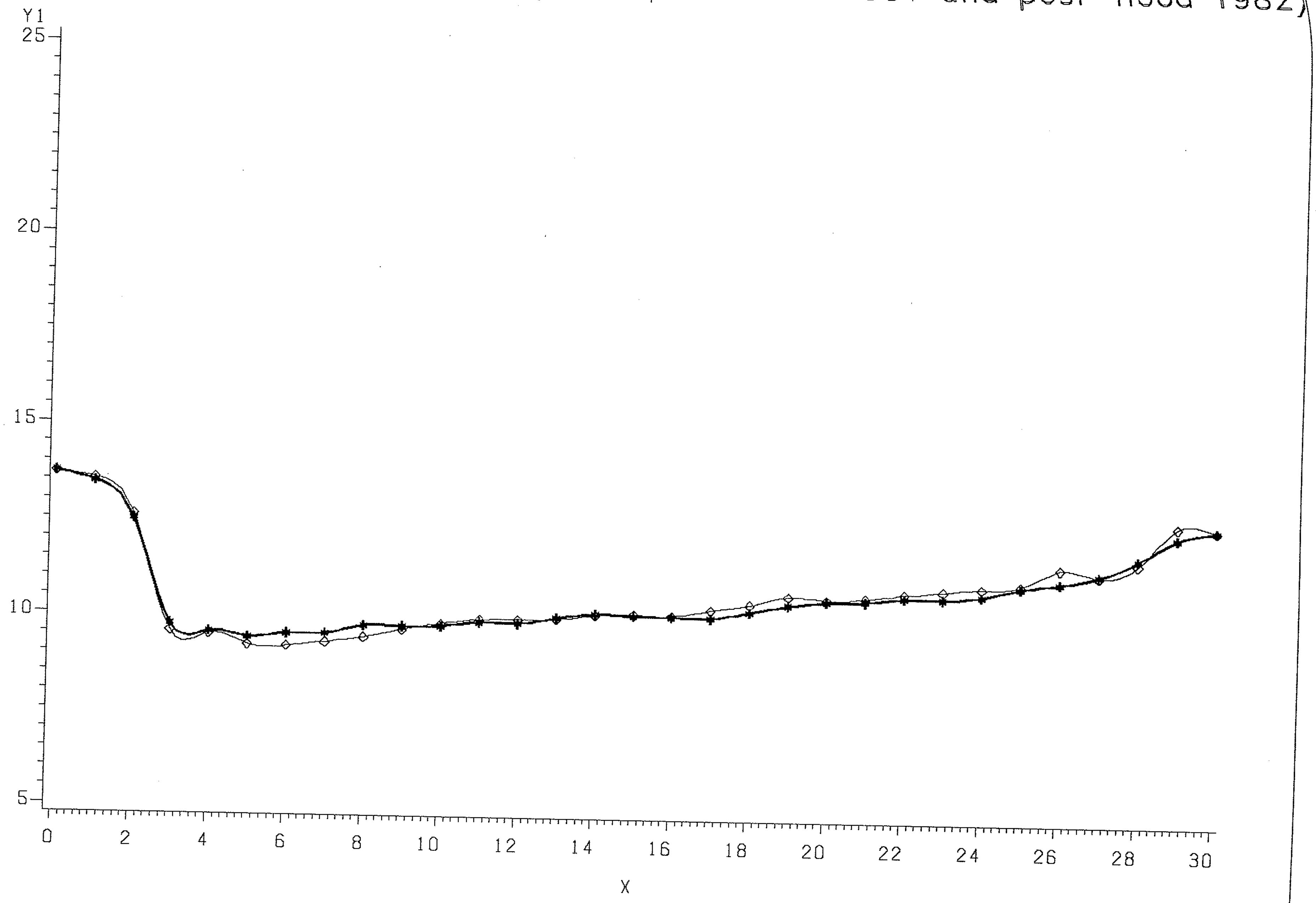

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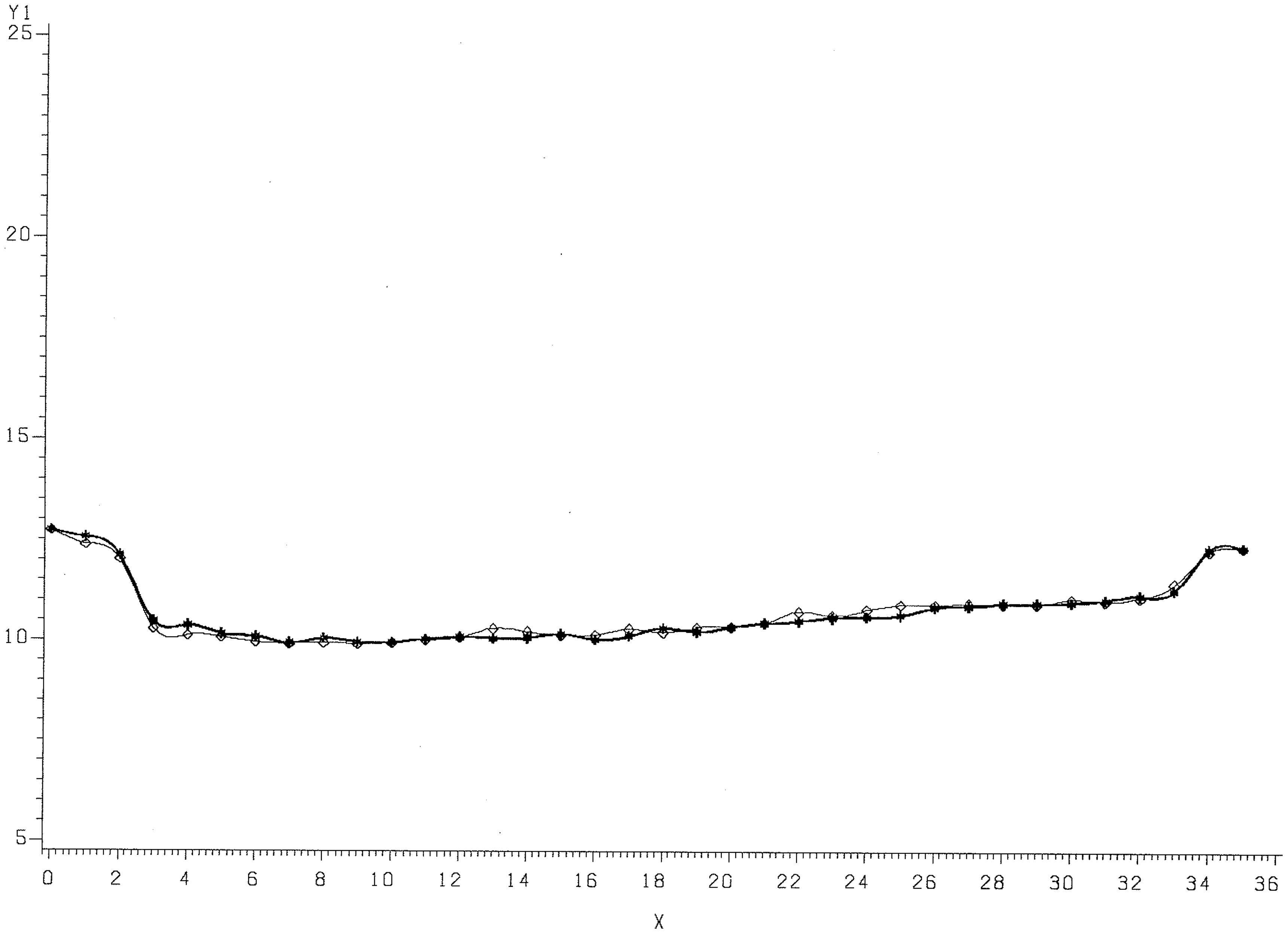

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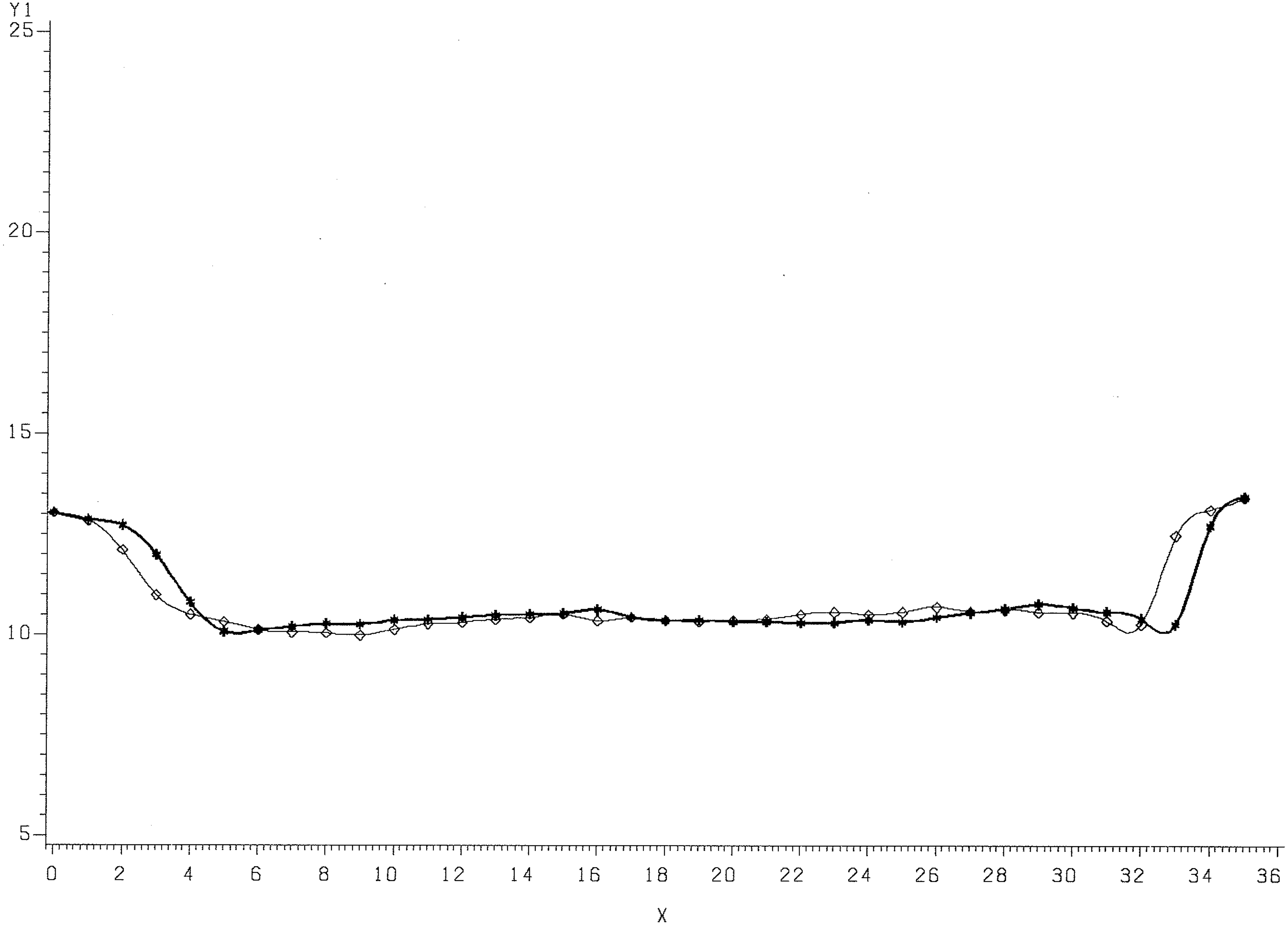

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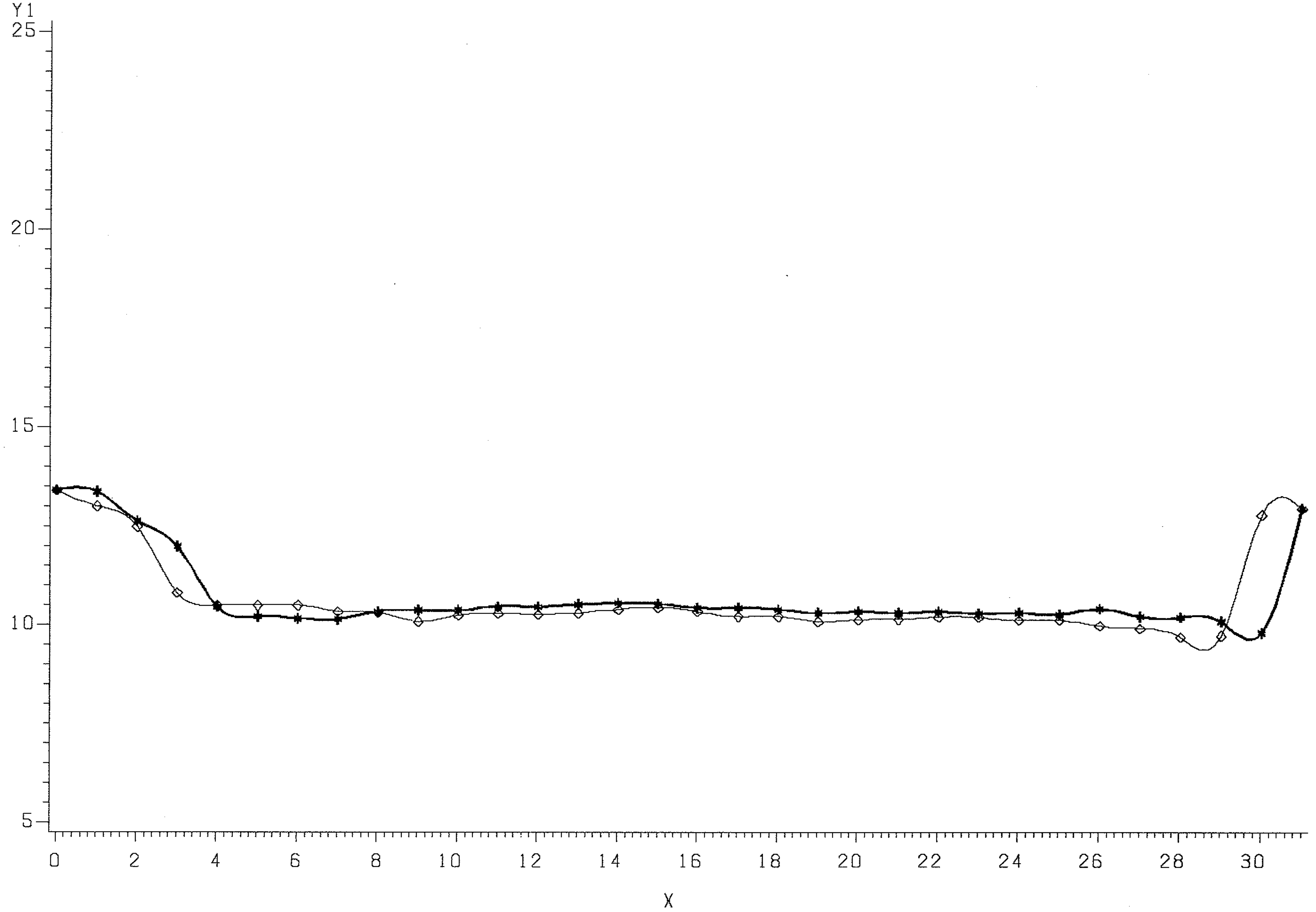

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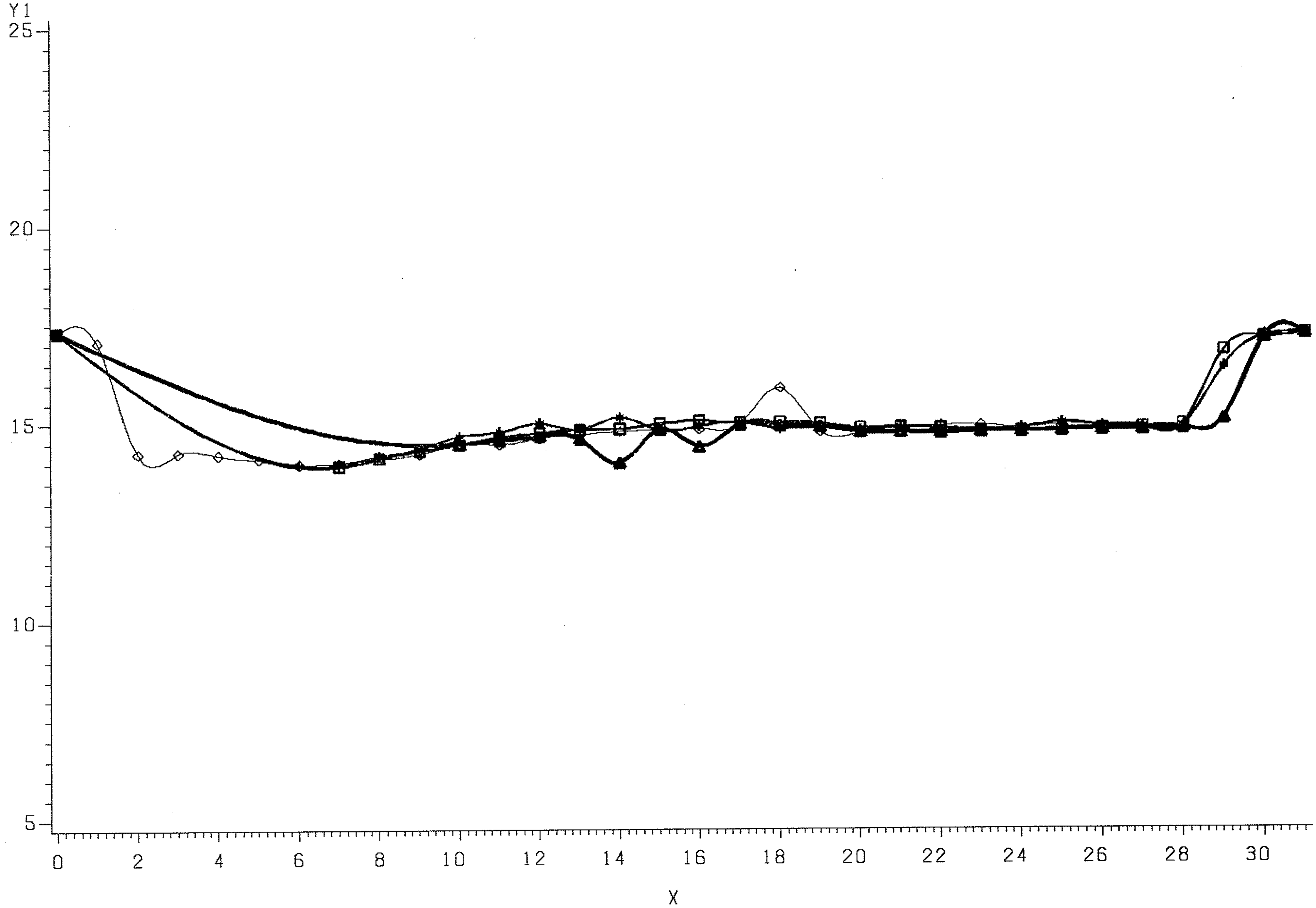

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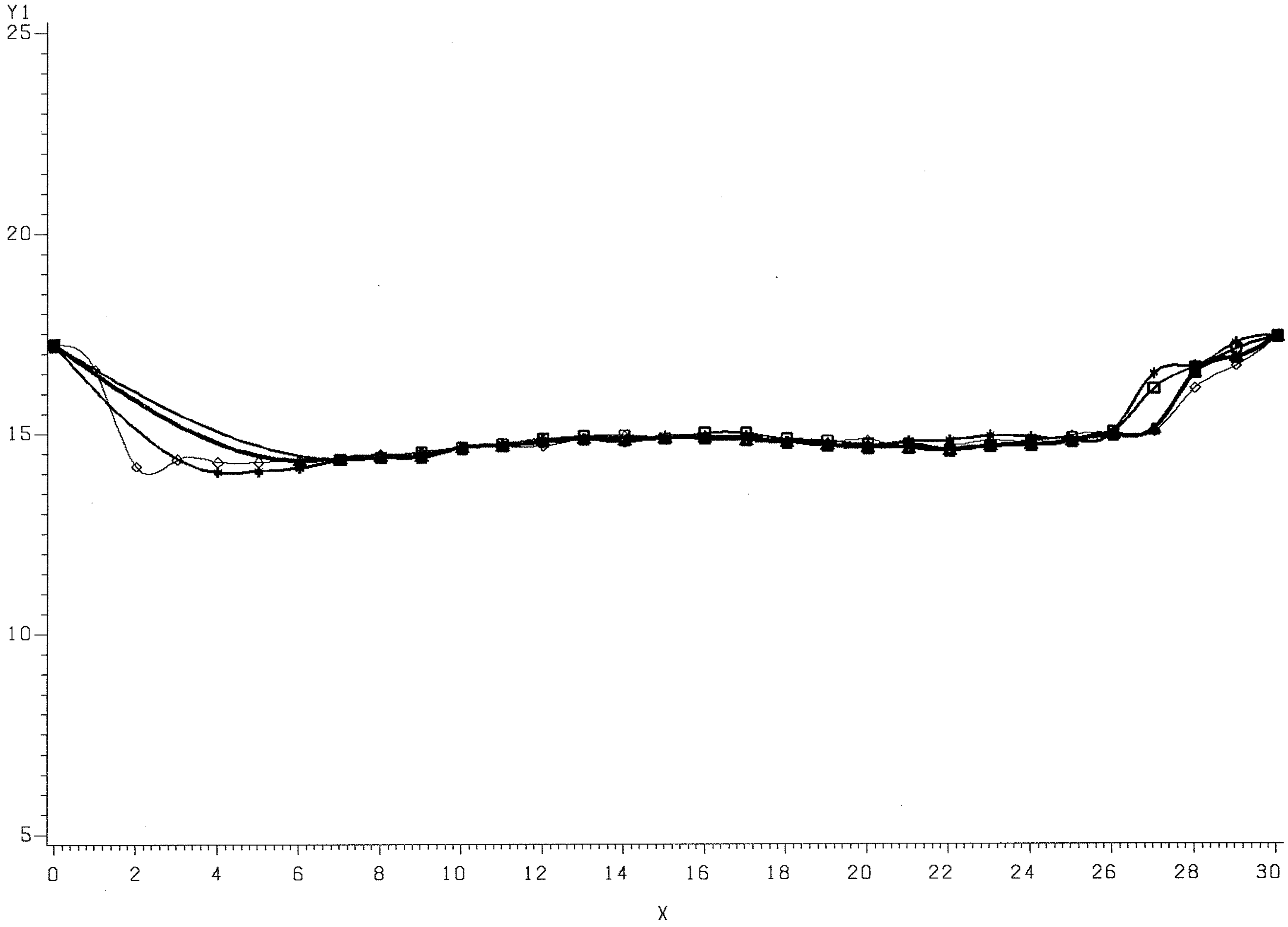

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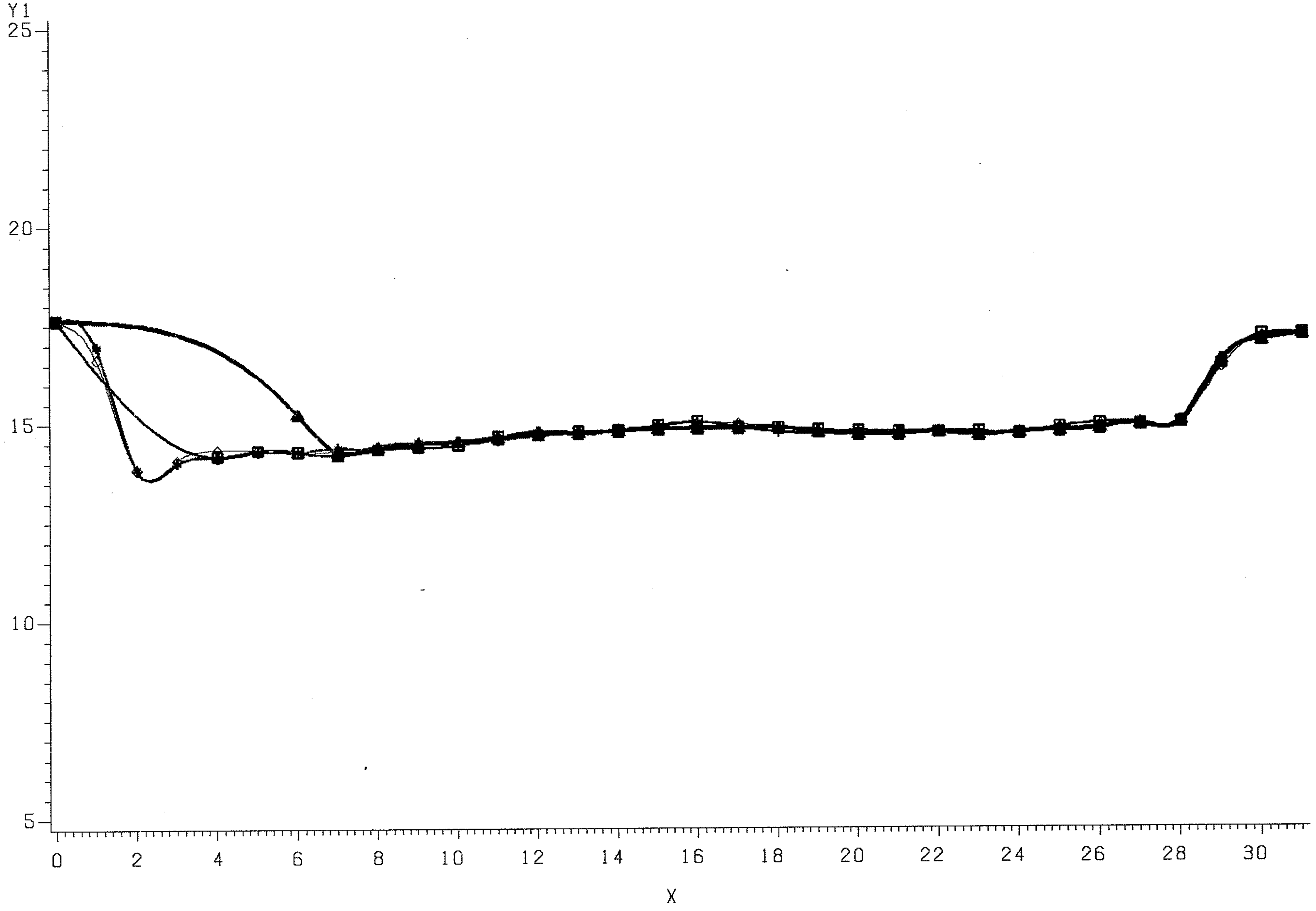

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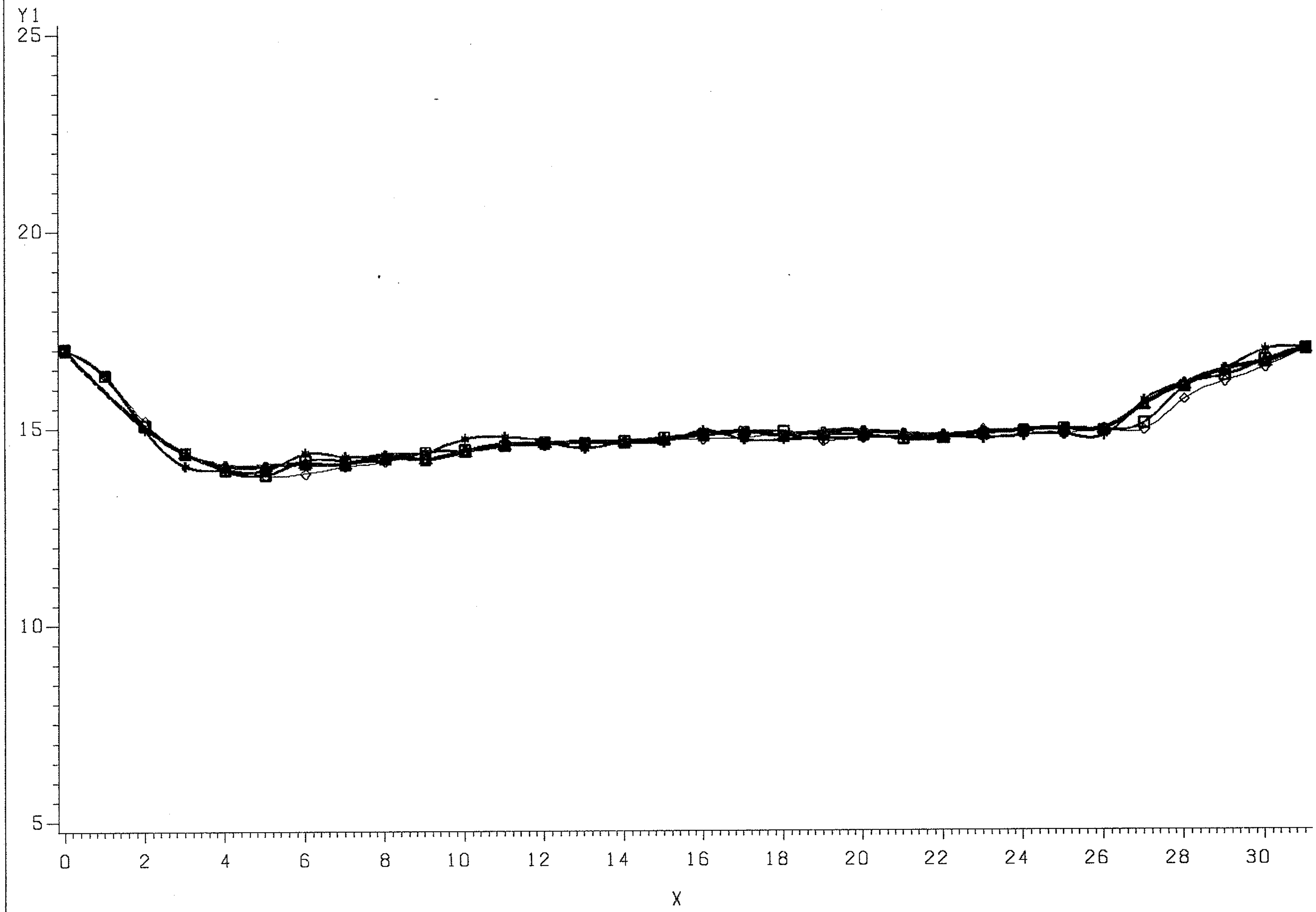

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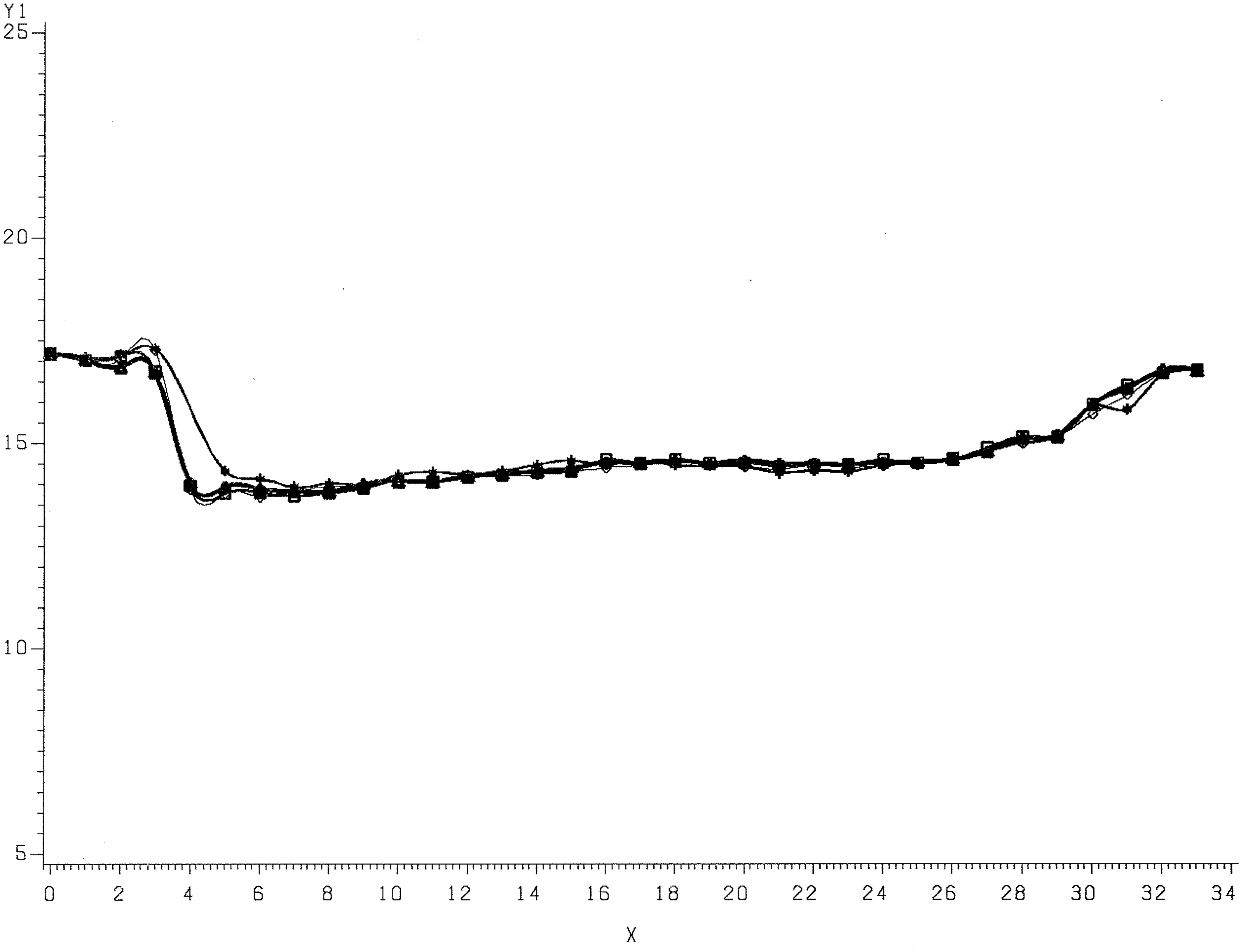

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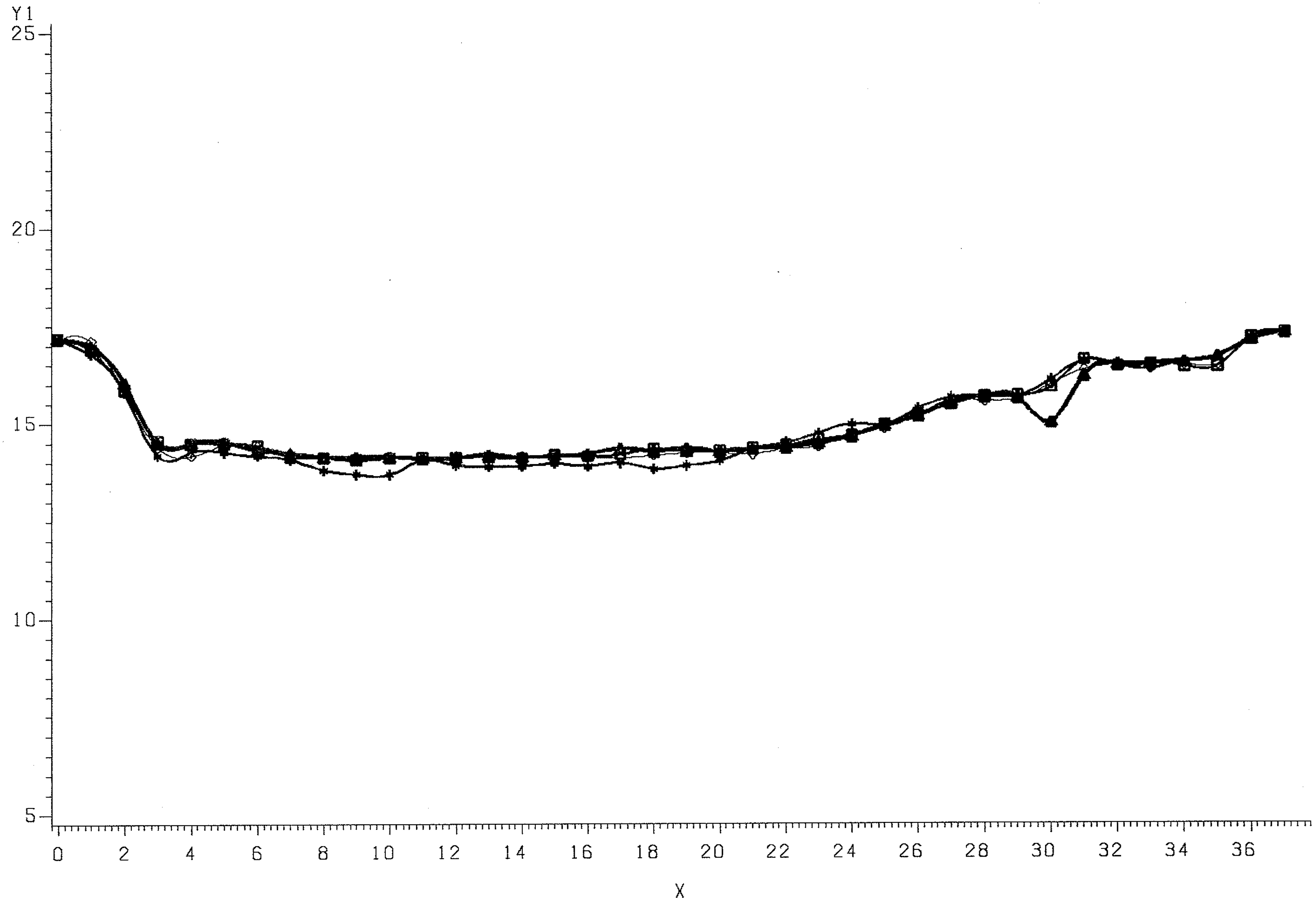

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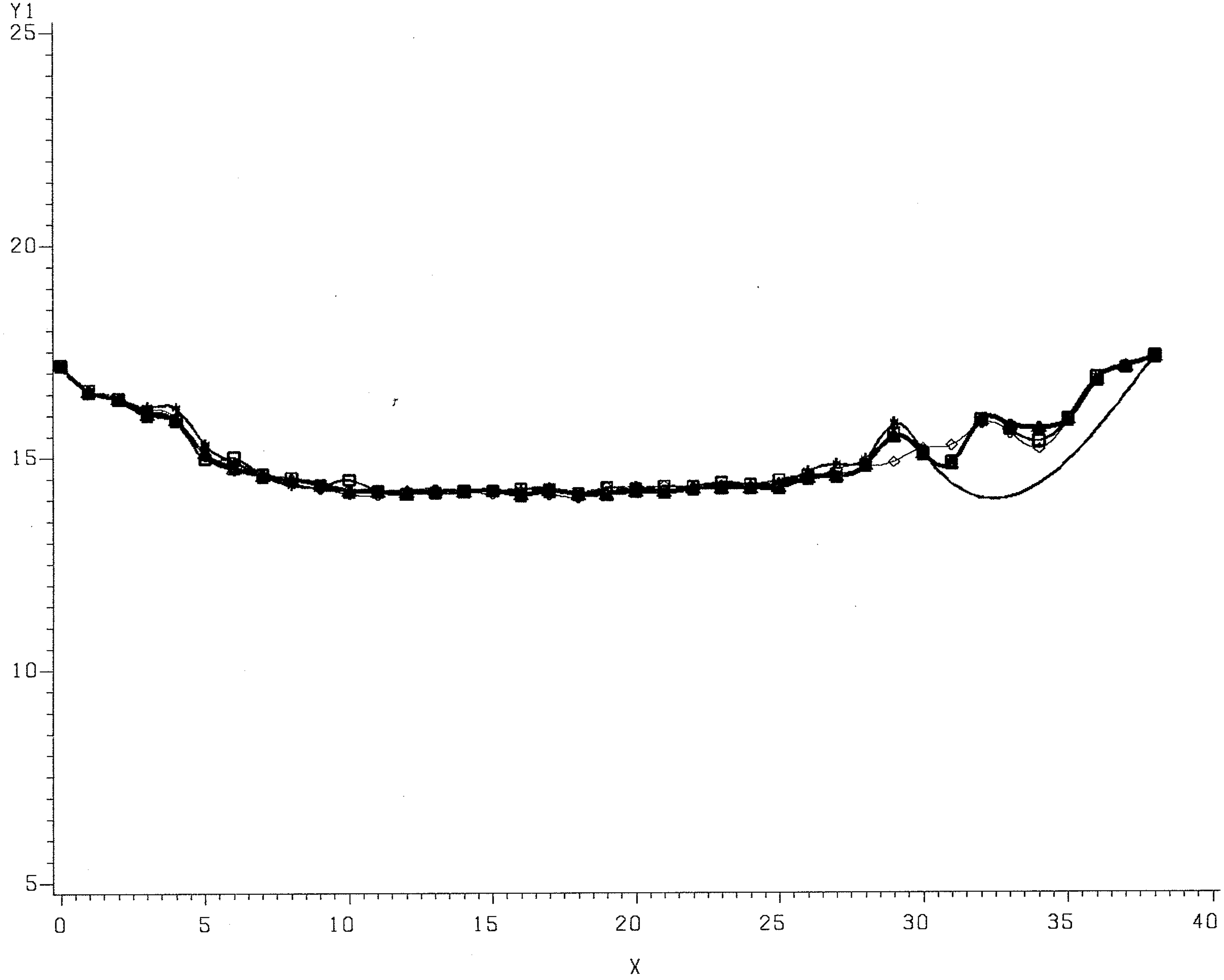

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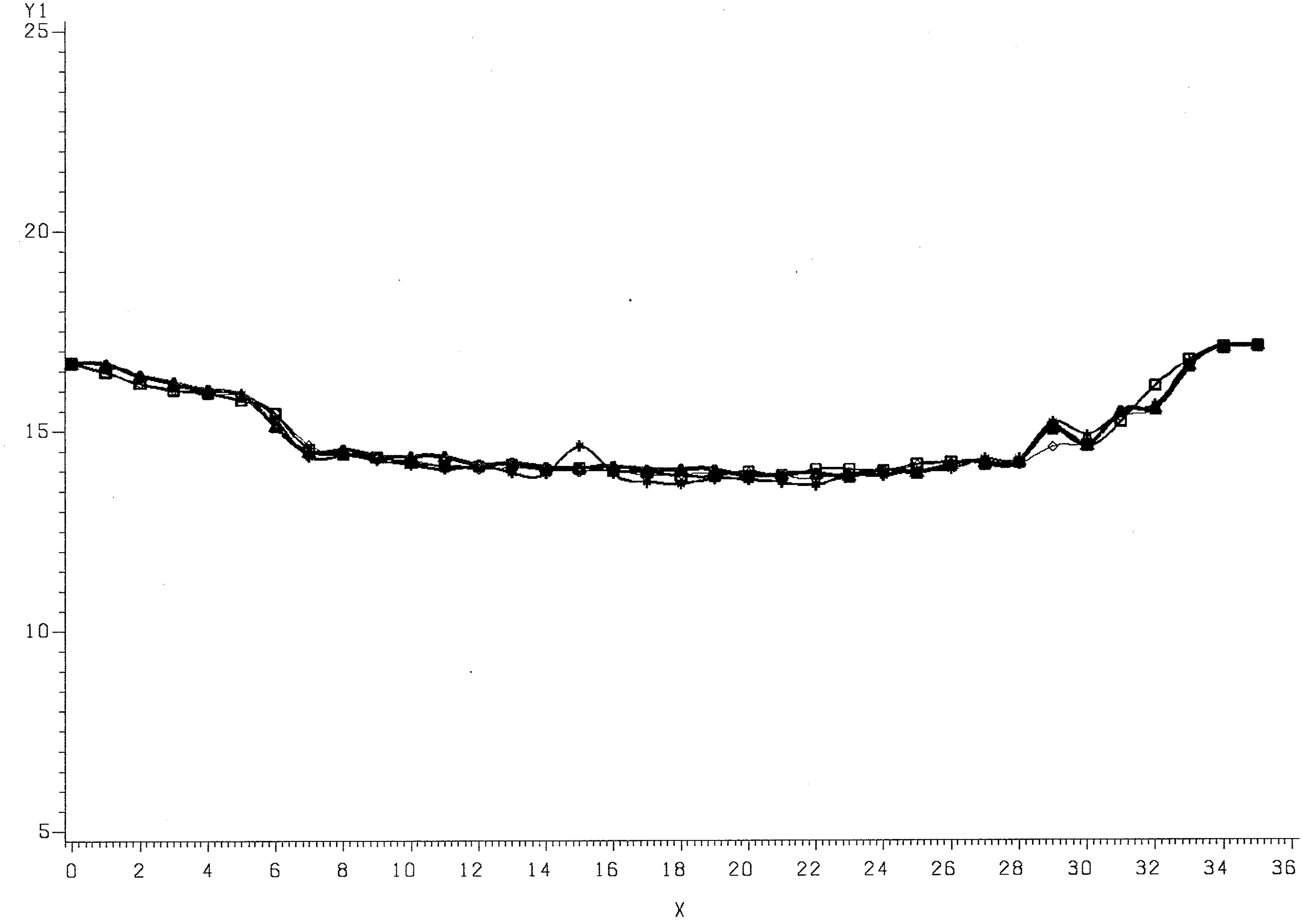

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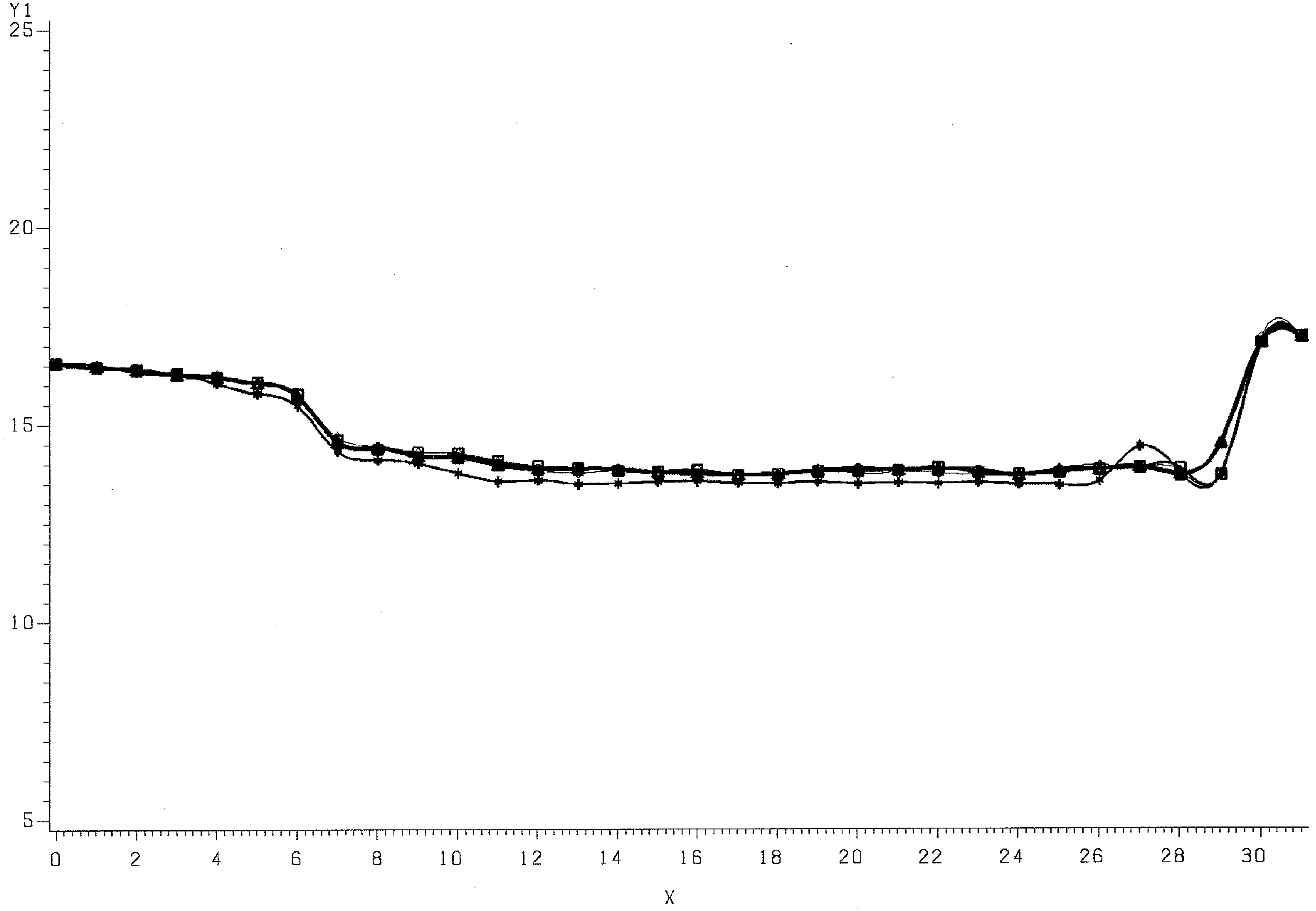

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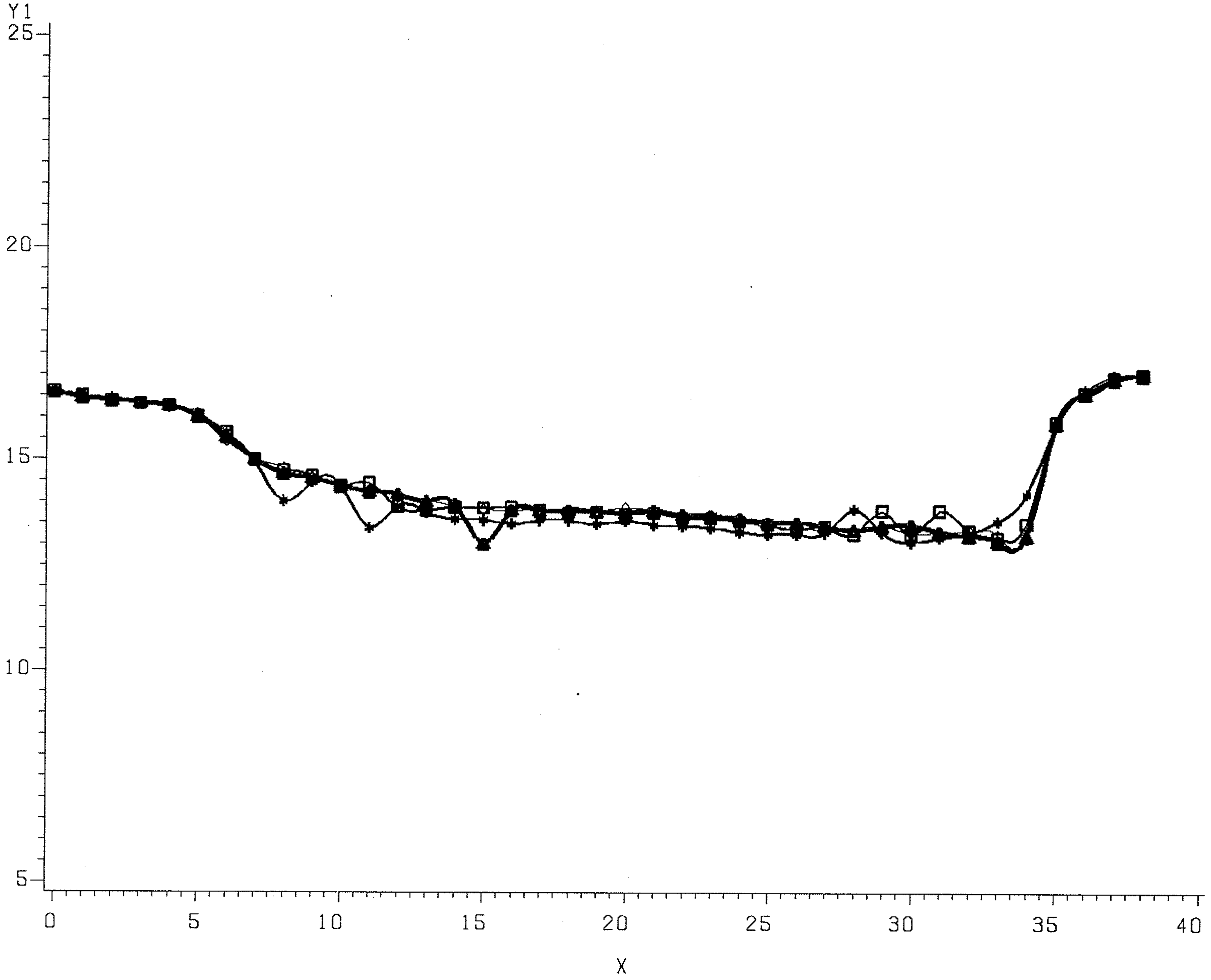
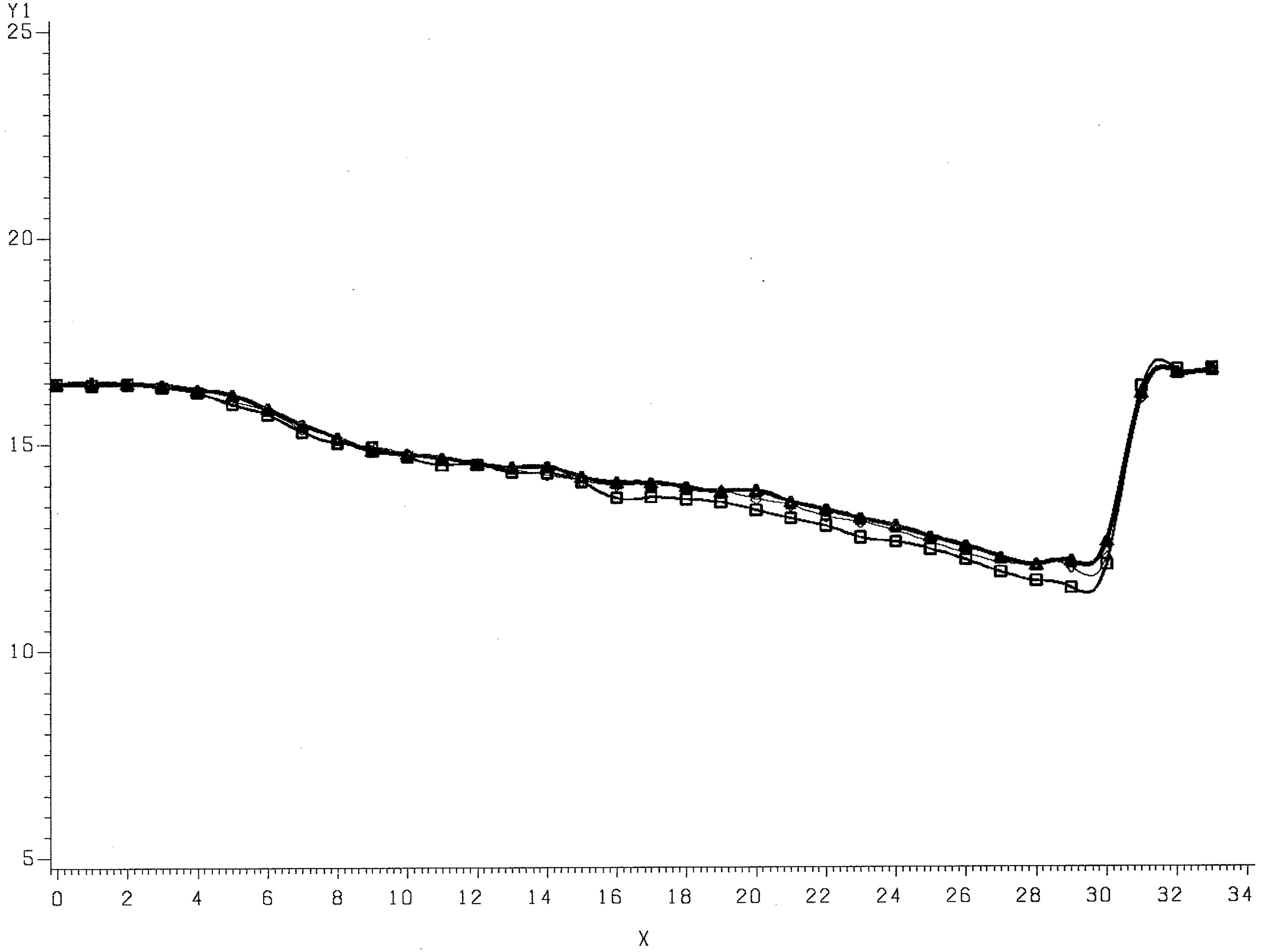
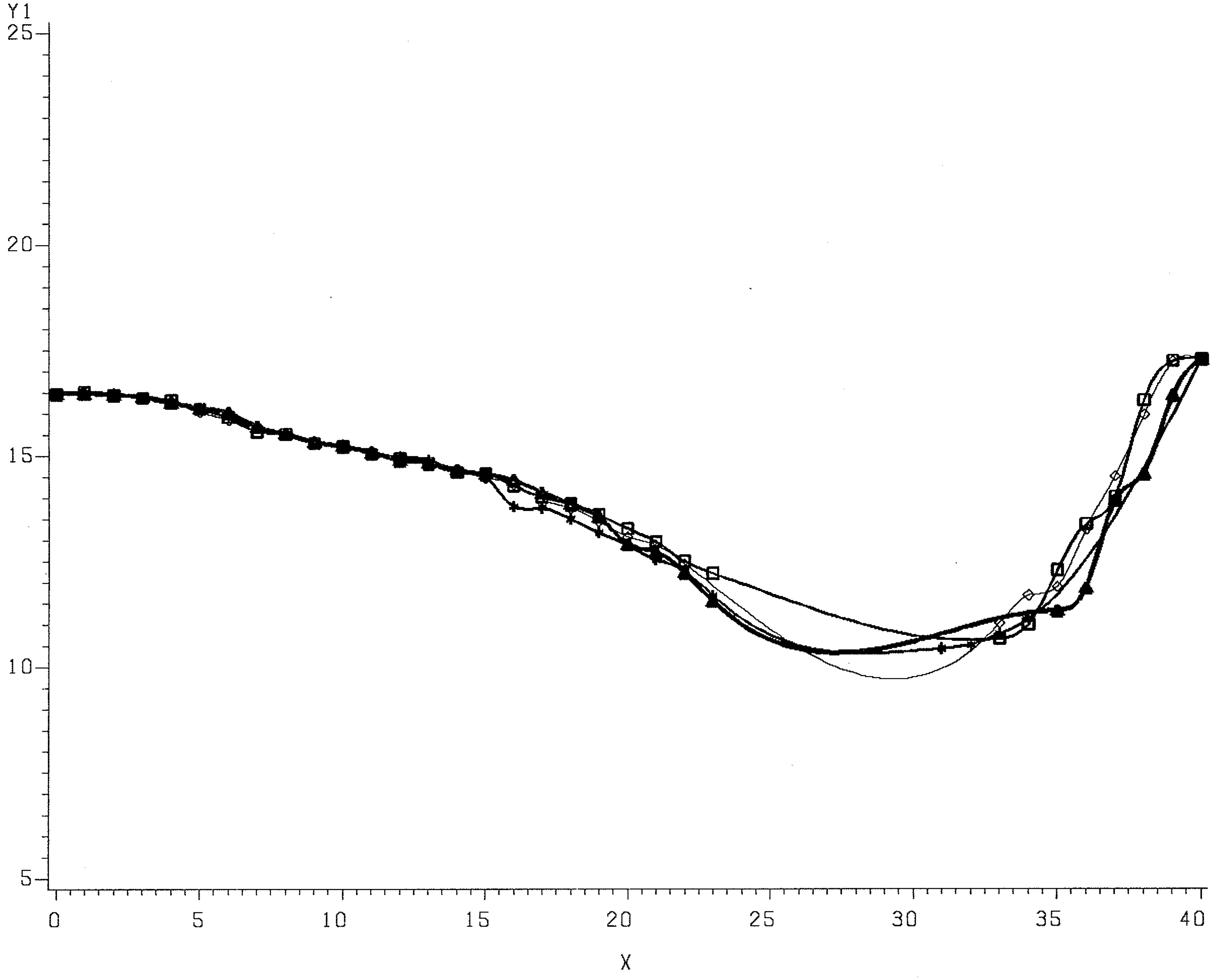


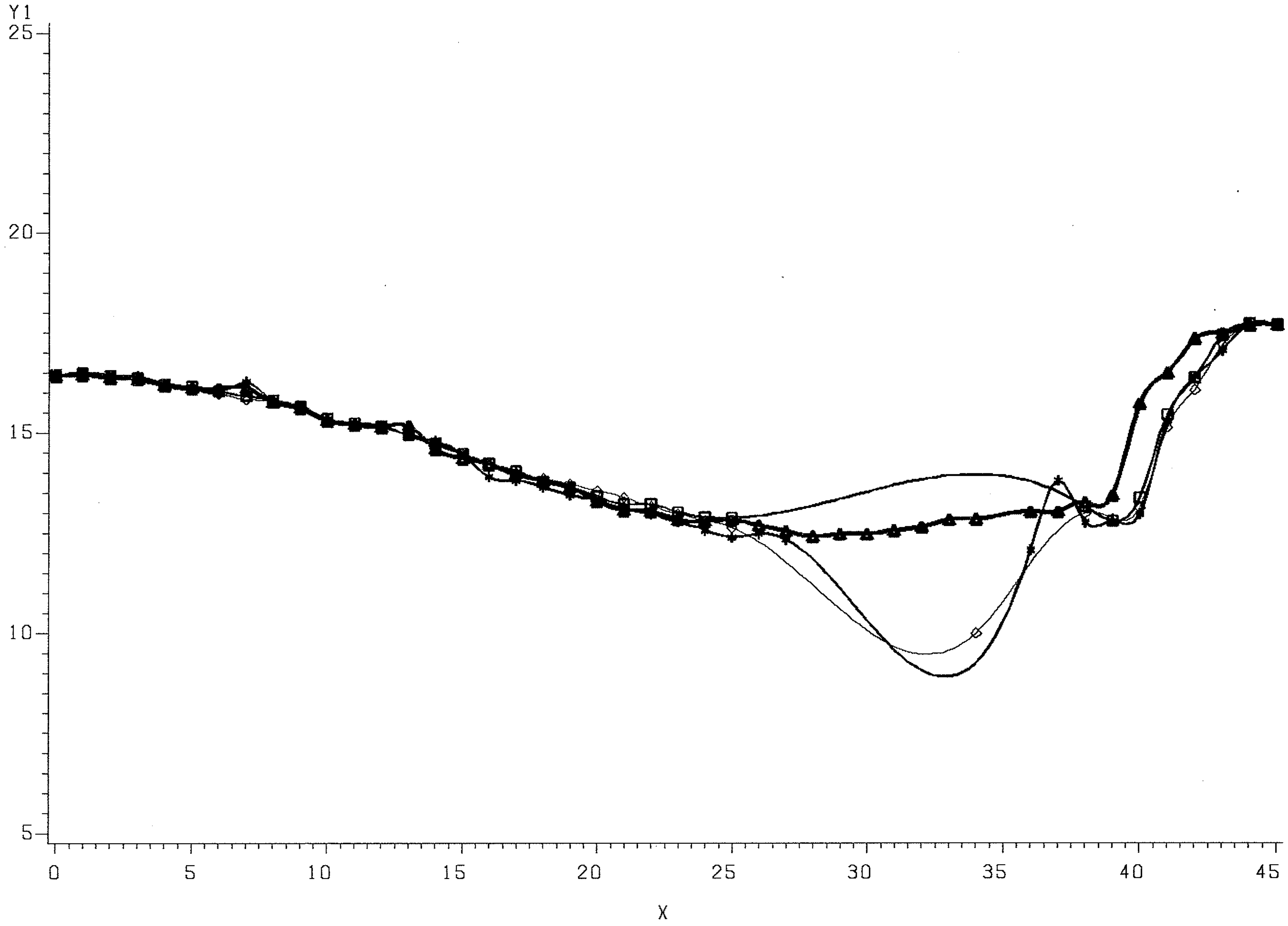
GRAVEL CREEK CROSS SECTION (B-11 1981,1982 post breakup,1982 postflood



GRAVEL CREEK CROSS SECTION (B-12 1981,1982 post breakup,1982 postflood



GRAVEL CREEK CROSS SECTION (B-13 1981,1982 post breakup,1982 postflood



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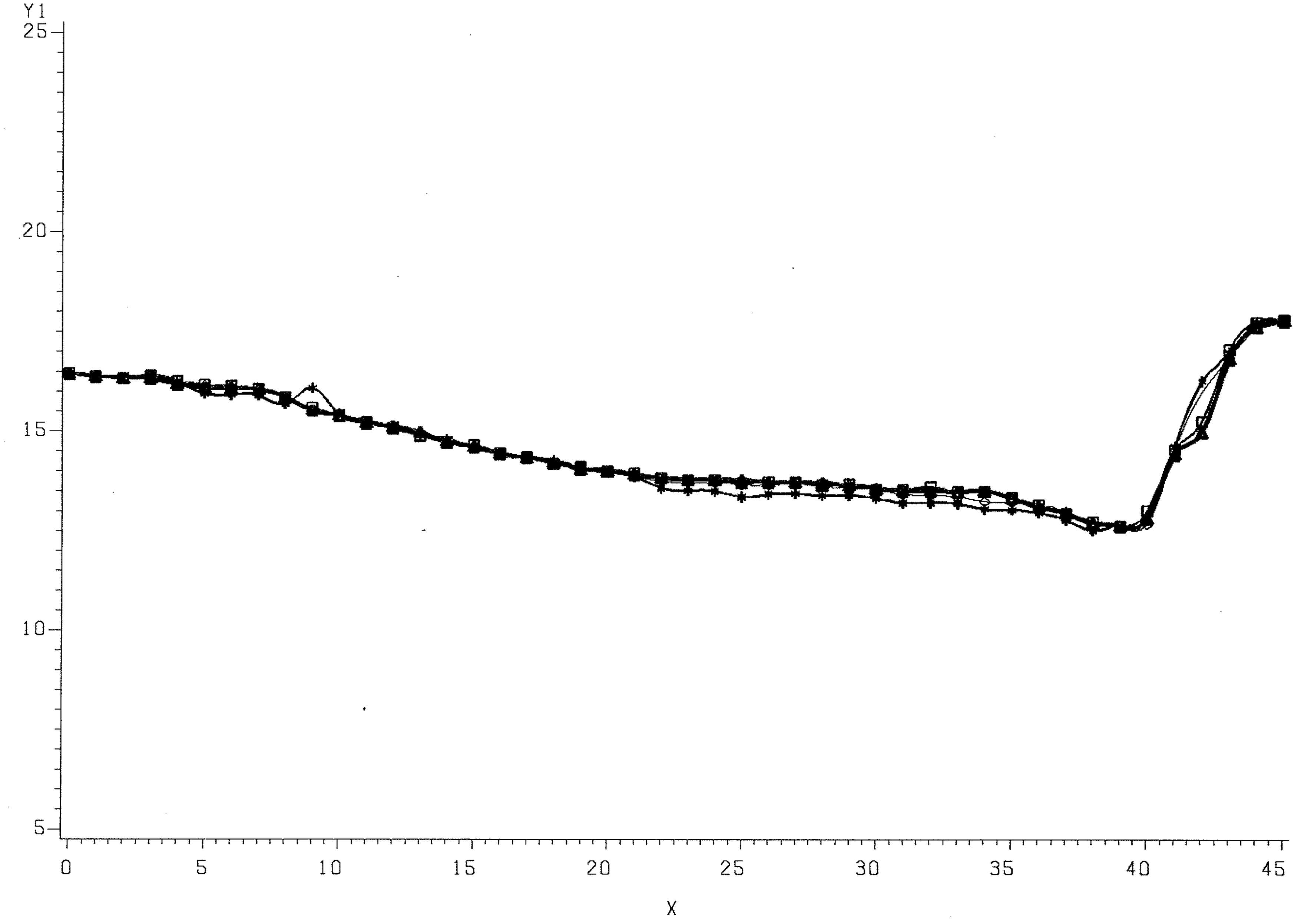
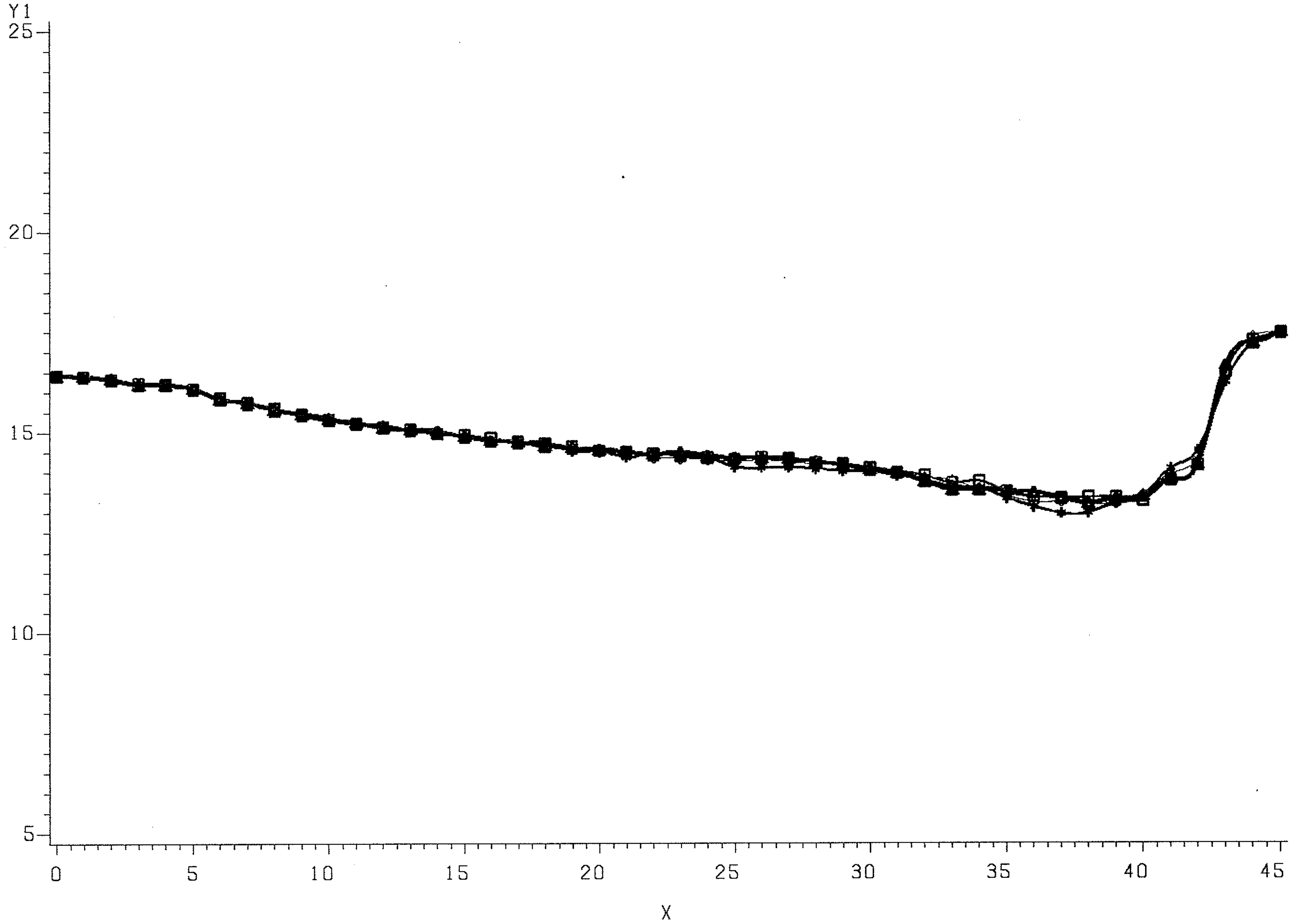
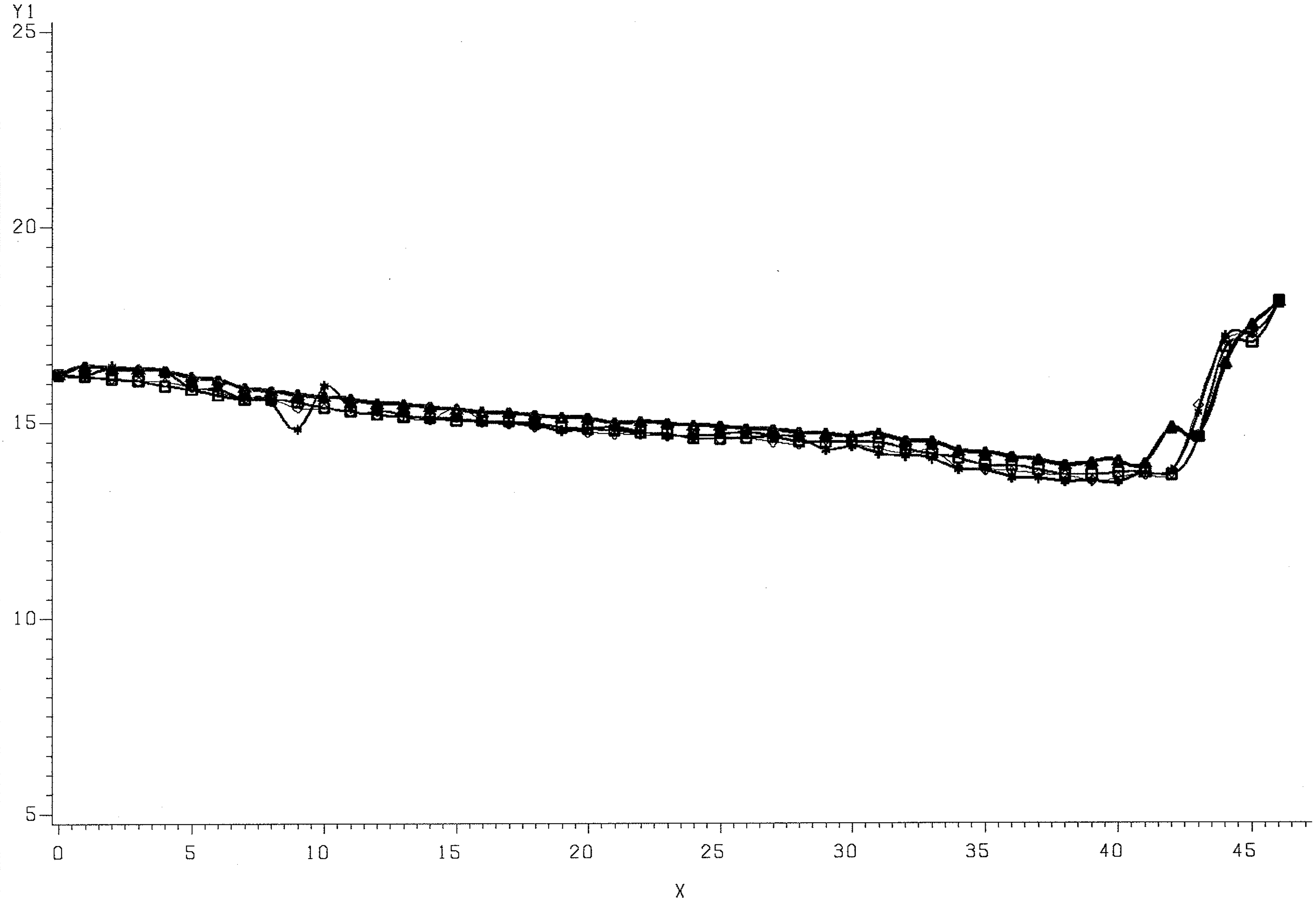
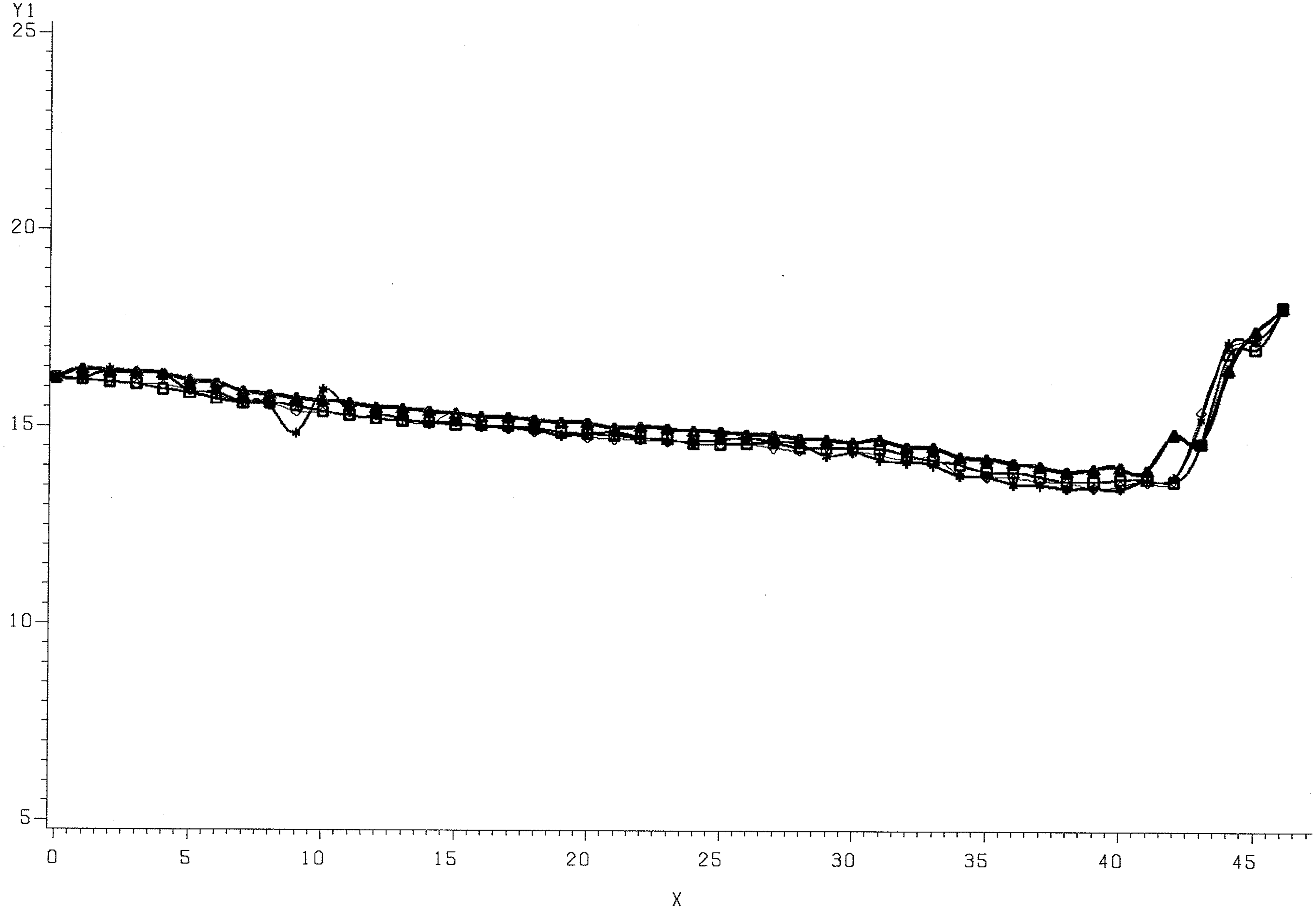


GRAVEL CREEK CROSS SECTION (B-15 1981,1982 post breakup,1982 postflood



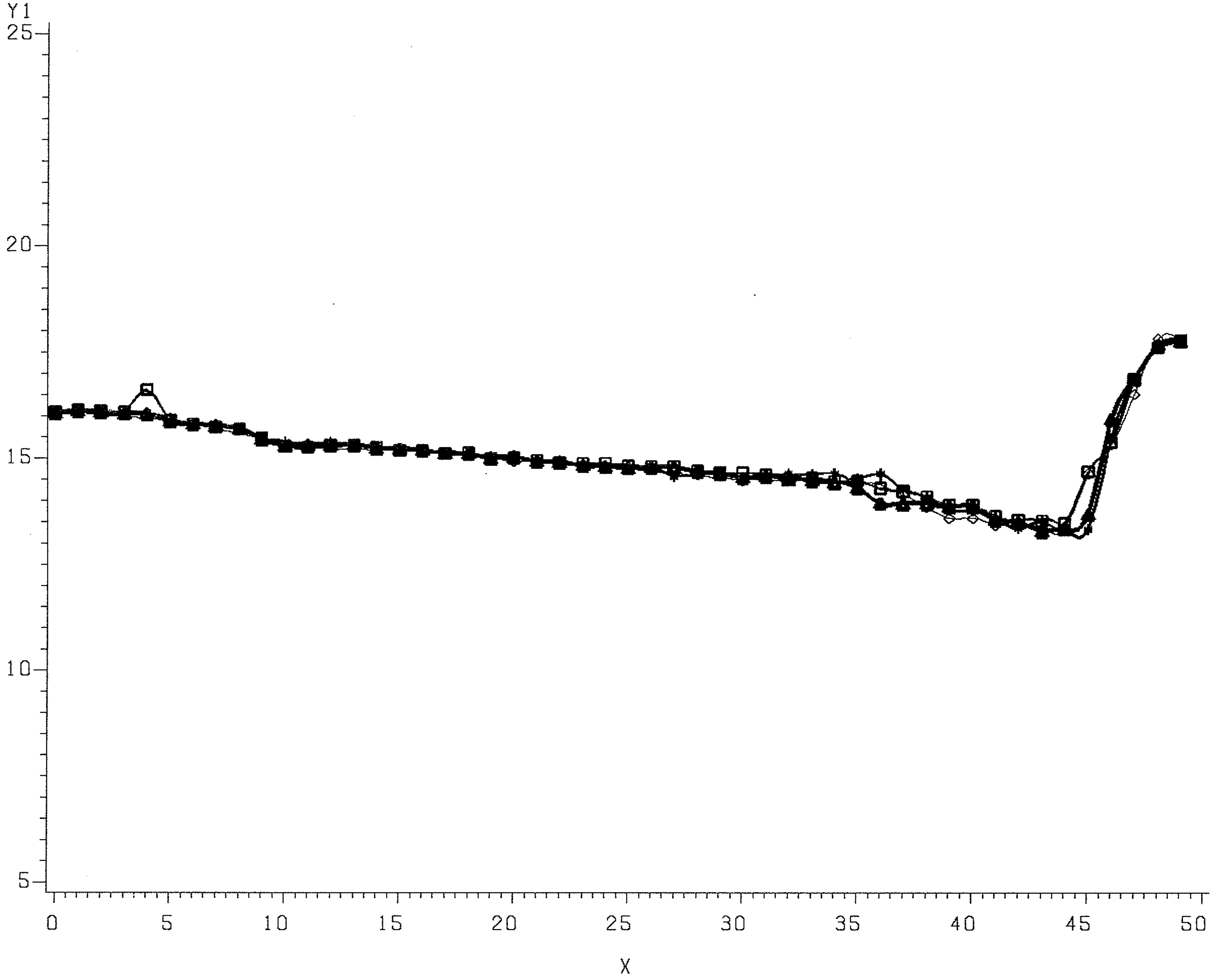
GRAVEL CREEK CROSS SECTION (B-16 1981,1982 post breakup,1982 postflood





GRAVEL CREEK CROSS SECTION (B-16 1981,1982 post breakup,1982 postflood

GRAVEL CREEK CROSS SECTION (B-17 1981,1982 post breakup,1982 postflood



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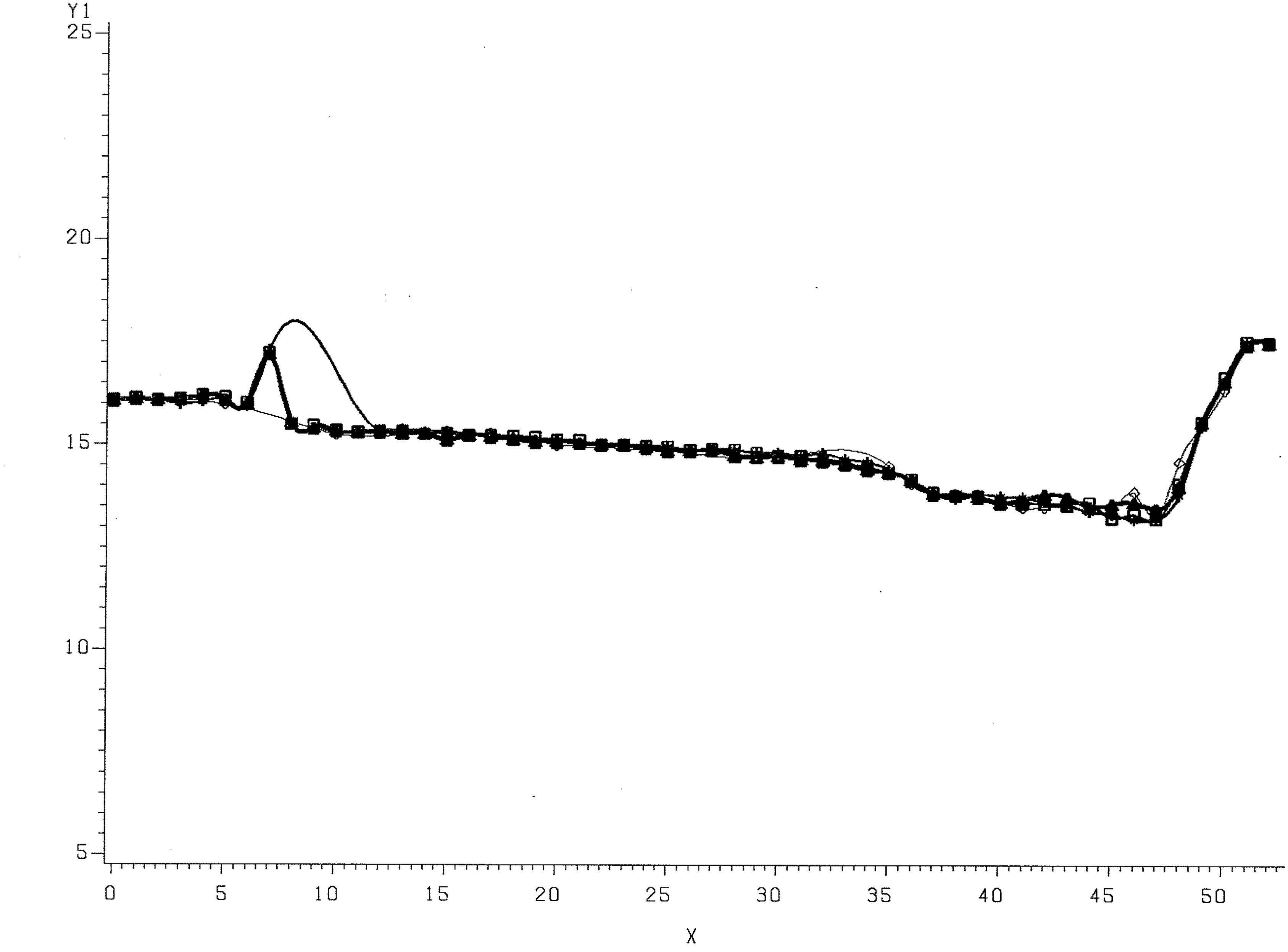
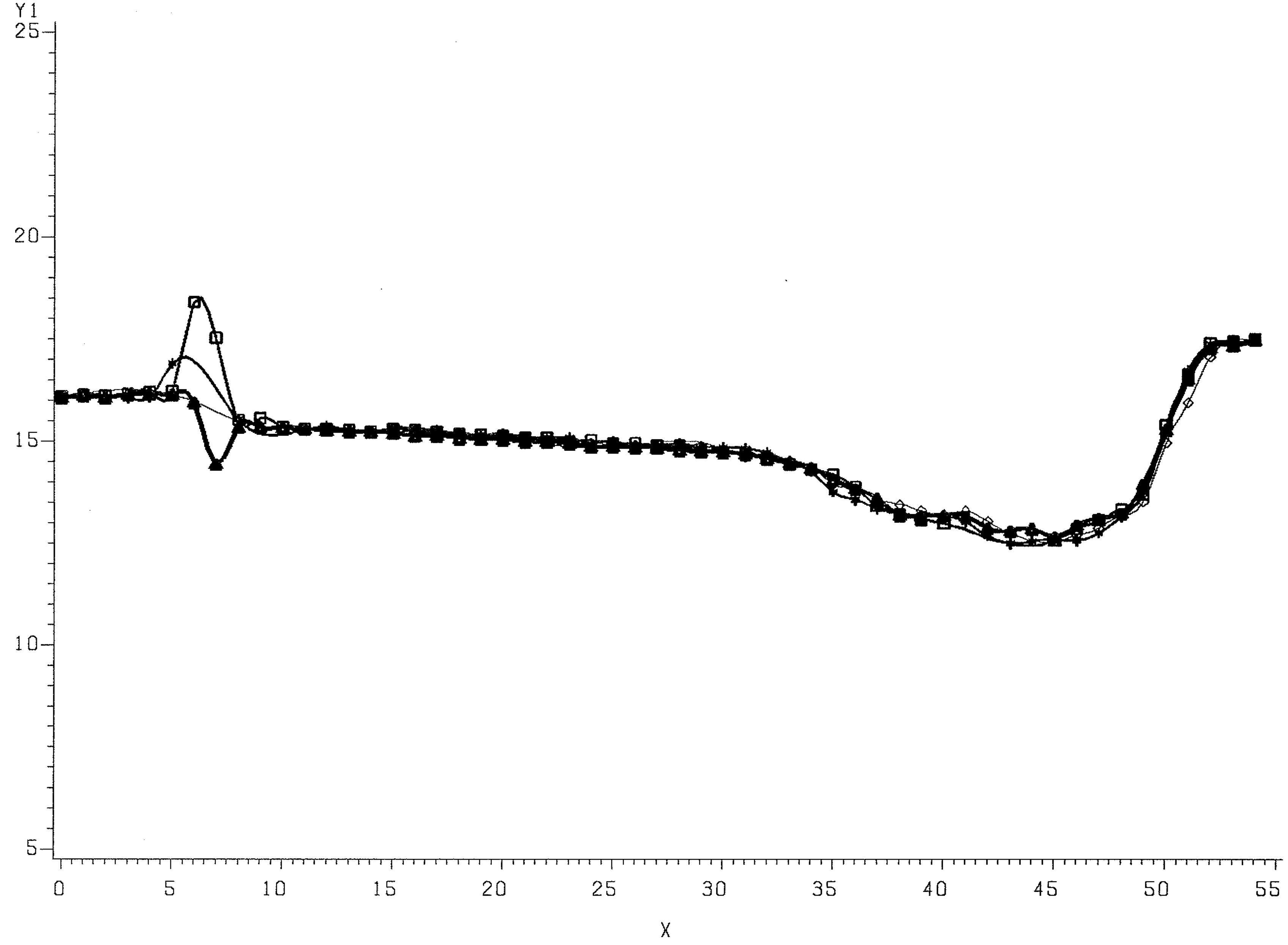


GRAVEL CREEK CROSS SECTION (B-18b 1981,1982 post breakup,1982 postfloo



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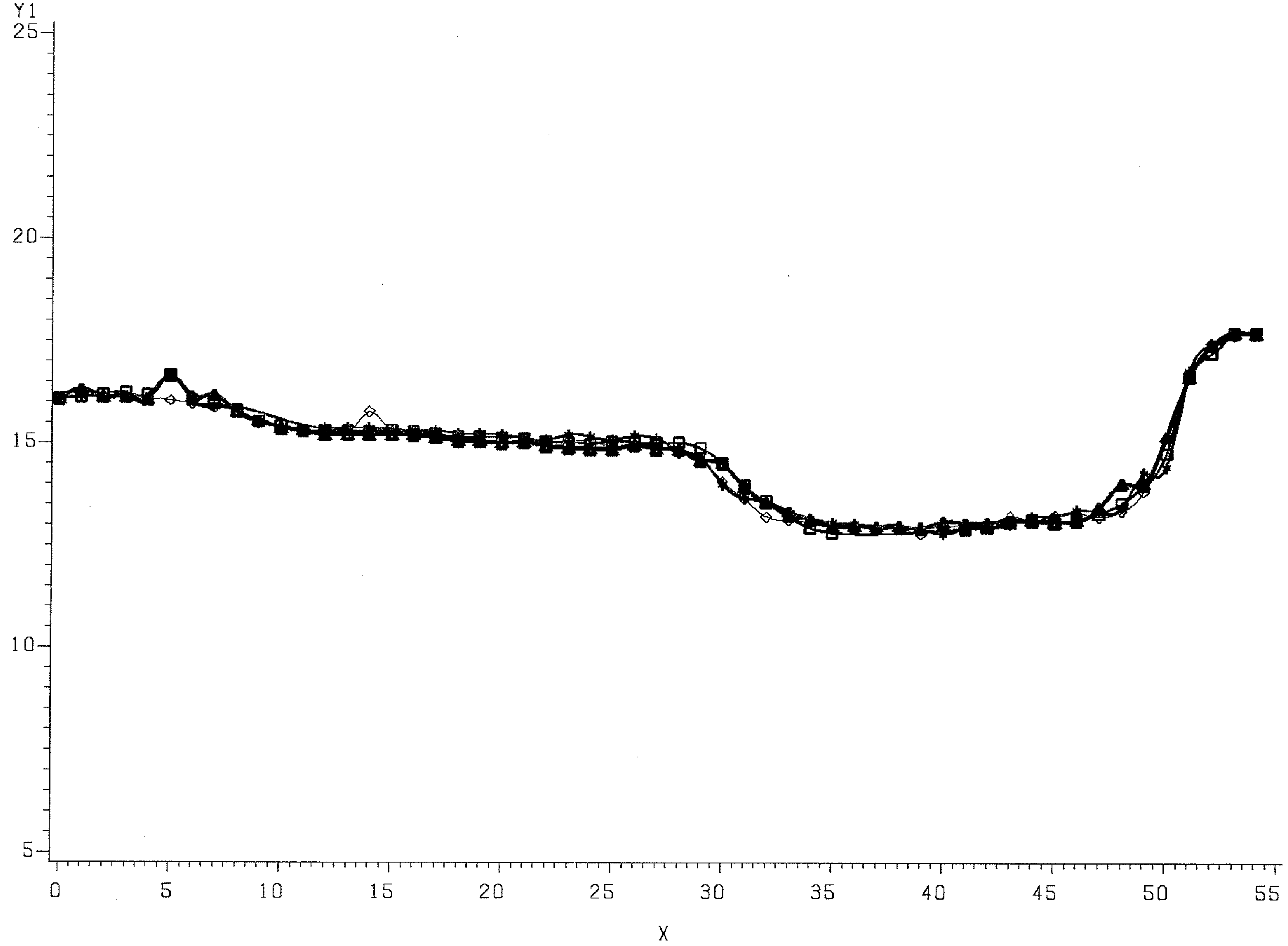

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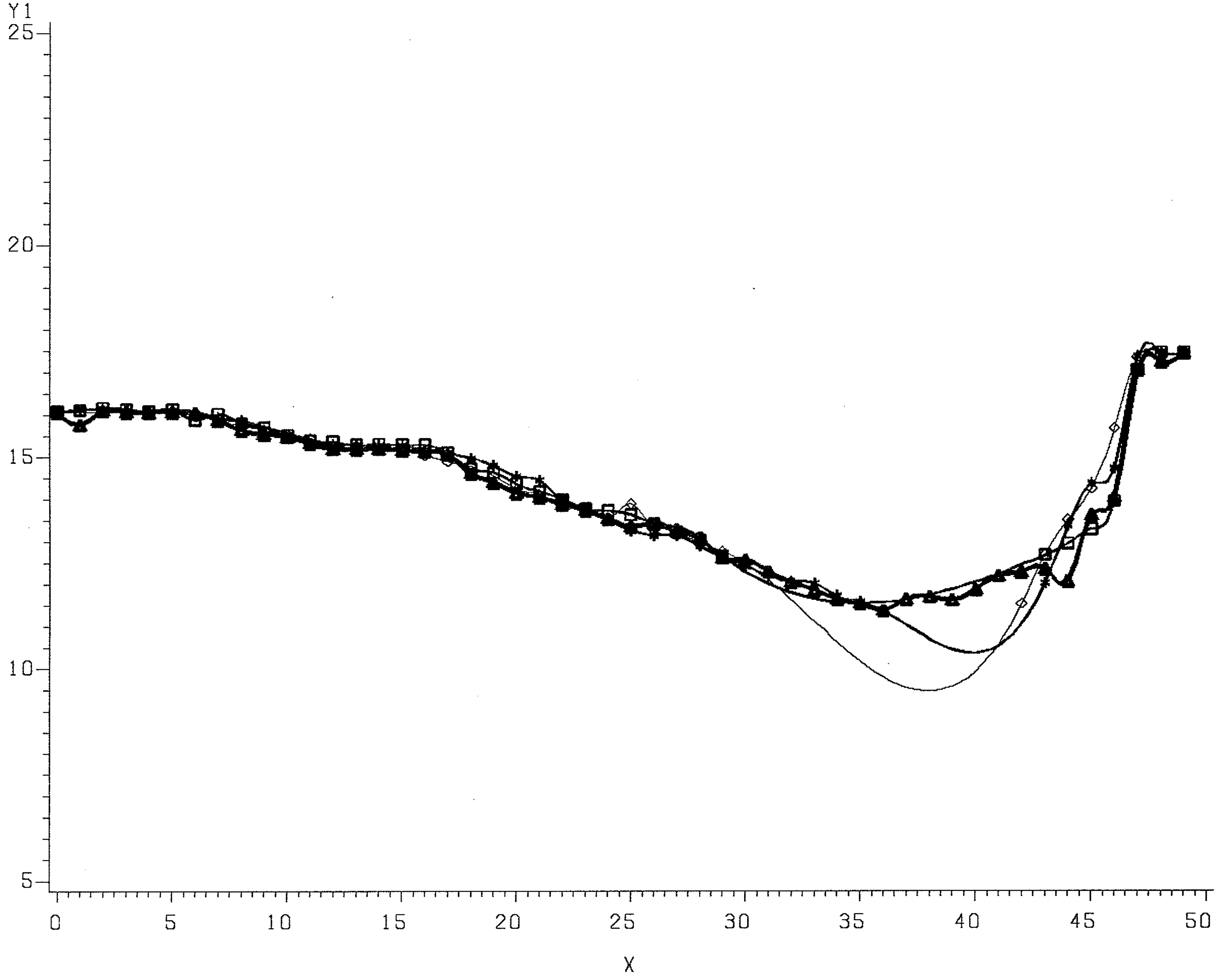
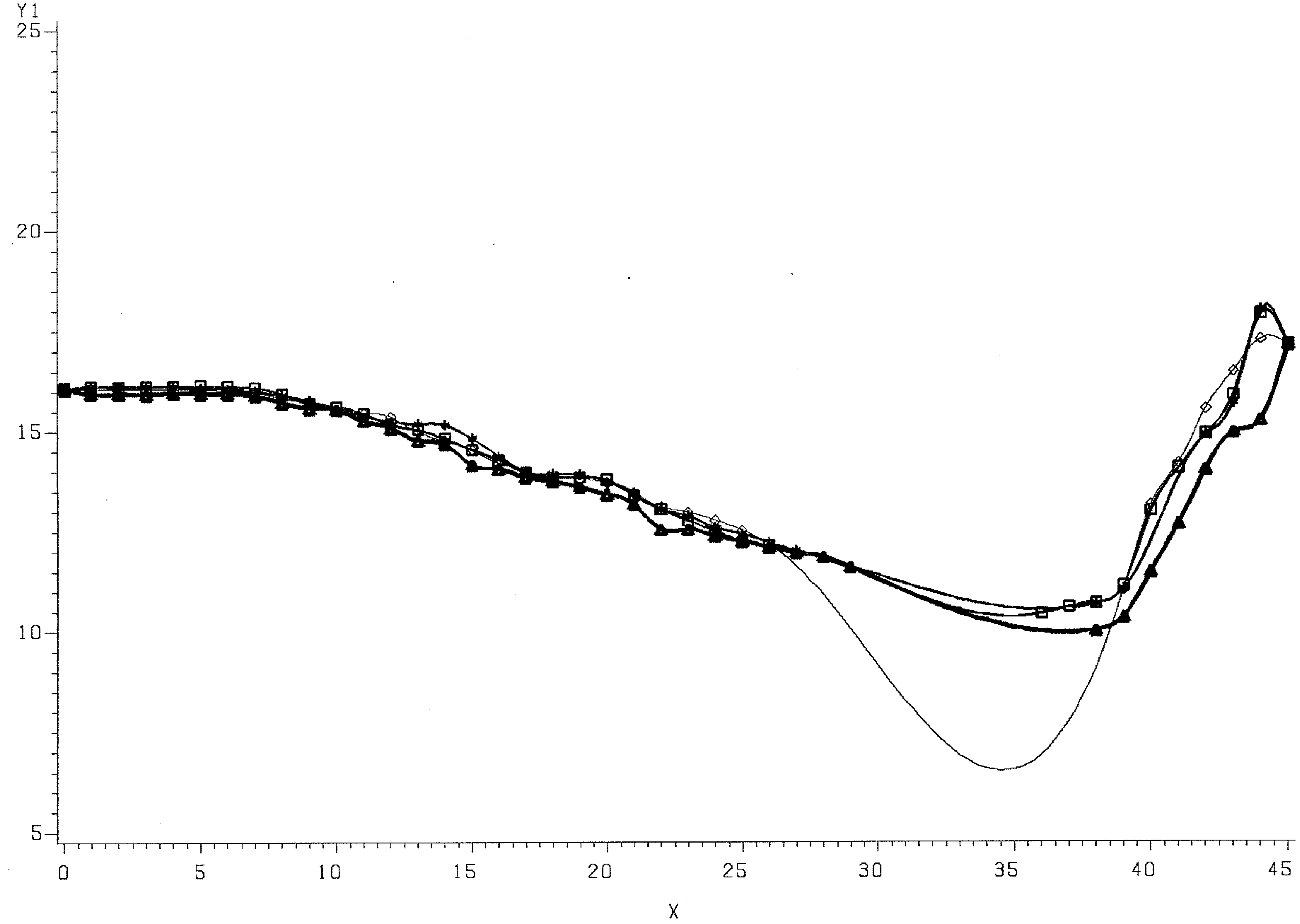


GRAVEL CREEK CROSS SECTION (B-18e 1981,1982 post breakup,1982 postfloo



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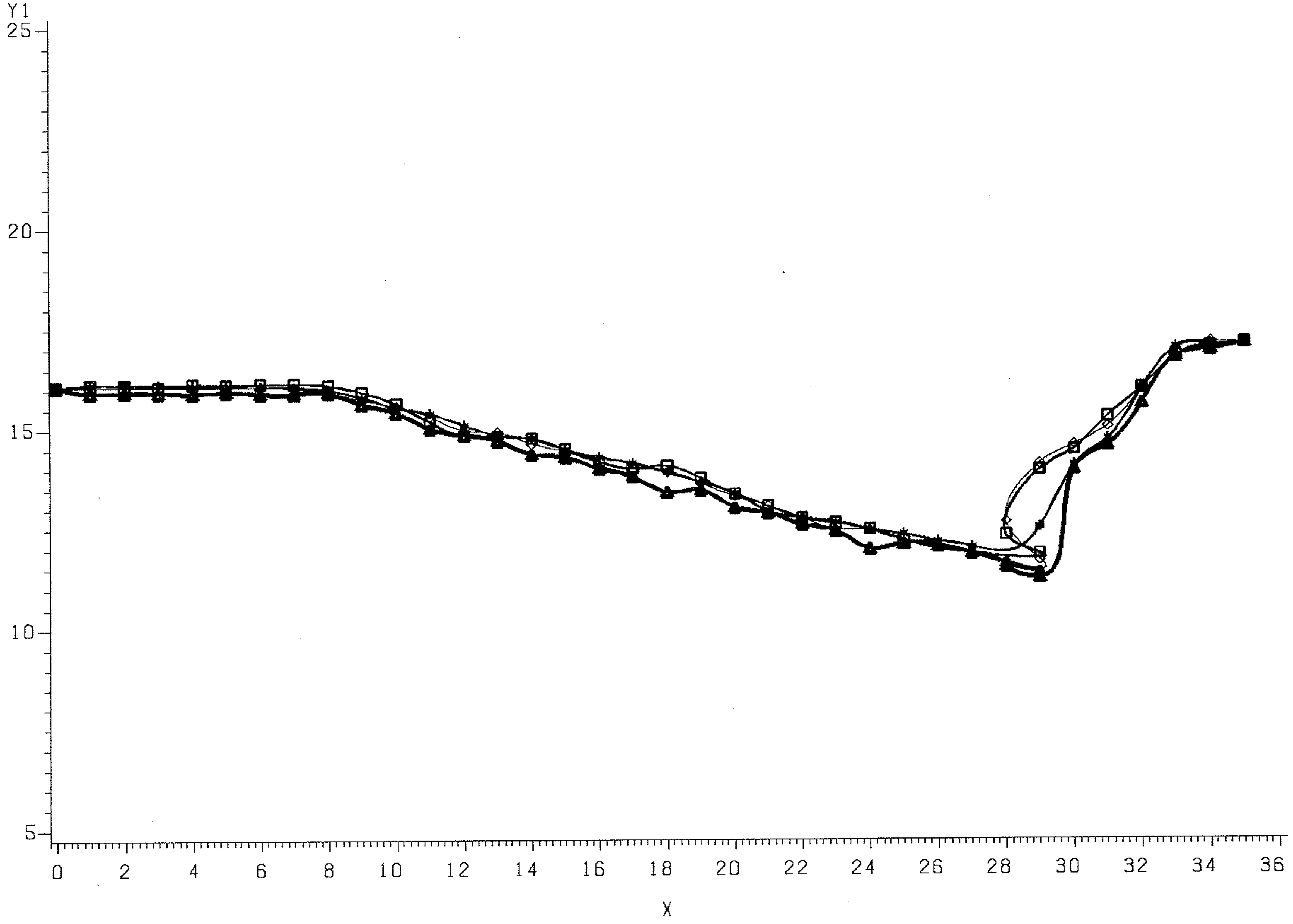
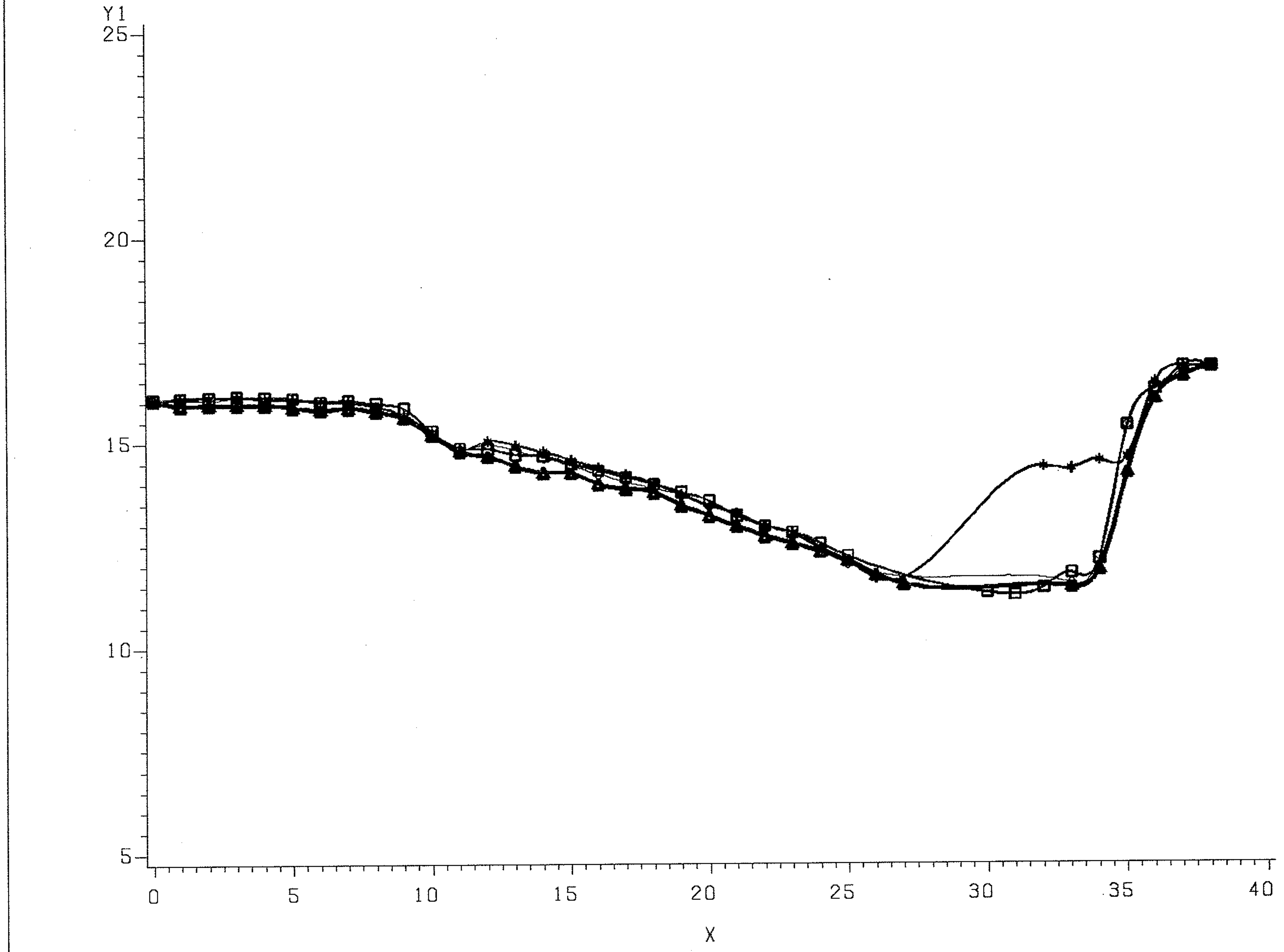
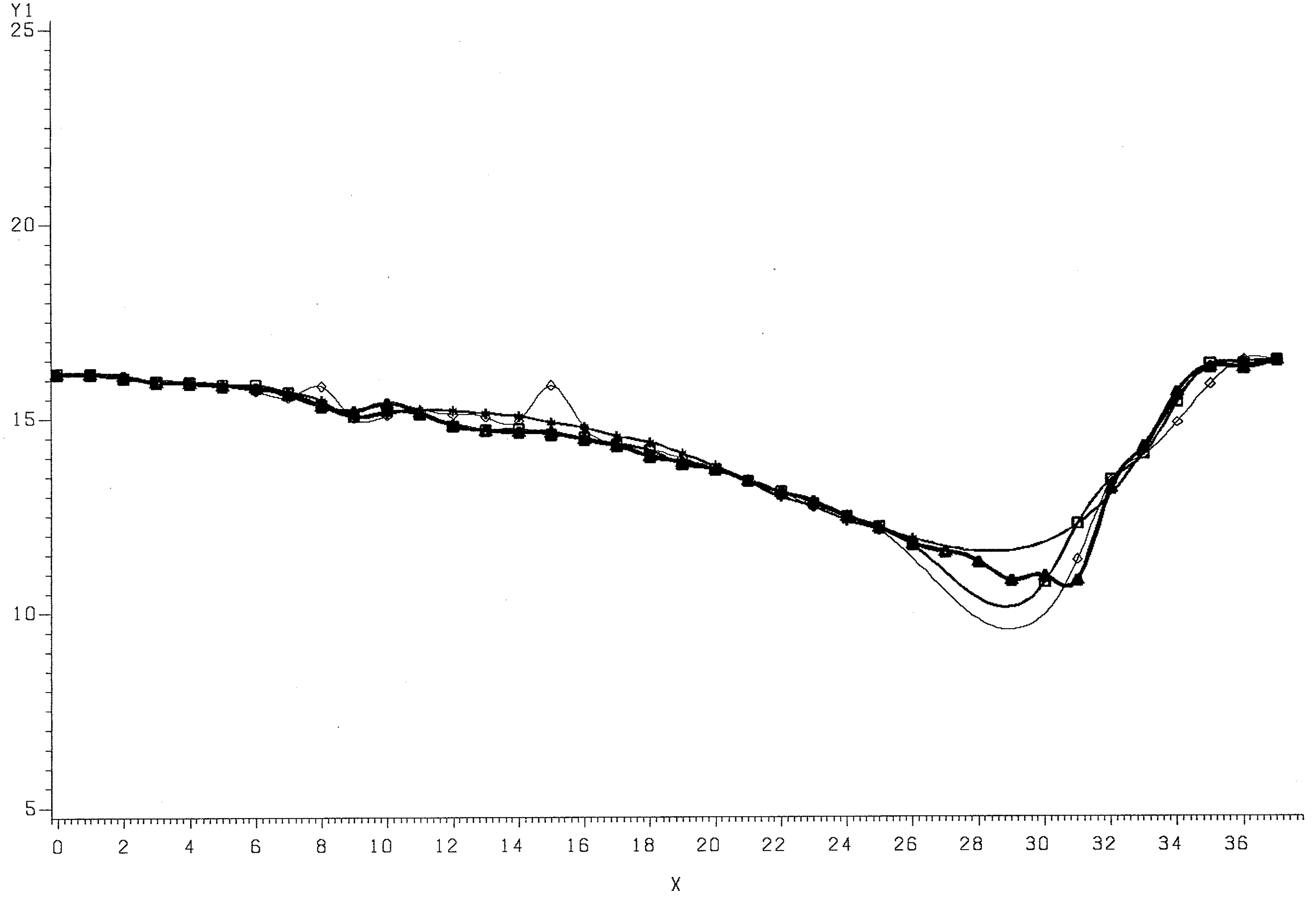


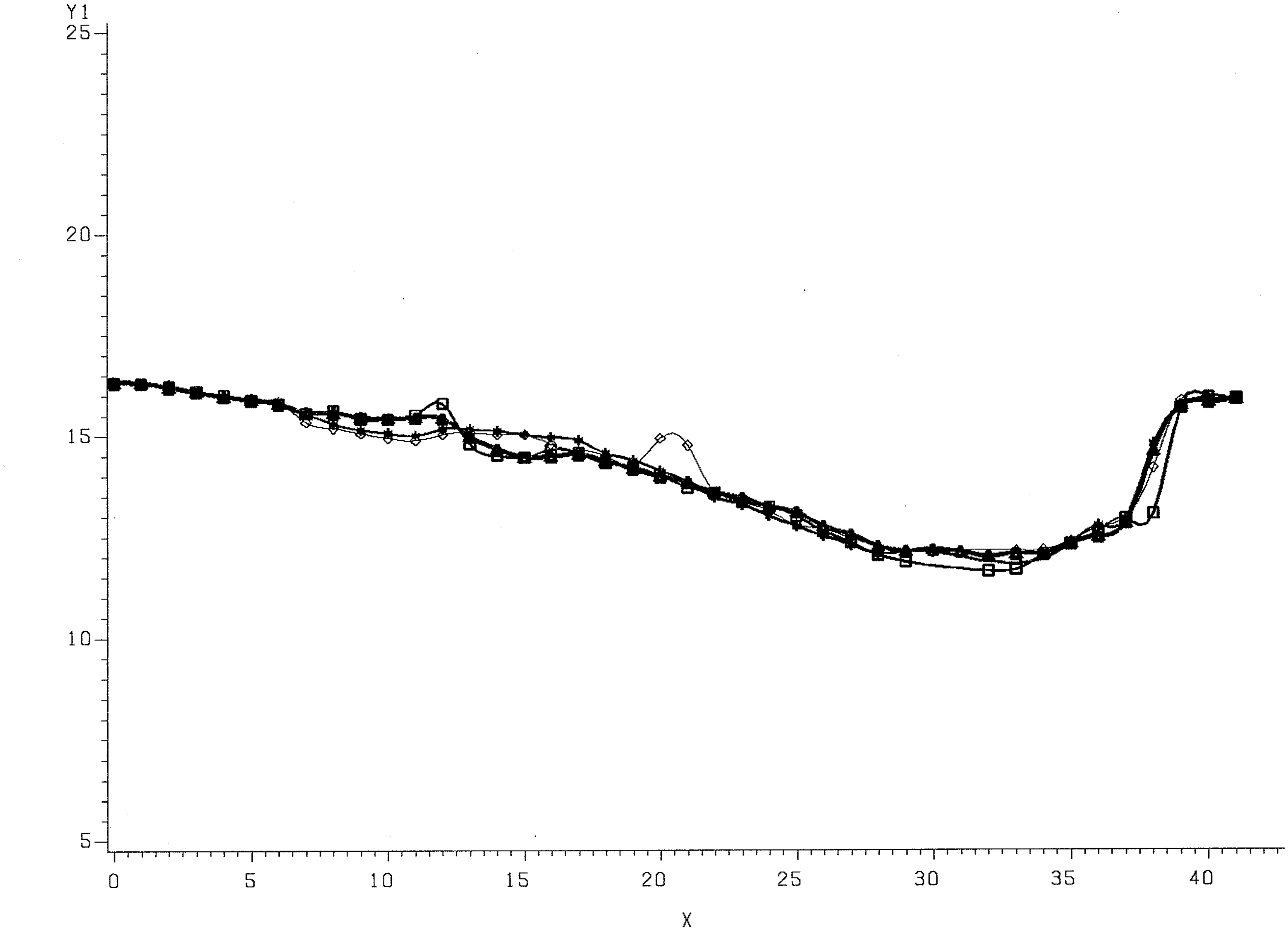
GRAVEL CREEK CROSS SECTION (B-18g 1981,1982 post breakup,1982 postfloo



GRAVEL CREEK CROSS SECTION (B-19 1981,1982 post breakup,1982 postflood



GRAVEL CREEK CROSS SECTION (B-20 1981,1982 post breakup,1982 postflood



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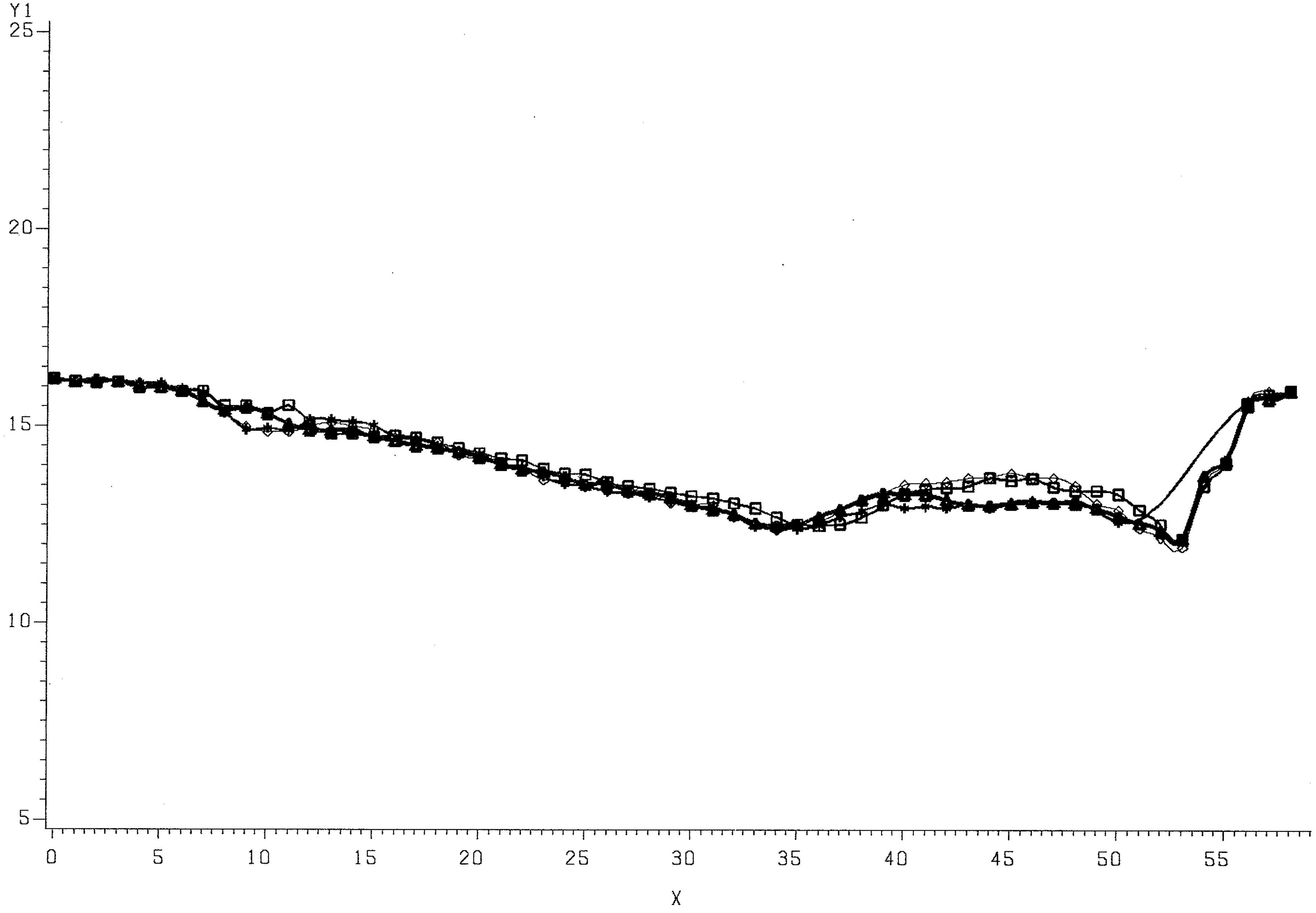
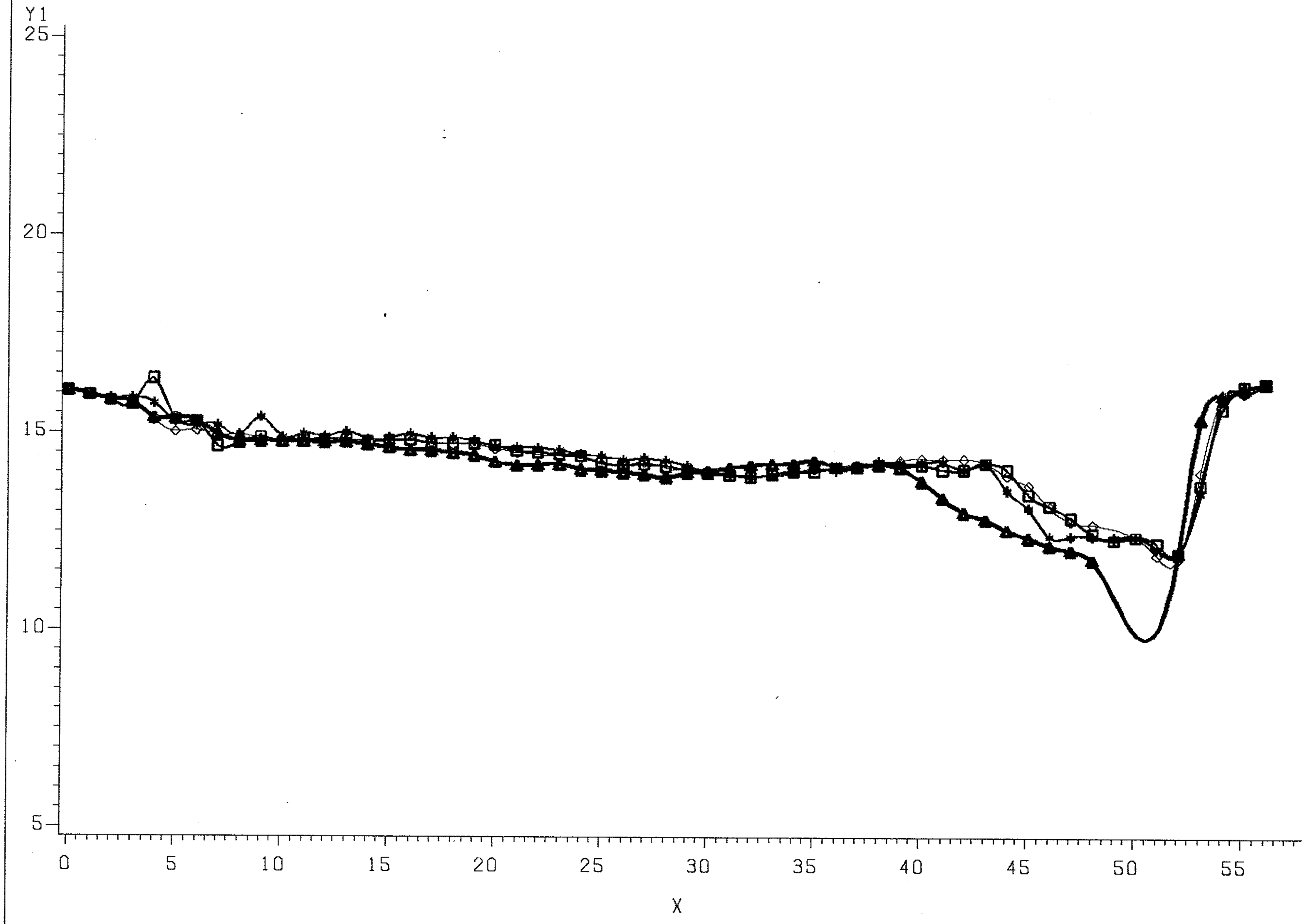
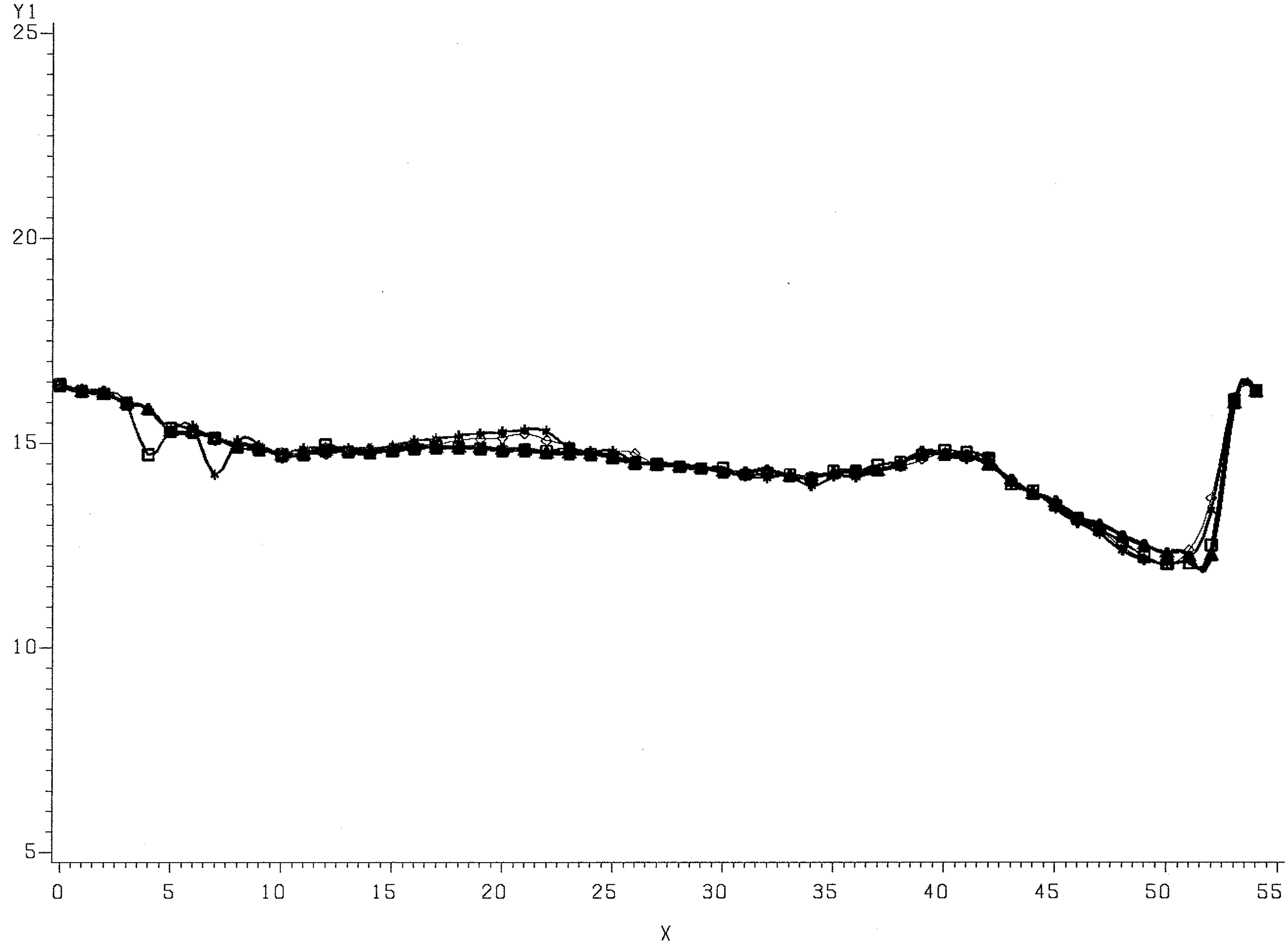


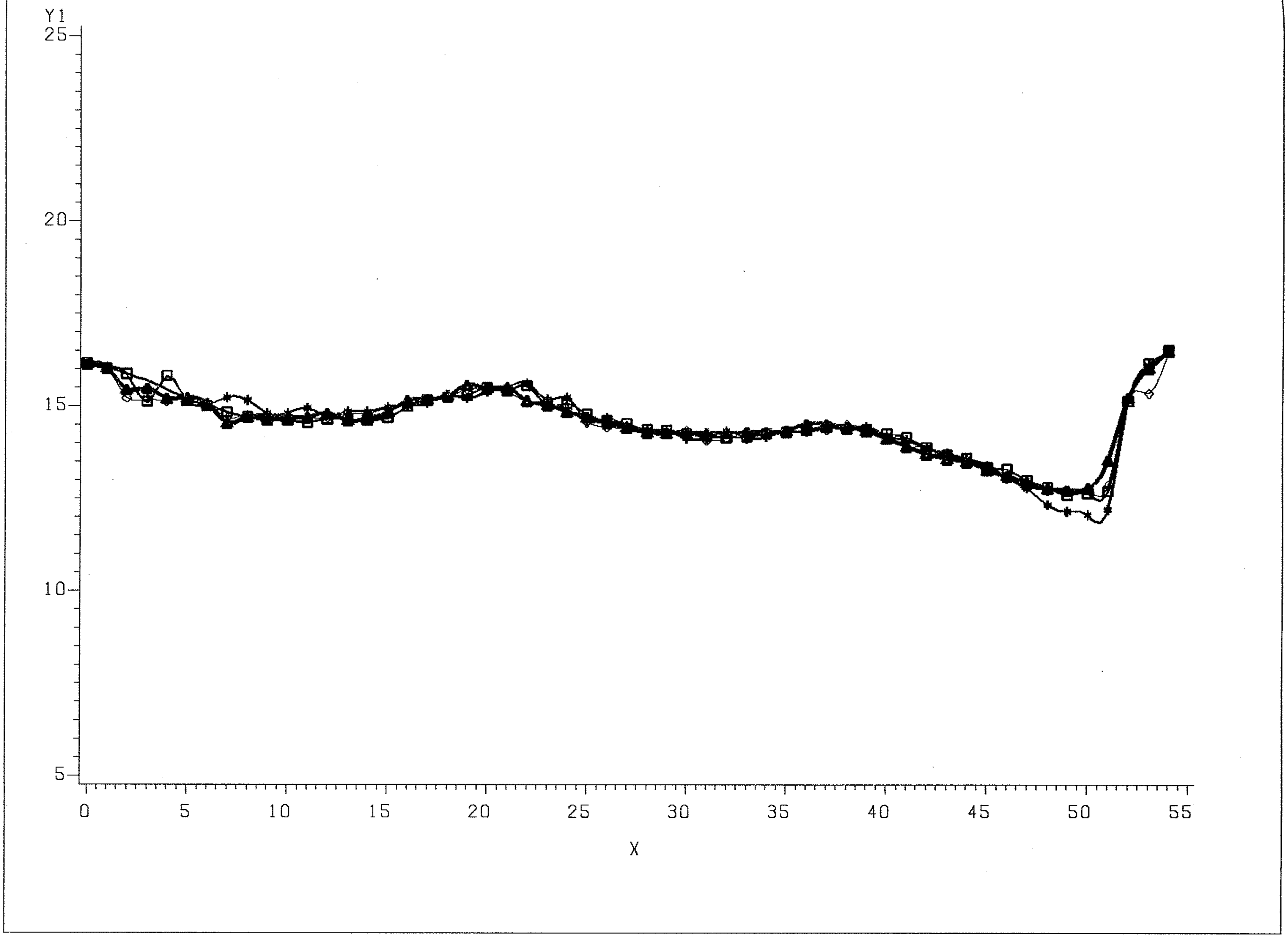
GRAVEL CREEK CROSS SECTION (B-22 1981,1982 post breakup,1982 postflood

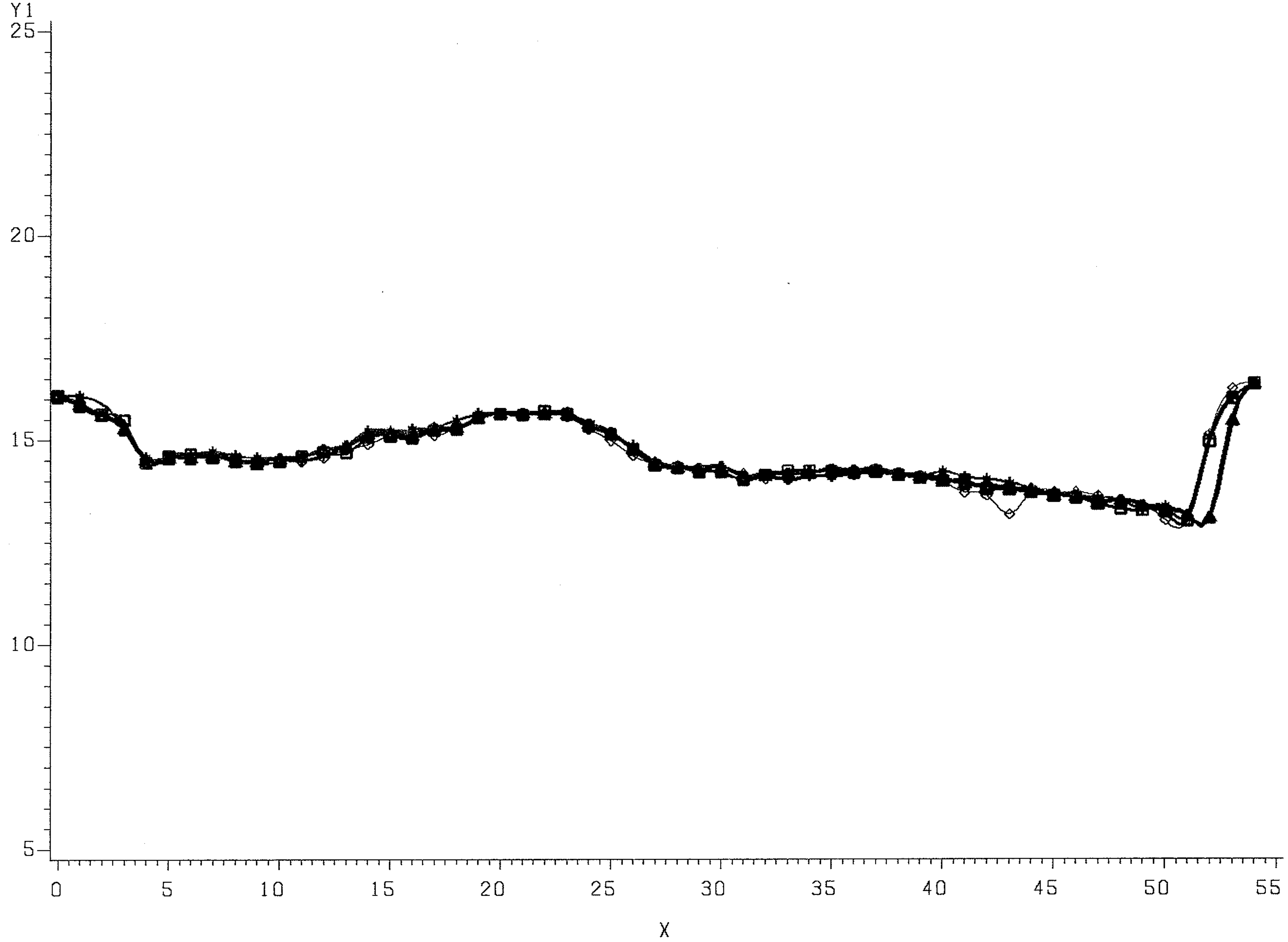


GRAVEL CREEK CROSS SECTION (B-23 1981,1982 post breakup,1982 postflood



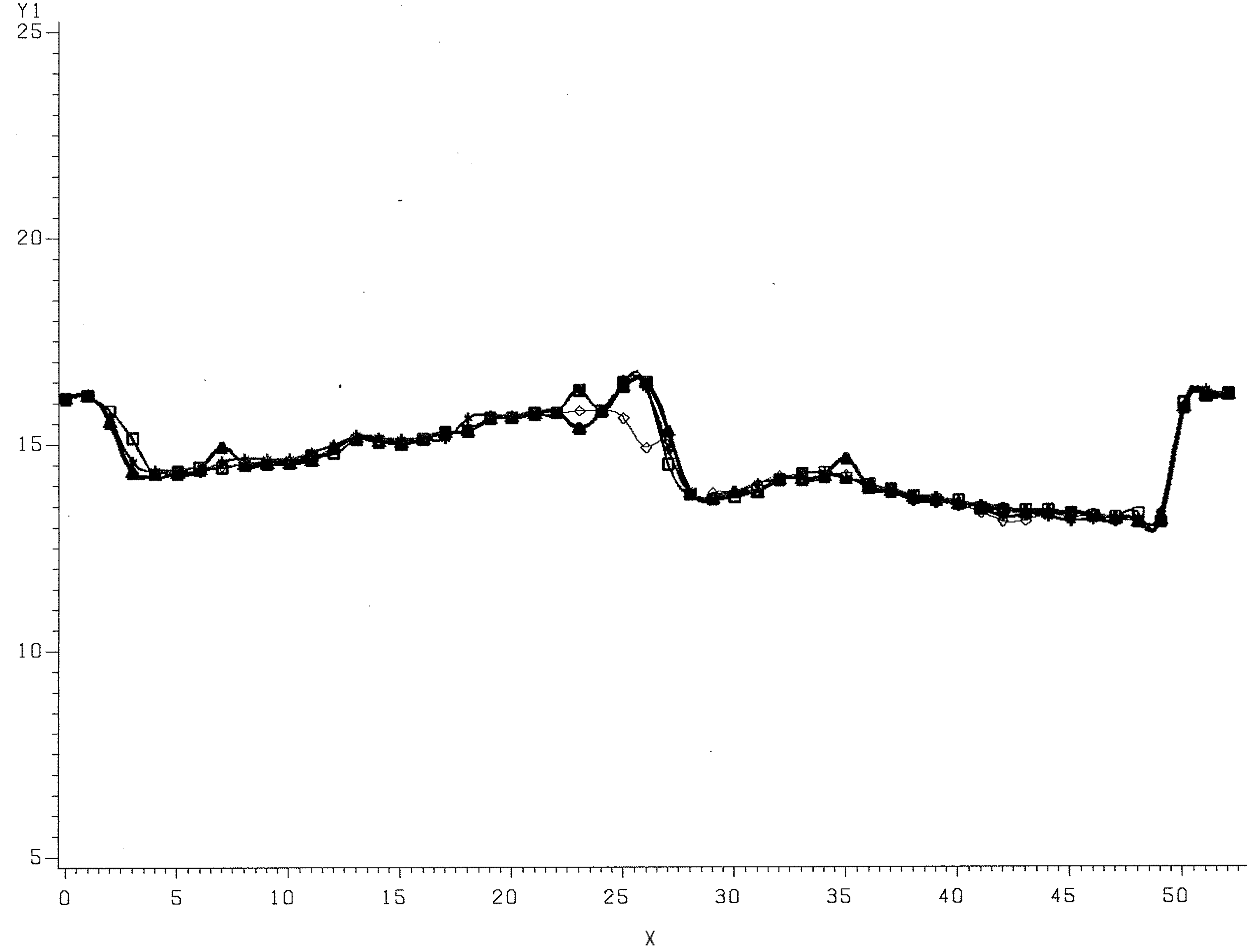
GRAVEL CREEK CROSS SECTION (B-24 1981,1982 post breakup,1982 postflood



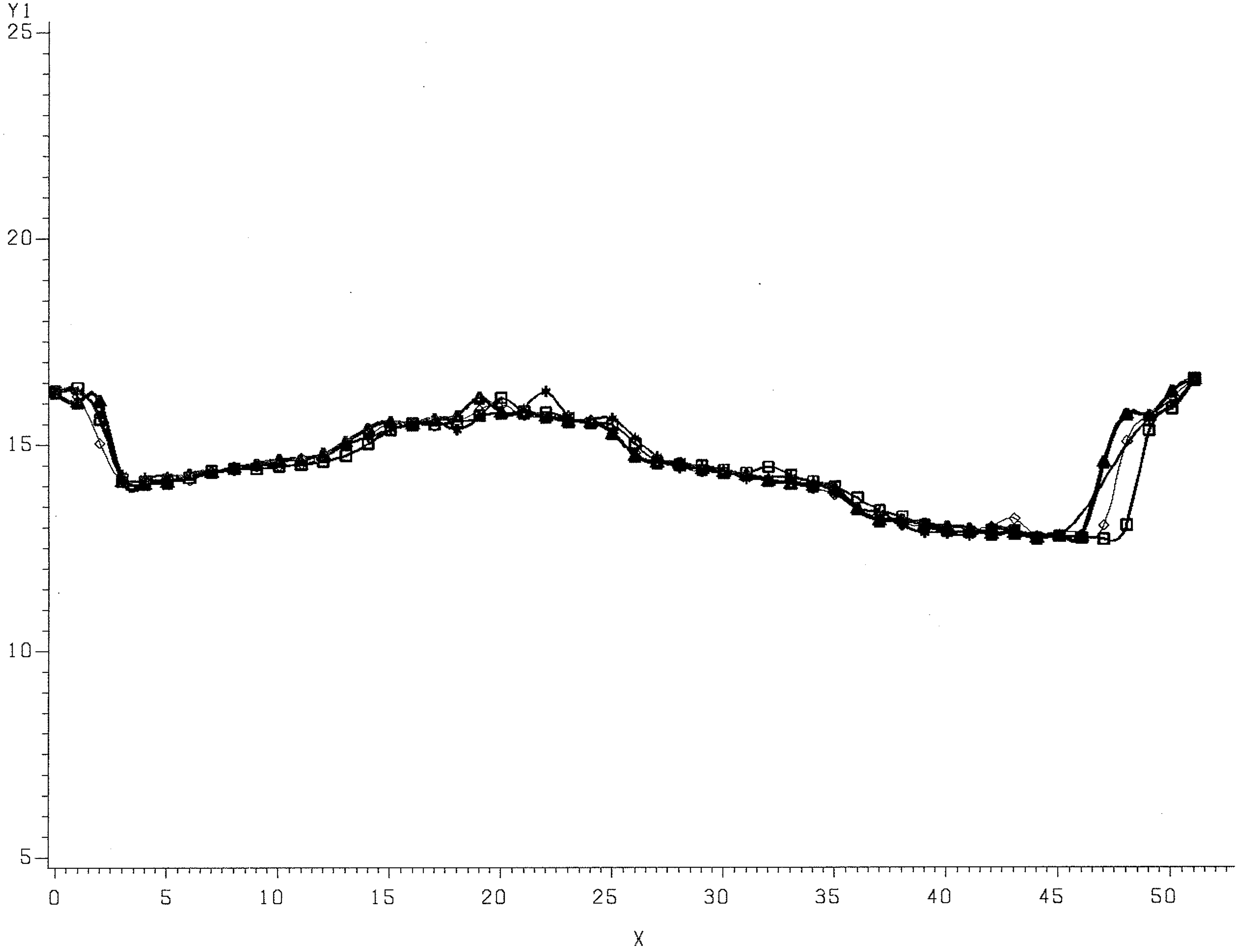


GRAVEL CREEK CROSS SECTION (B-25 1981,1982 post breakup,1982 postflood

GRAVEL CREEK CROSS SECTION (B-26 1981,1982 post breakup,1982 postflood



GRAVEL CREEK CROSS SECTION (B-27 1981,1982 post breakup,1982 postflood



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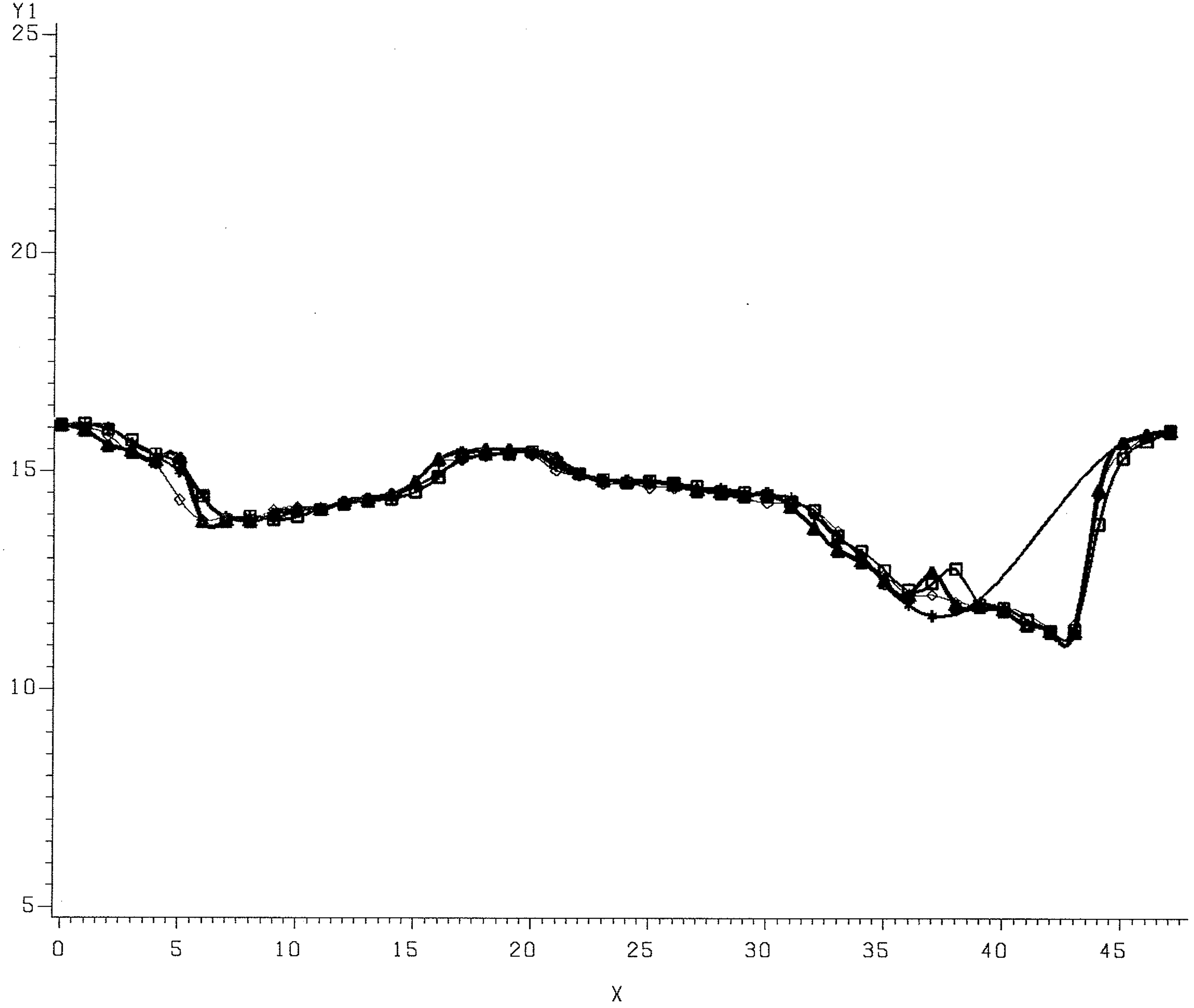

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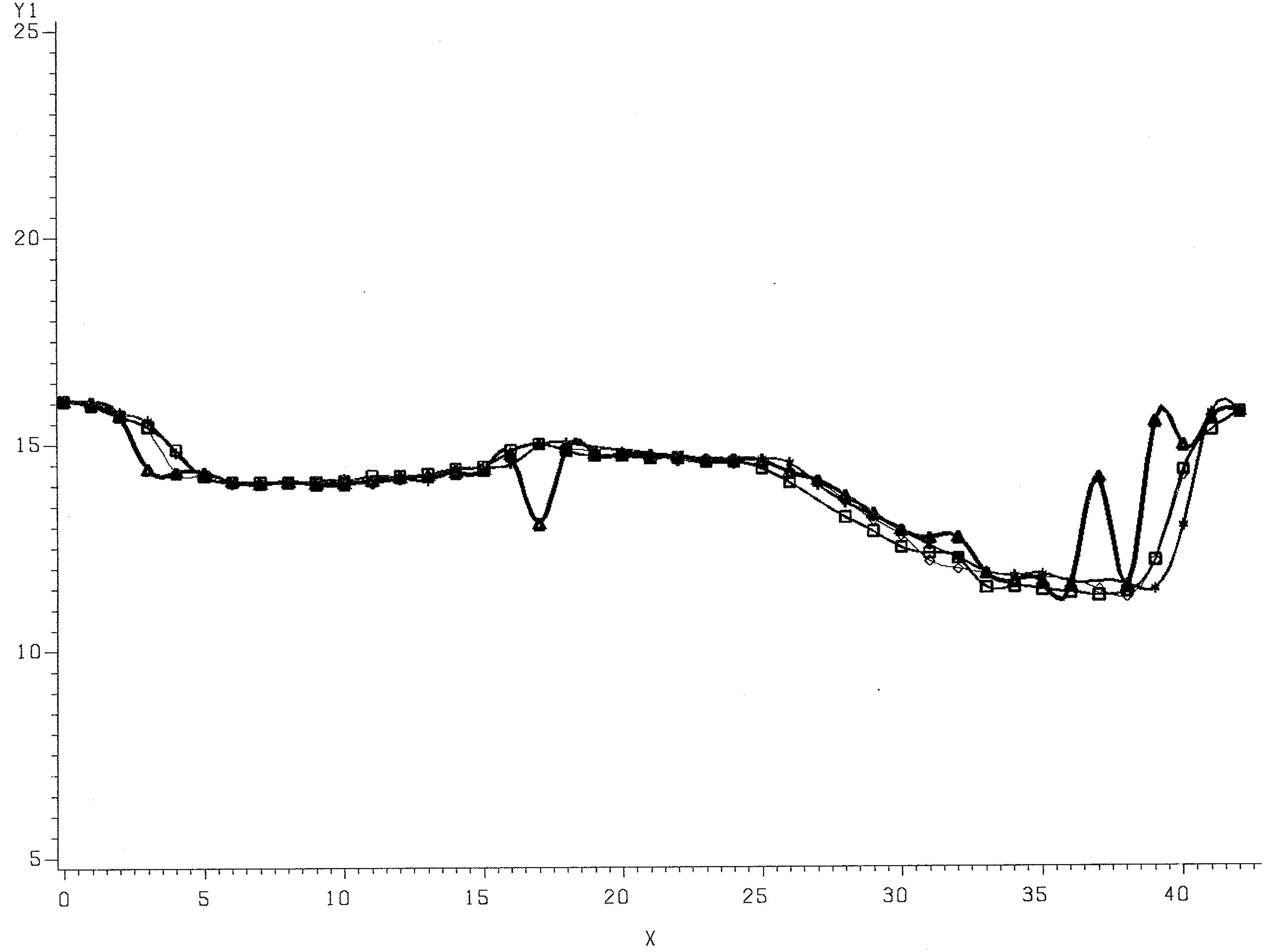
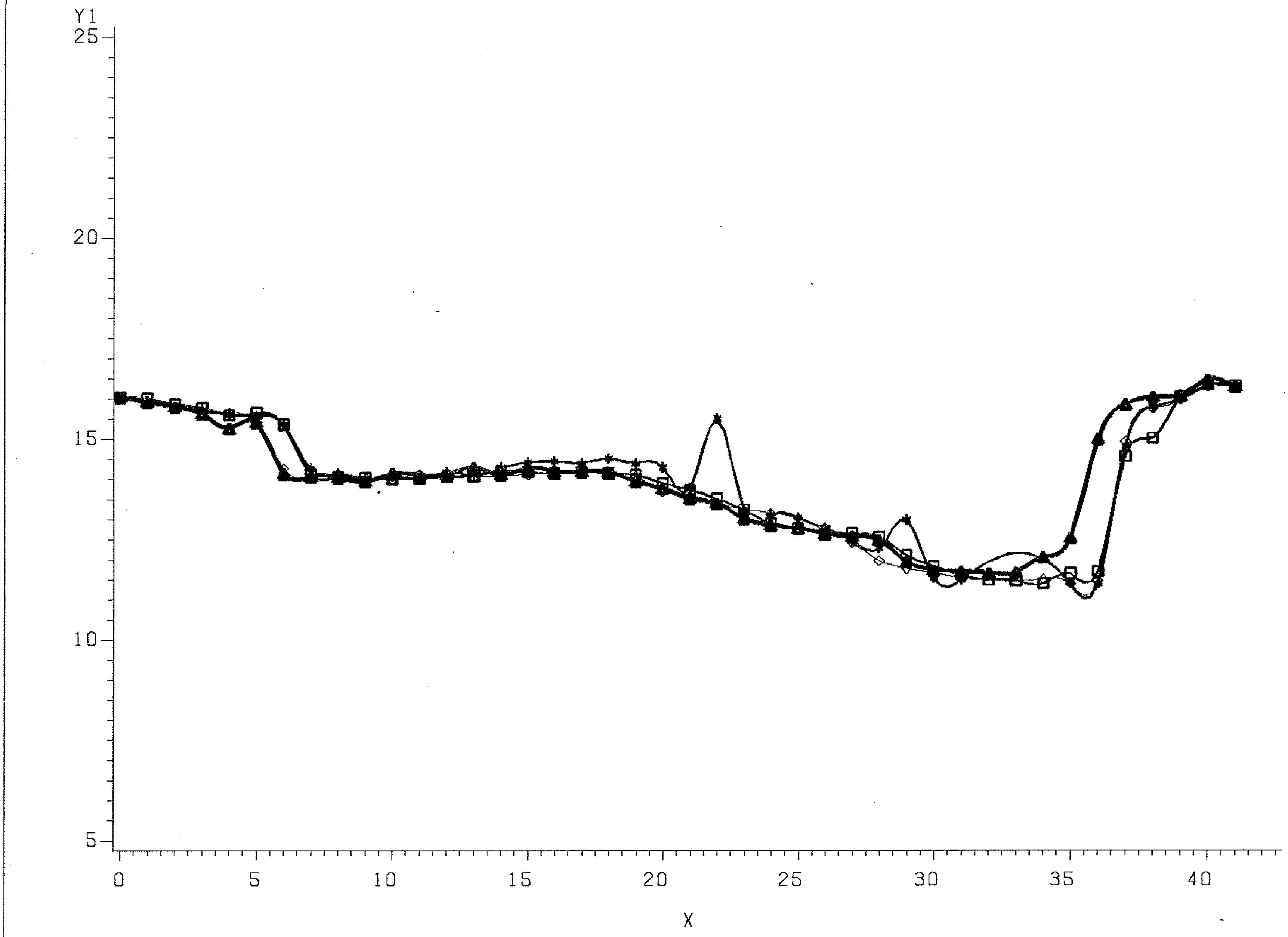
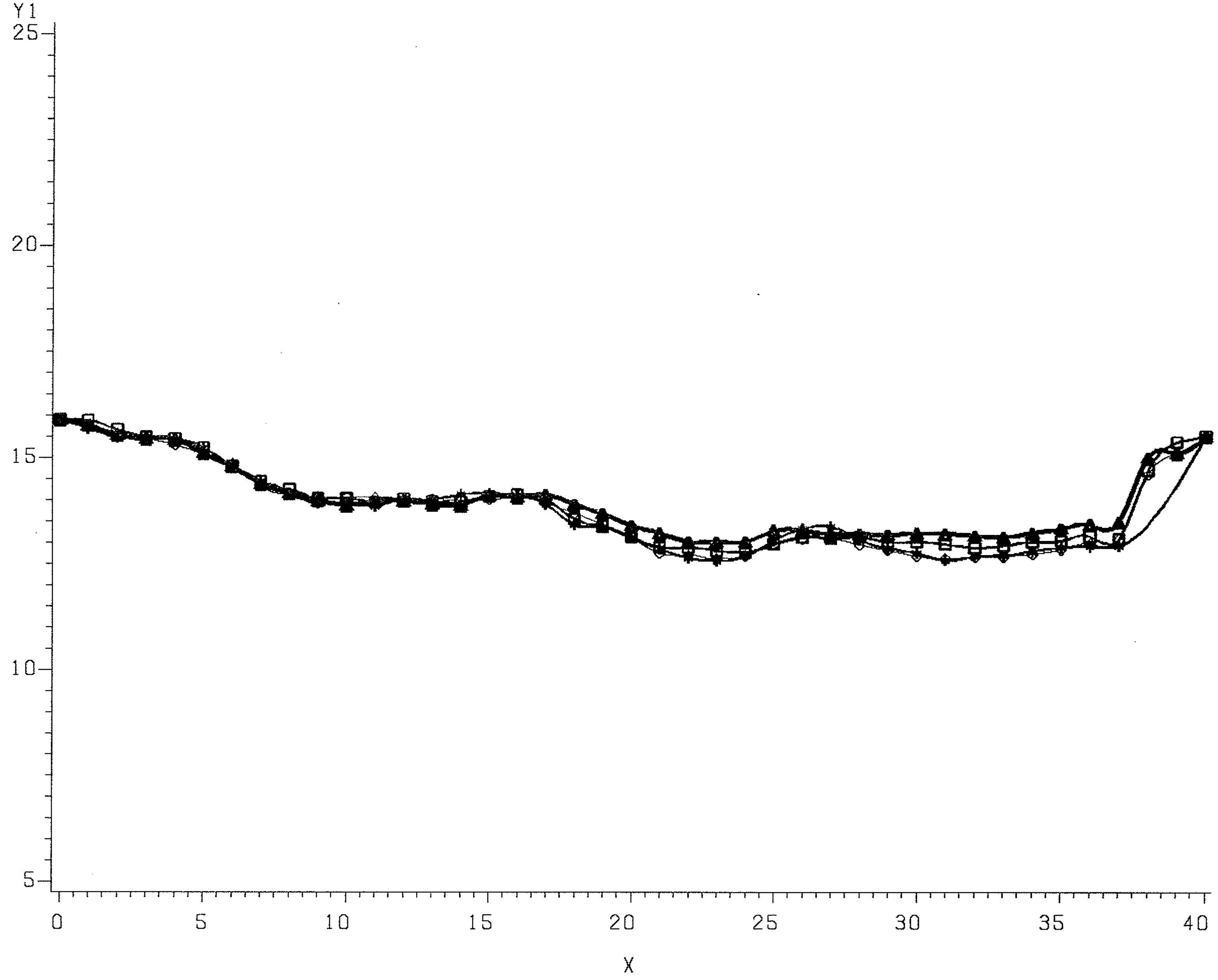


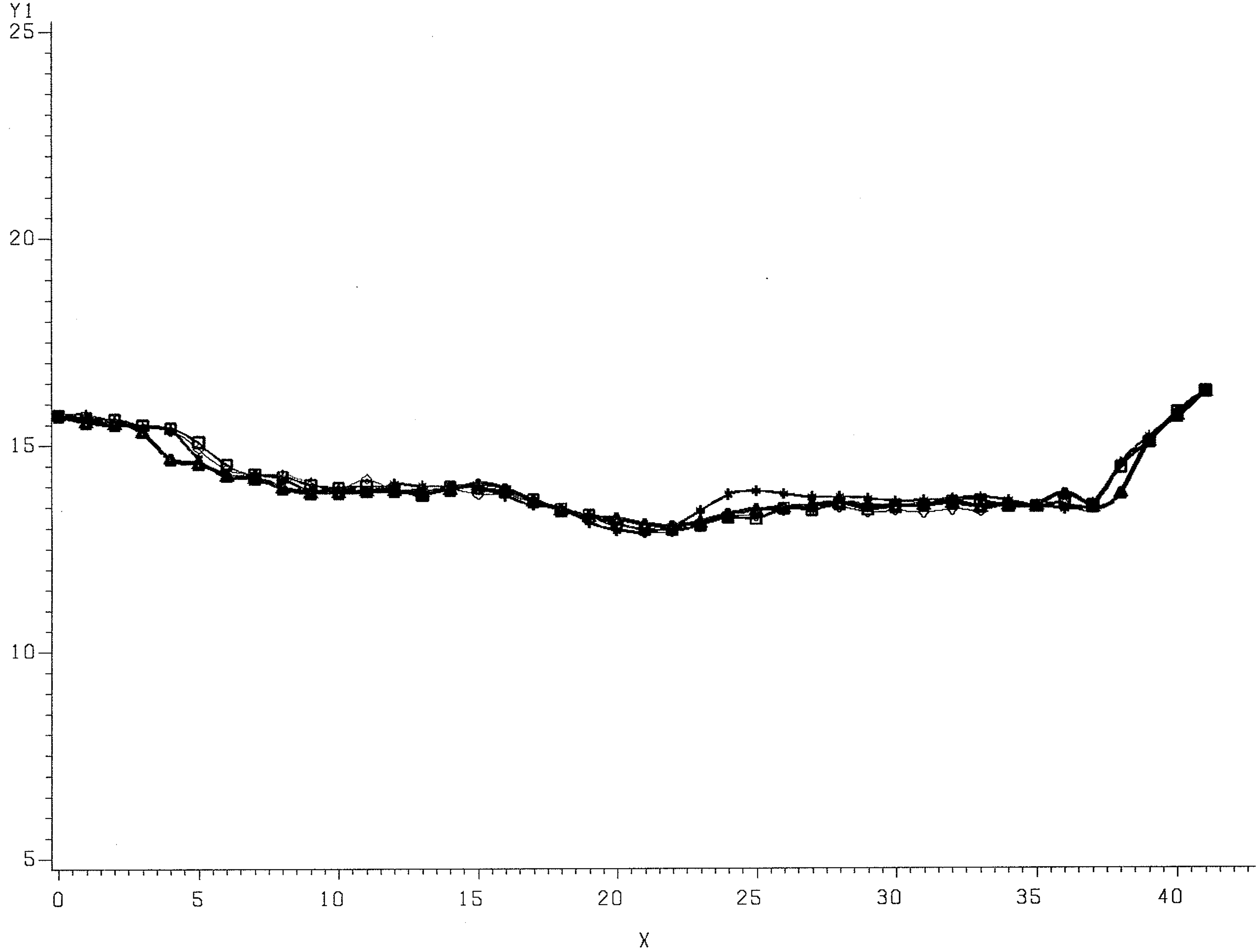
GRAVEL CREEK CROSS SECTION (B-30 1981,1982 post breakup,1982 postflood



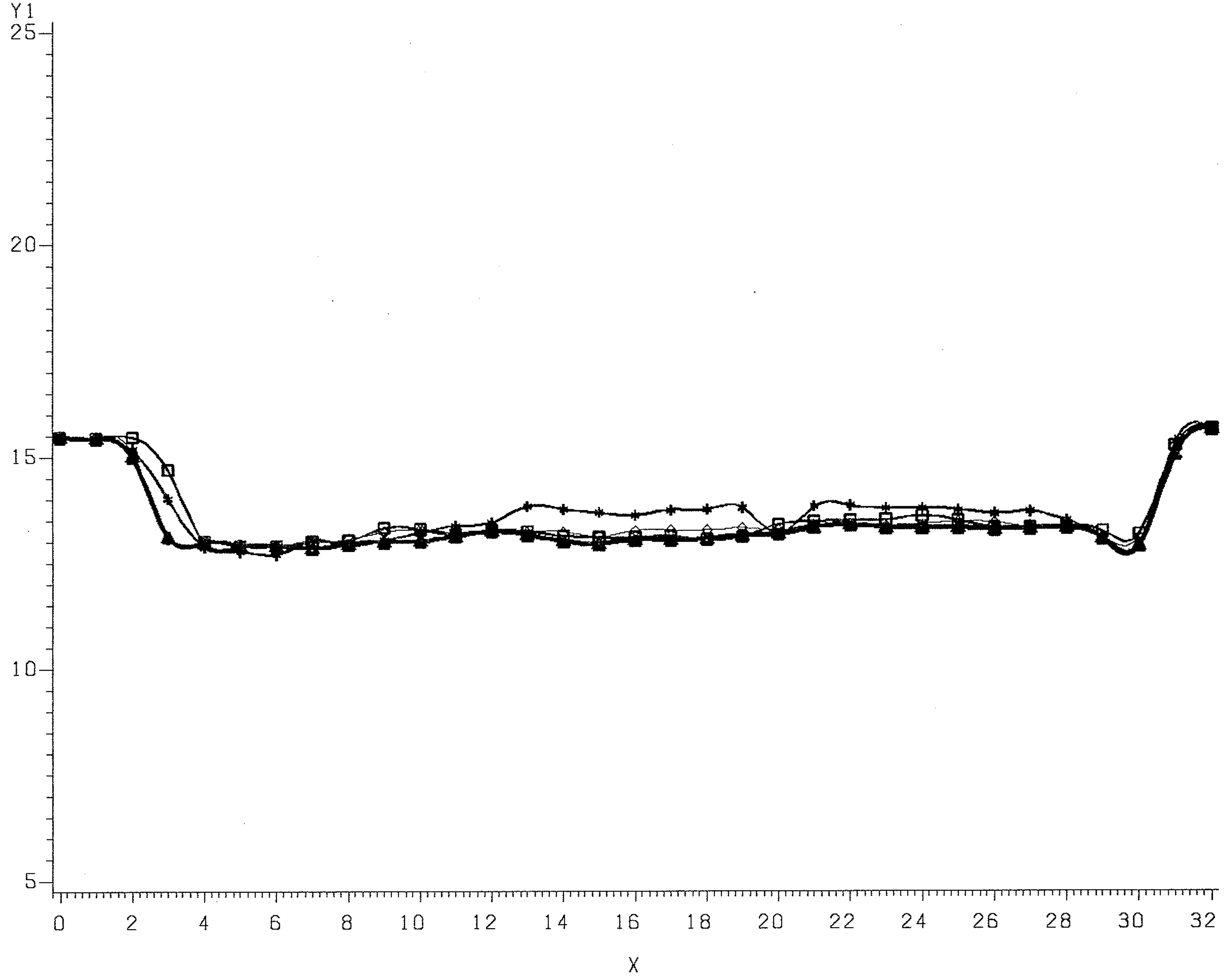
GRAVEL CREEK CROSS SECTION (B-31 1981,1982 post breakup,1982 postflood



GRAVEL CREEK CROSS SECTION (B-32 1981,1982 post breakup,1982 postflood



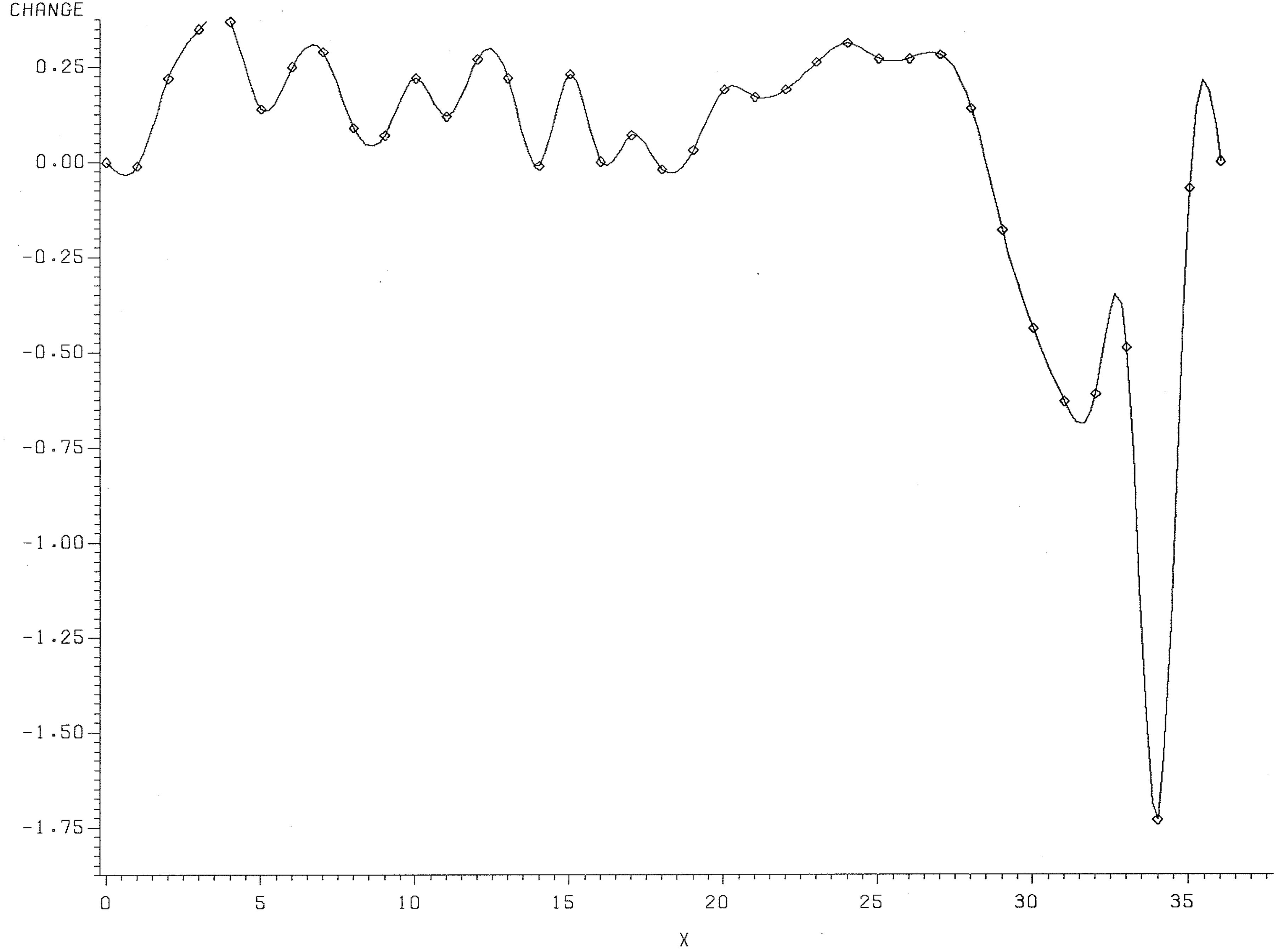
GRAVEL CREEK CROSS SECTION (B-34 1981,1982 post breakup,1982 postflood



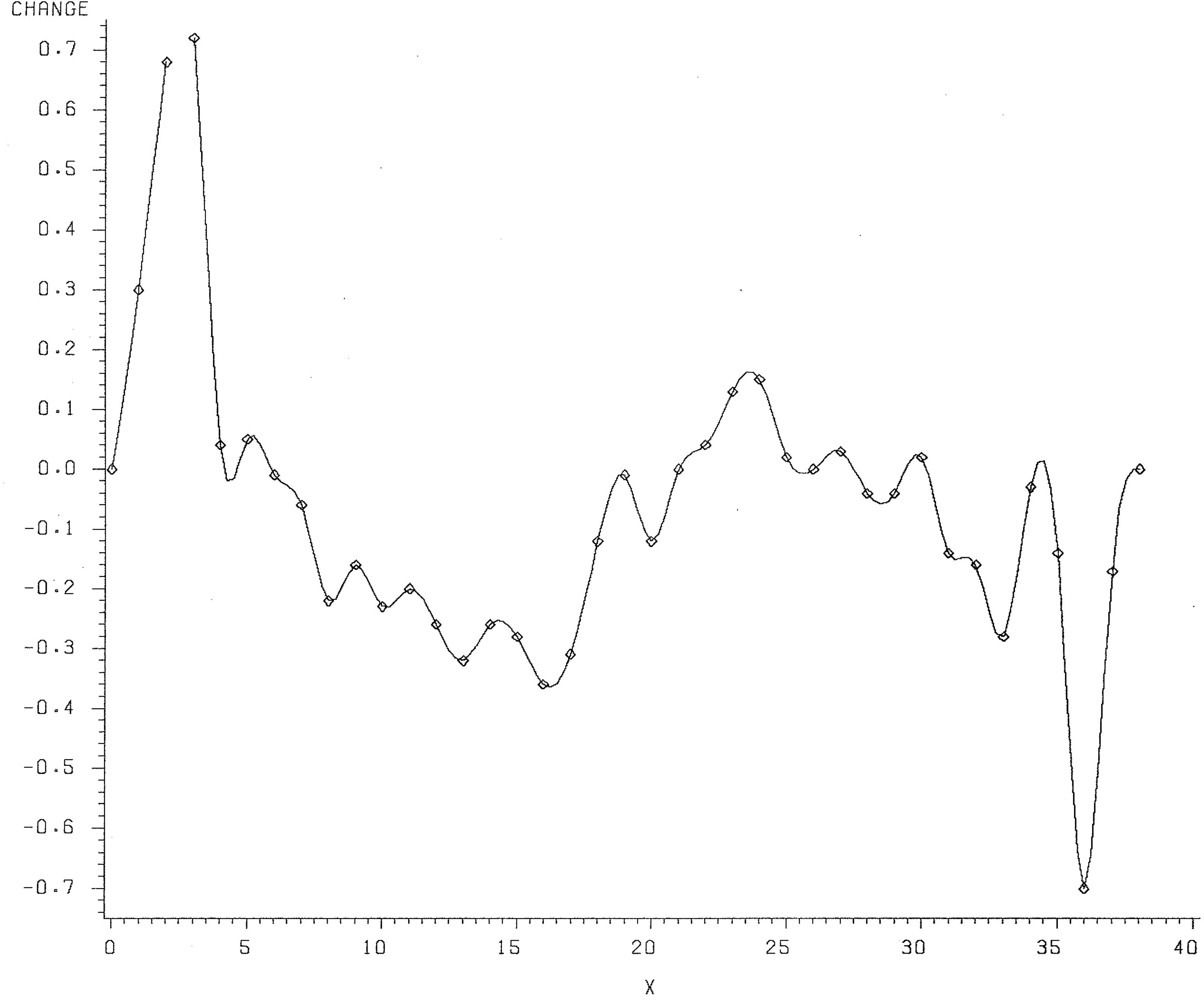
Appendix B

GRAVEL CREEK CHANNEL CHANGE

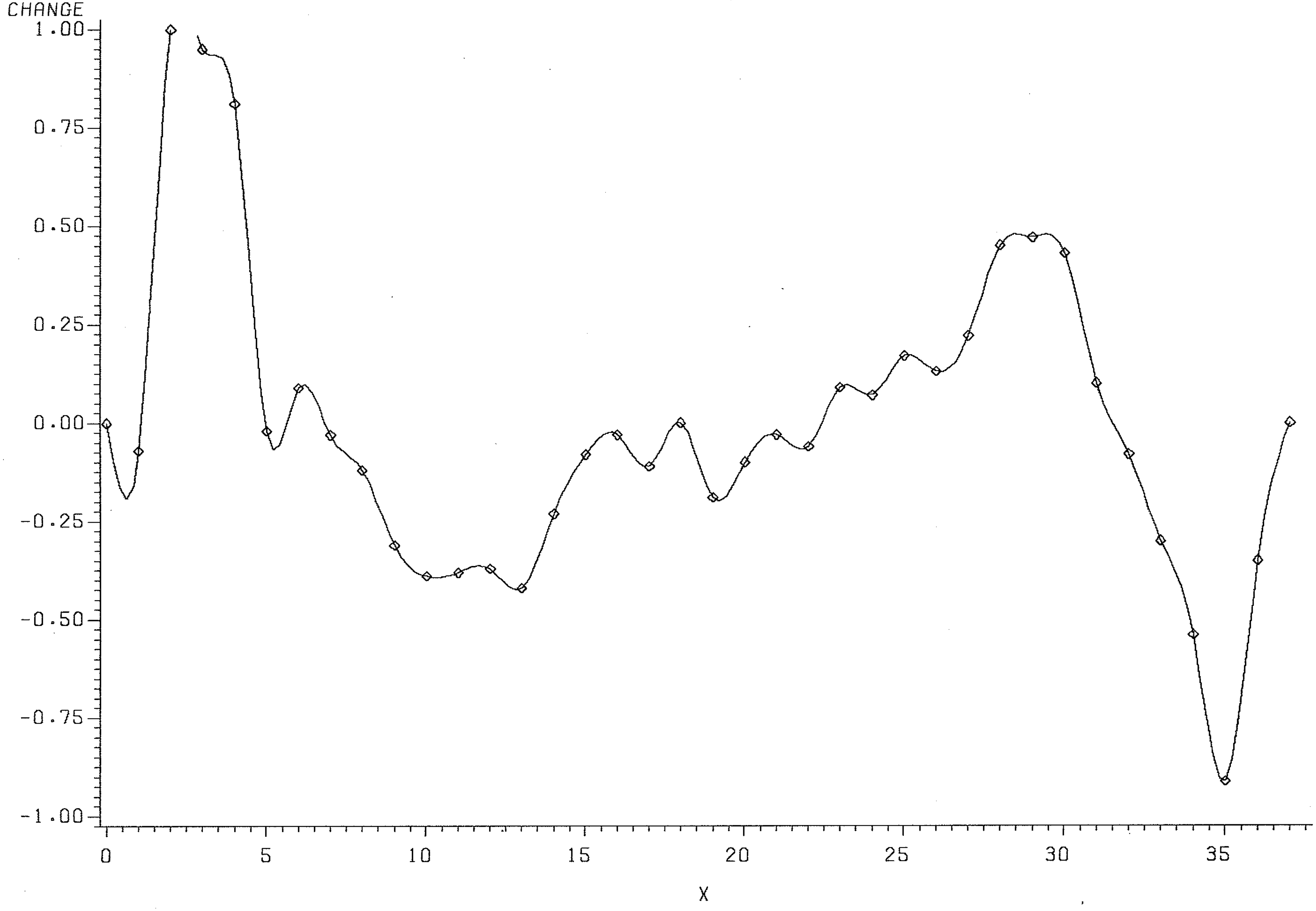
GRAVEL CREEK CHANNEL CHANGE A-REACH (A-1 1981 post-flood to 1982 post-



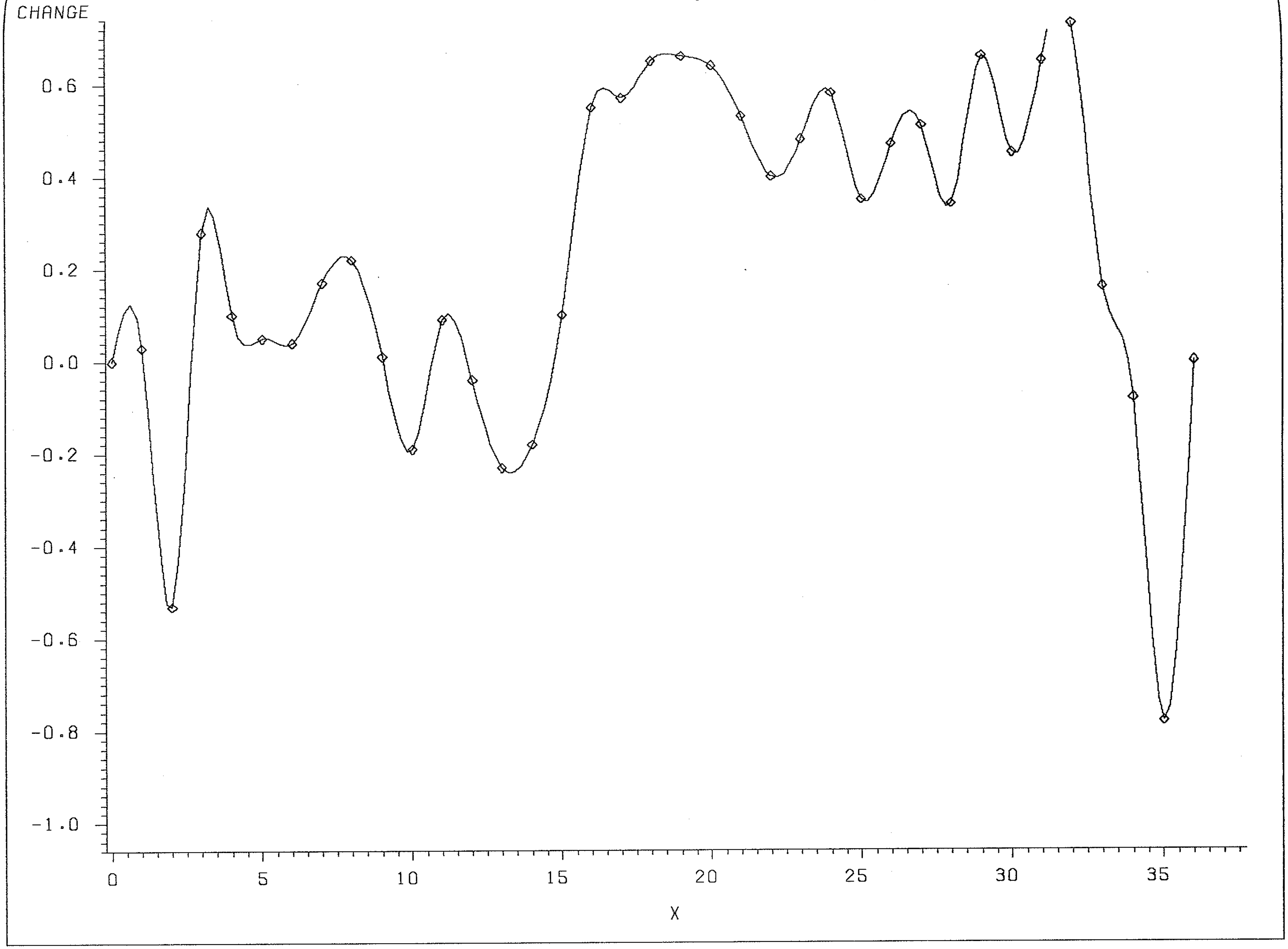
GRAVEL CREEK CHANNEL CHANGE A-REACH (A-2 1981 post-flood to 1982 post-

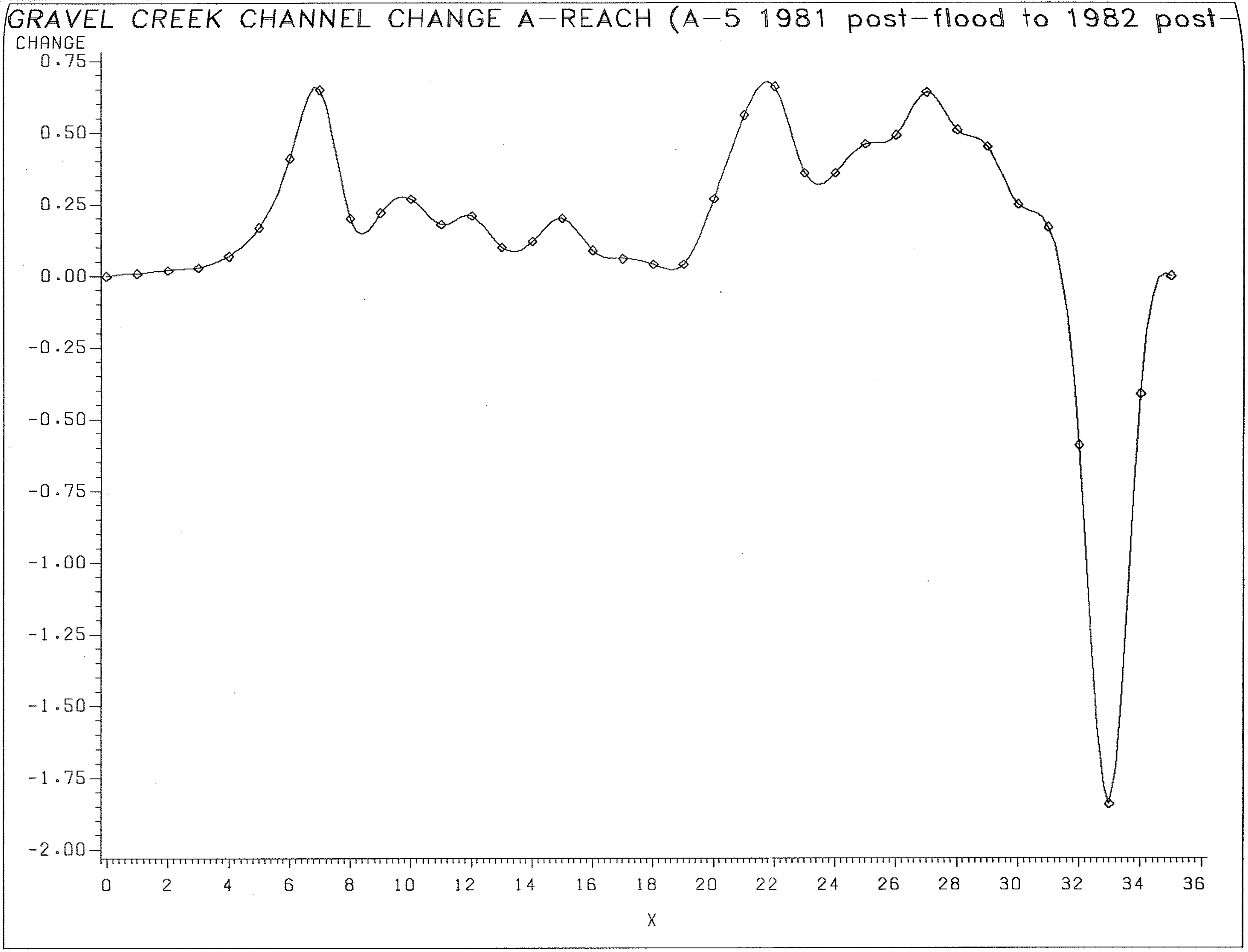


GRAVEL CREEK CHANNEL CHANGE A-REACH (A-3 1981 post-flood to 1982 post-



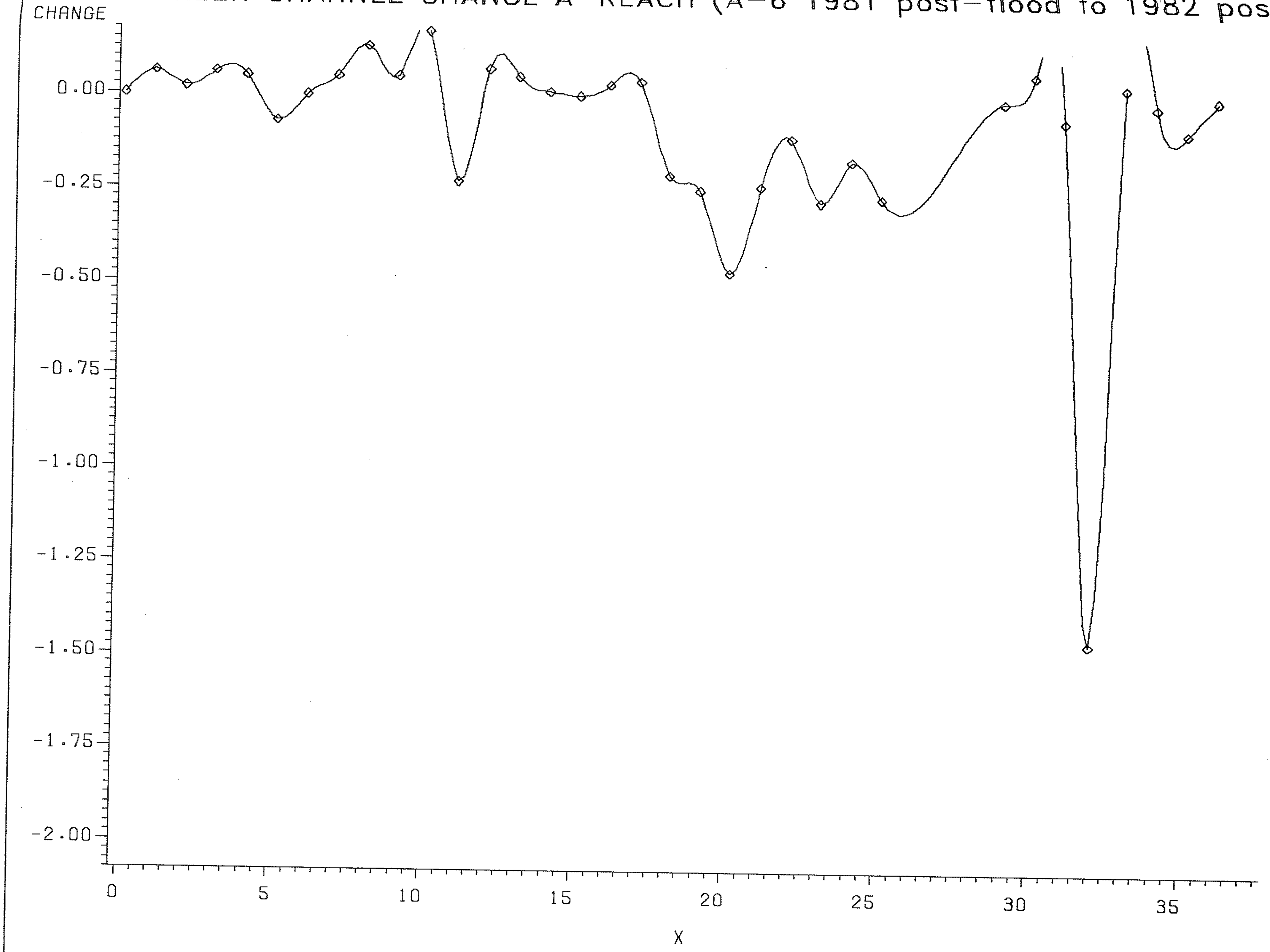
GRAVEL CREEK CHANNEL CHANGE A–REACH (A–4 1981 post–flood to 1982 post–

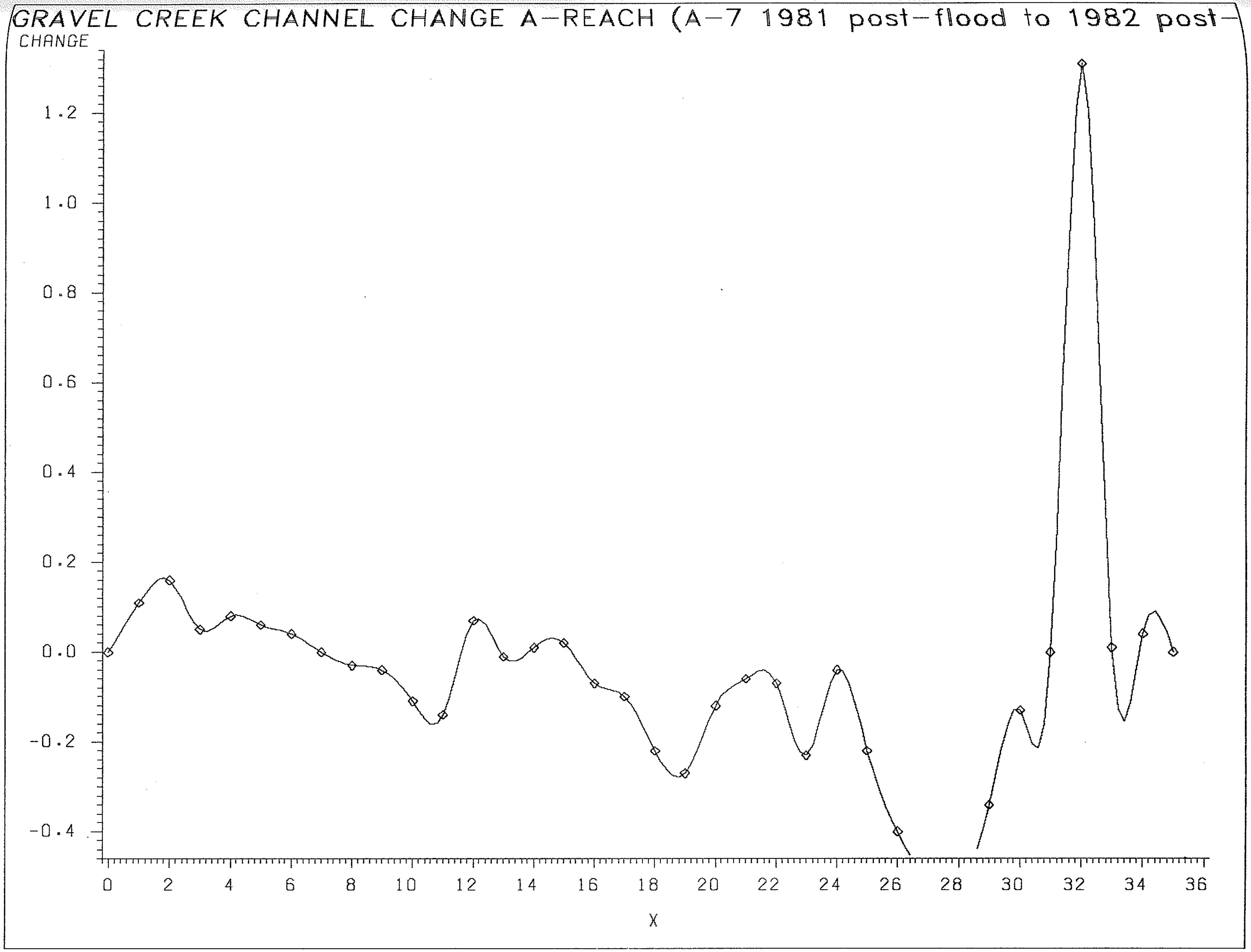




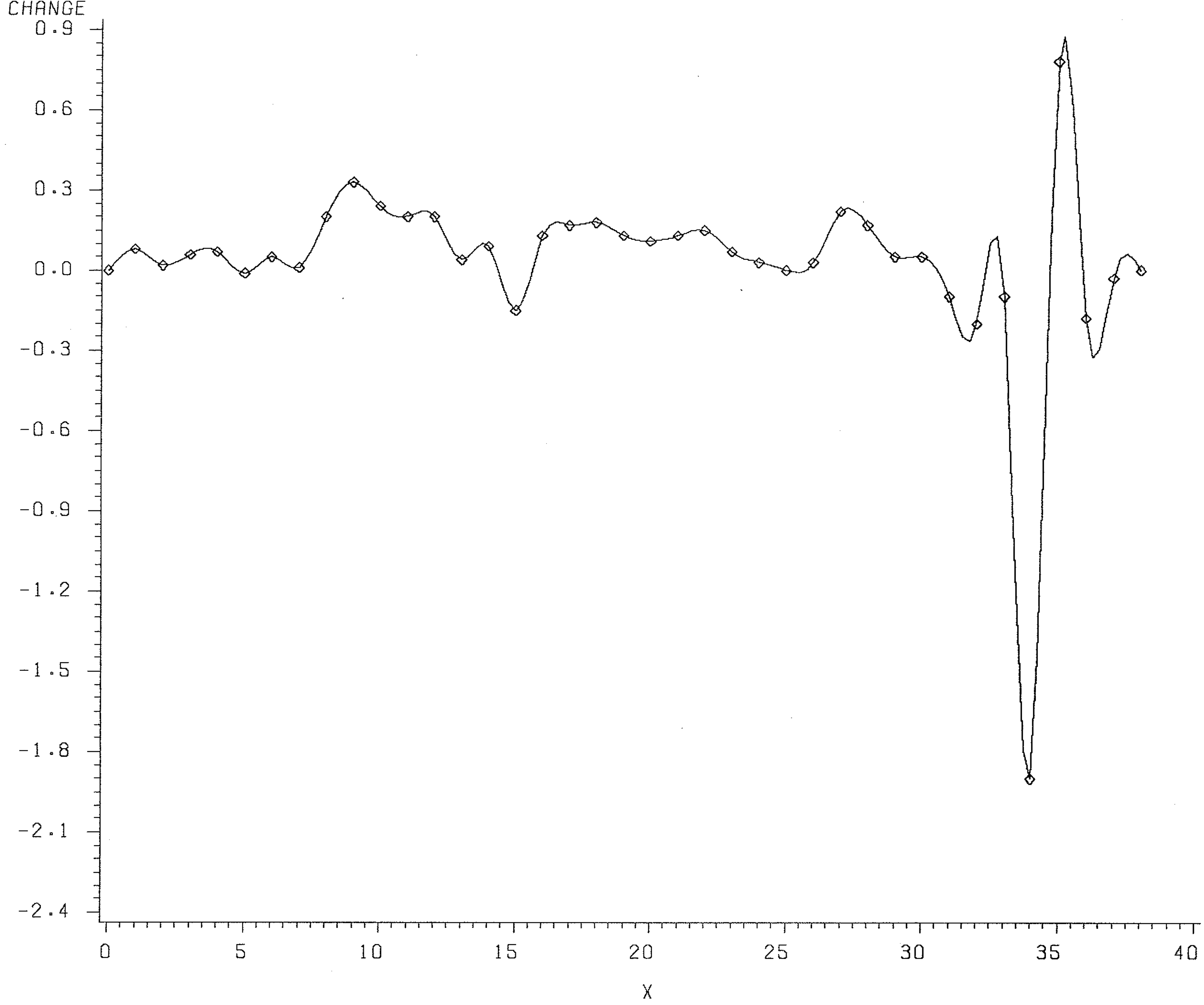
GRAVEL CREEK CHANNEL CHANGE A–REACH (A–5 1981 post–flood to 1982 post–

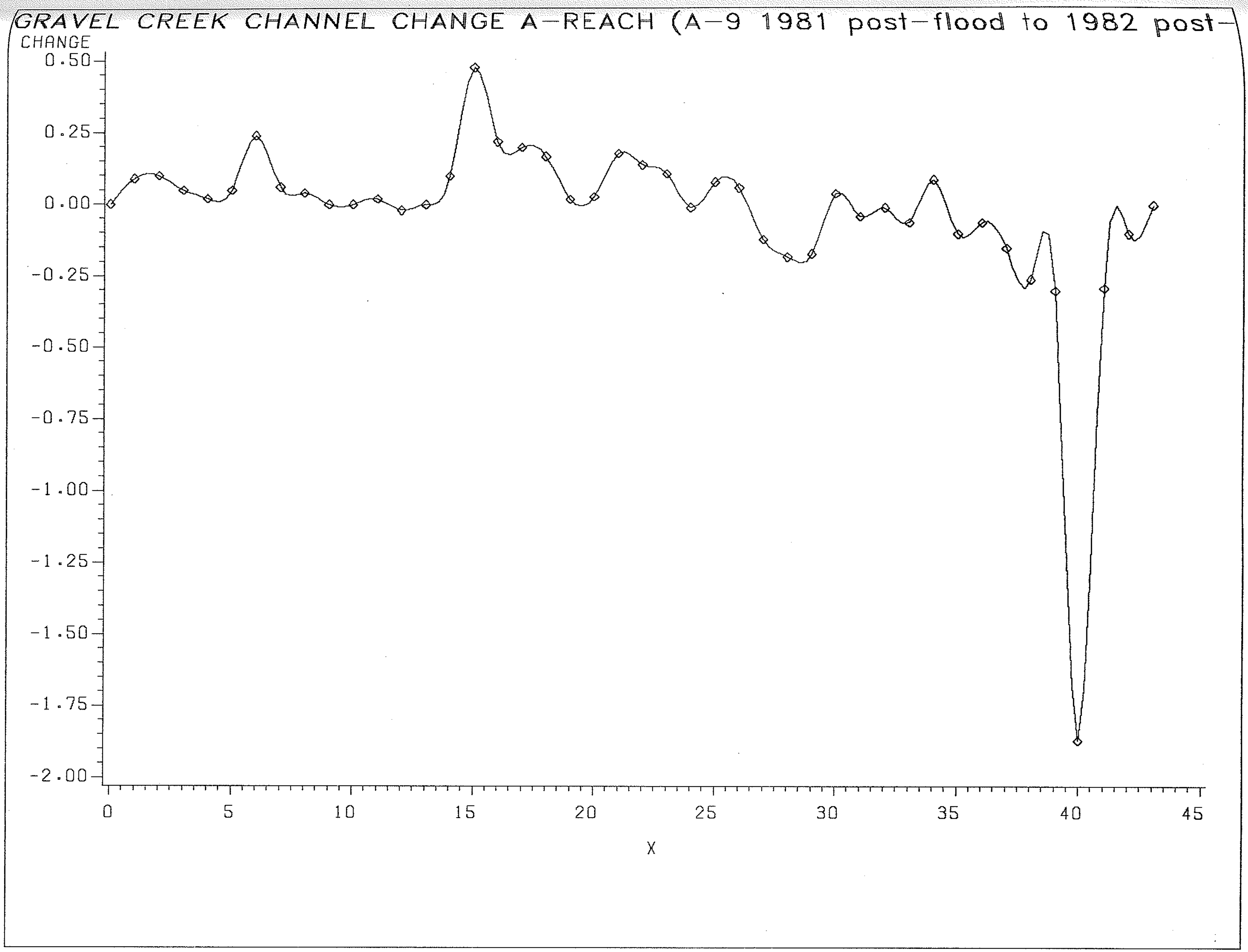
GRAVEL CREEK CHANNEL CHANGE A-REACH (A-6 1981 post-flood to 1982 post-



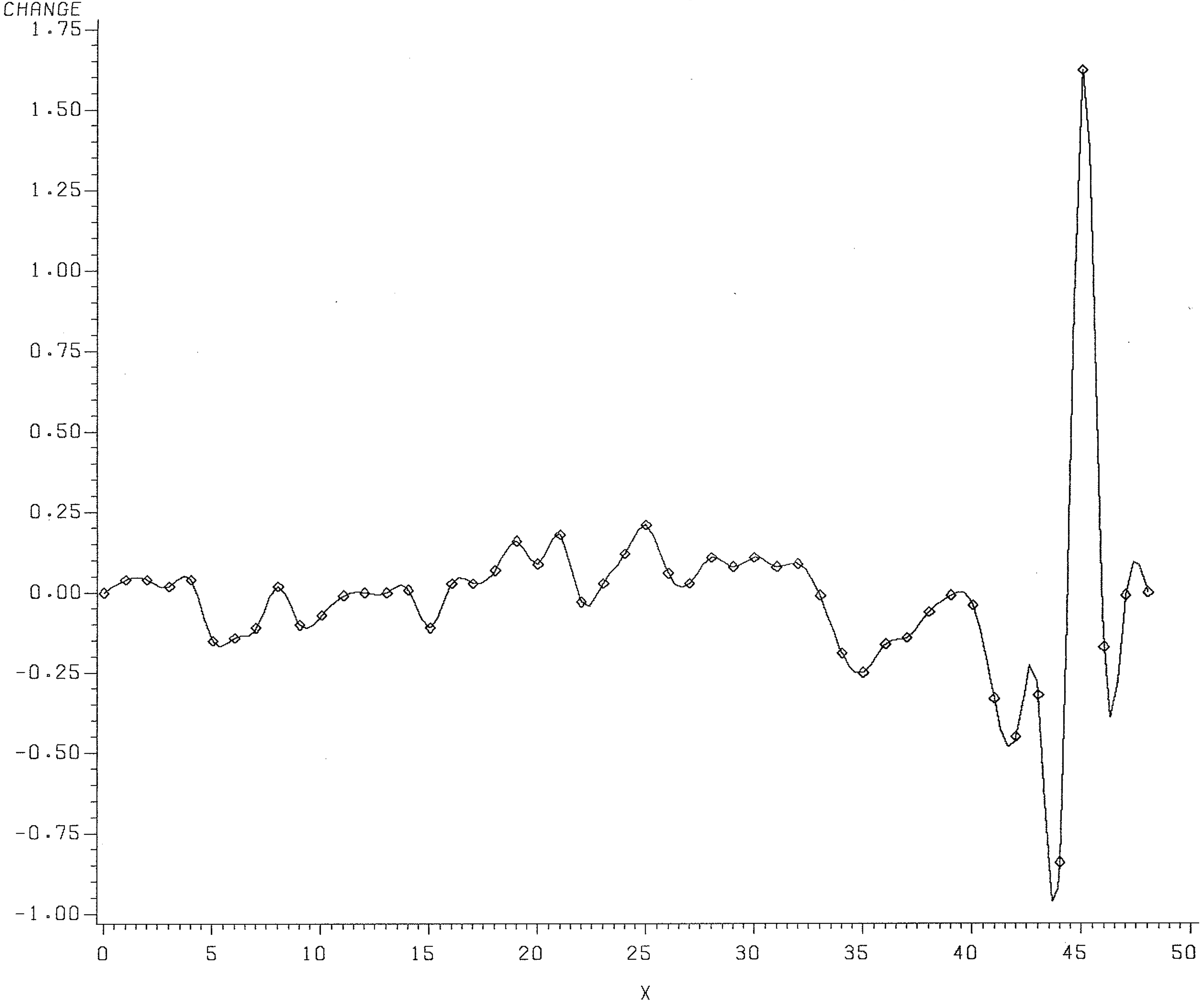

GRAVEL CREEK CHANNEL CHANGE A-REACH (A-7 1981 post-flood to 1982 post-
CHANGE
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
X

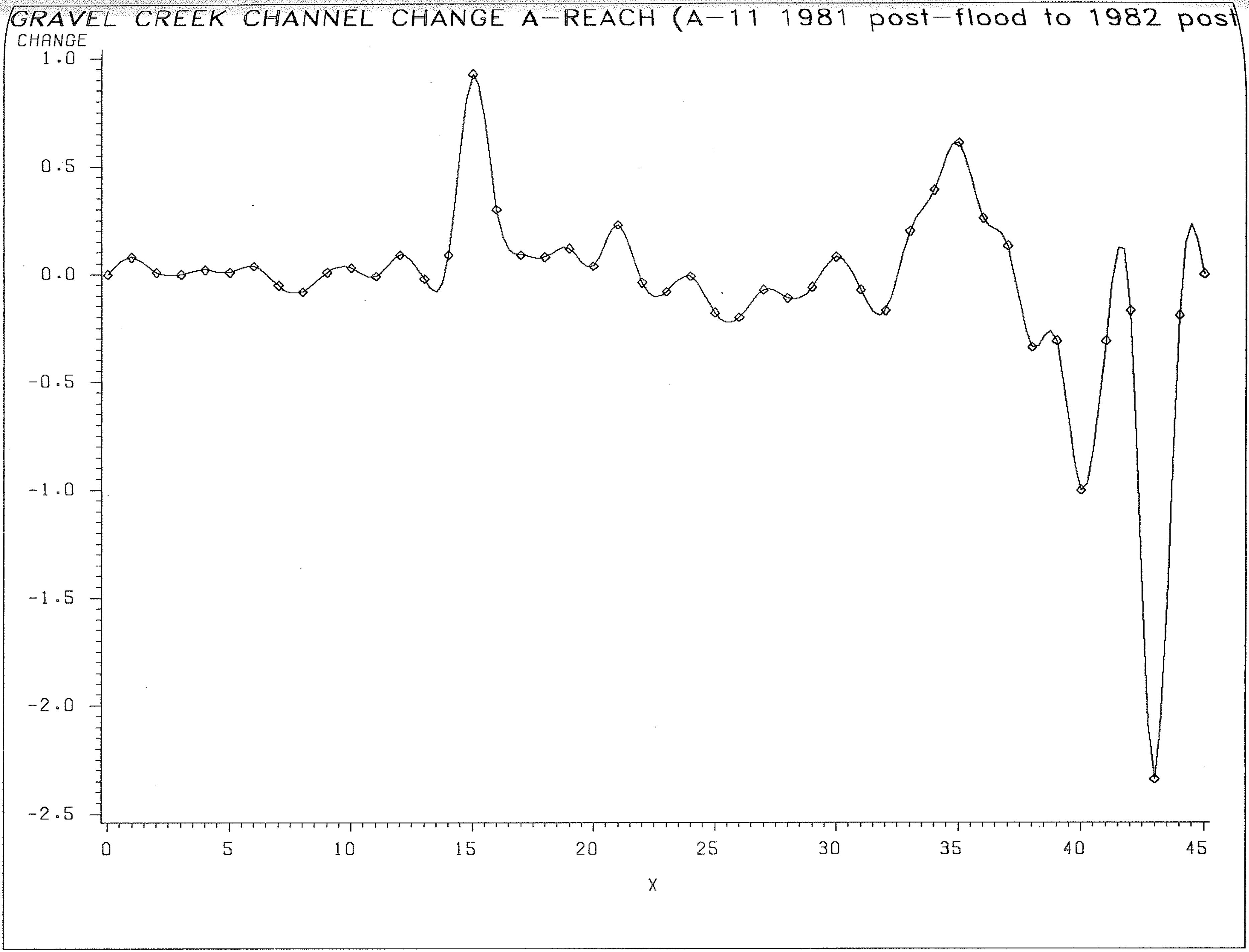
GRAVEL CREEK CHANNEL CHANGE A–REACH (A–8 1981 post–flood to 1982 post–




GRAVEL CREEK CHANNEL CHANGE A-REACH (A-9 1981 post-flood to 1982 post-
CHANGE
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.50
-1.75
-2.00
0
5
10
15
20
25
30
35
40
45
X

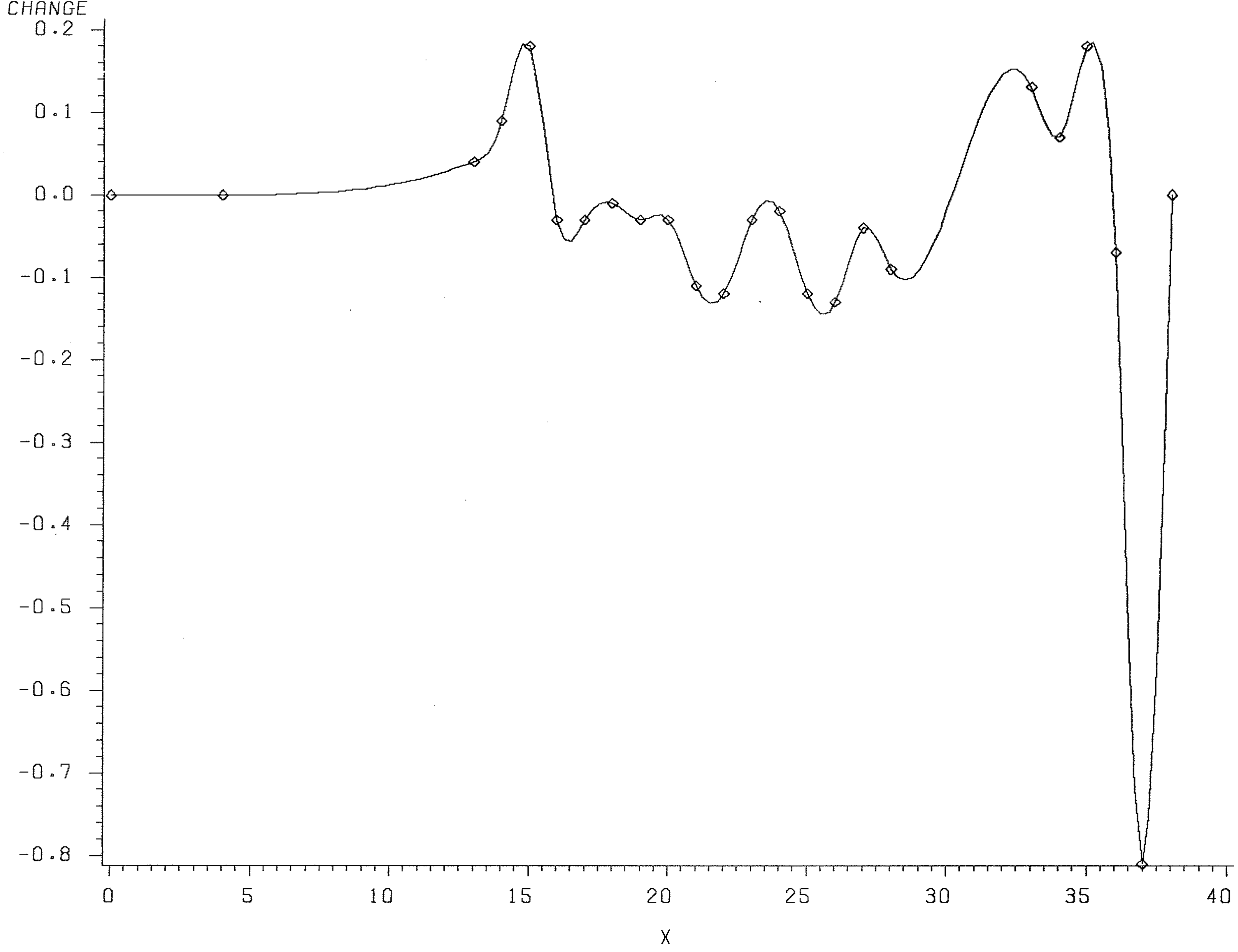
GRAVEL CREEK CHANNEL CHANGE A–REACH (A–10 1981 post–flood to 1982 post



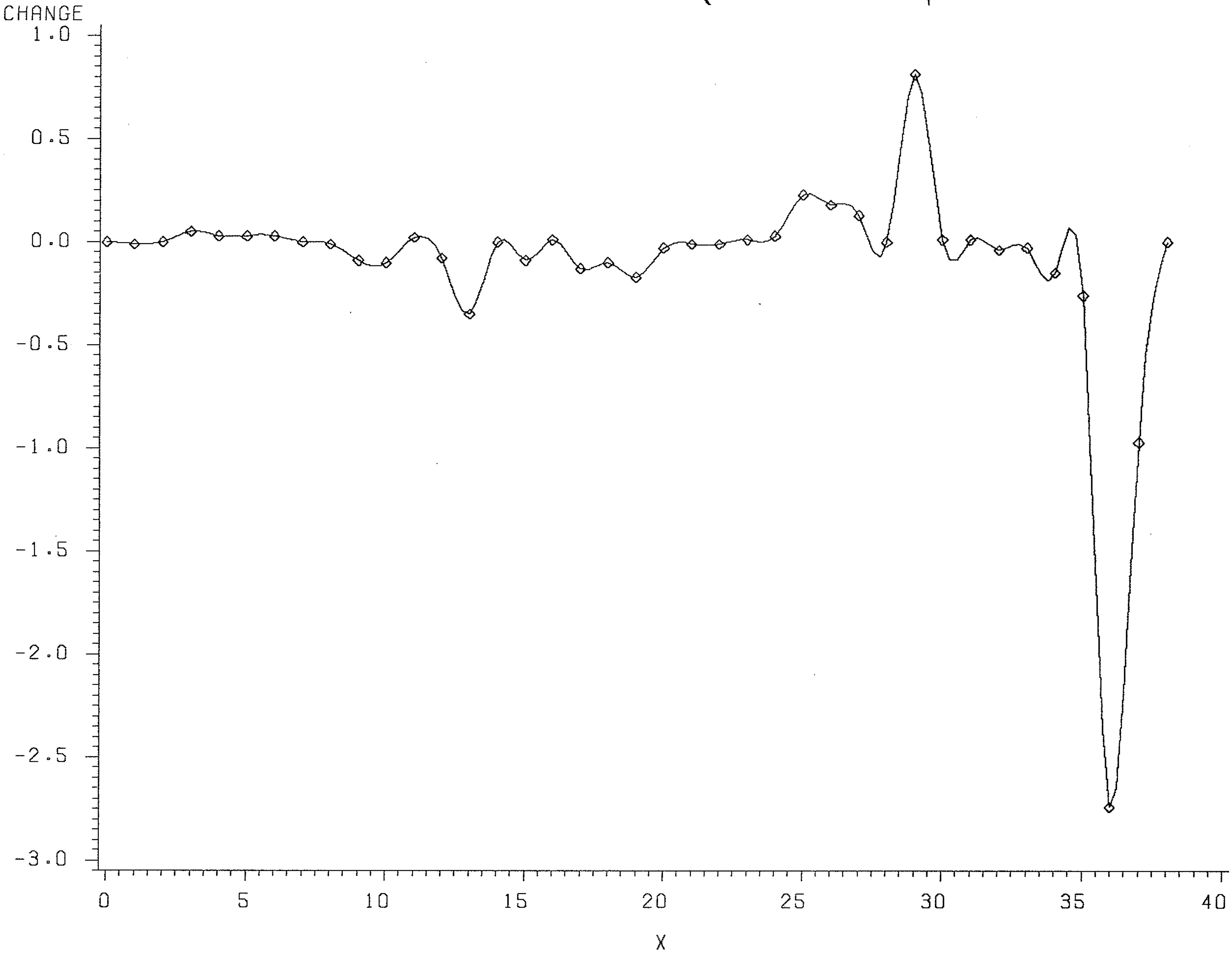


GRAVEL CREEK CHANNEL CHANGE A-REACH (A-11 1981 post-flood to 1982 post

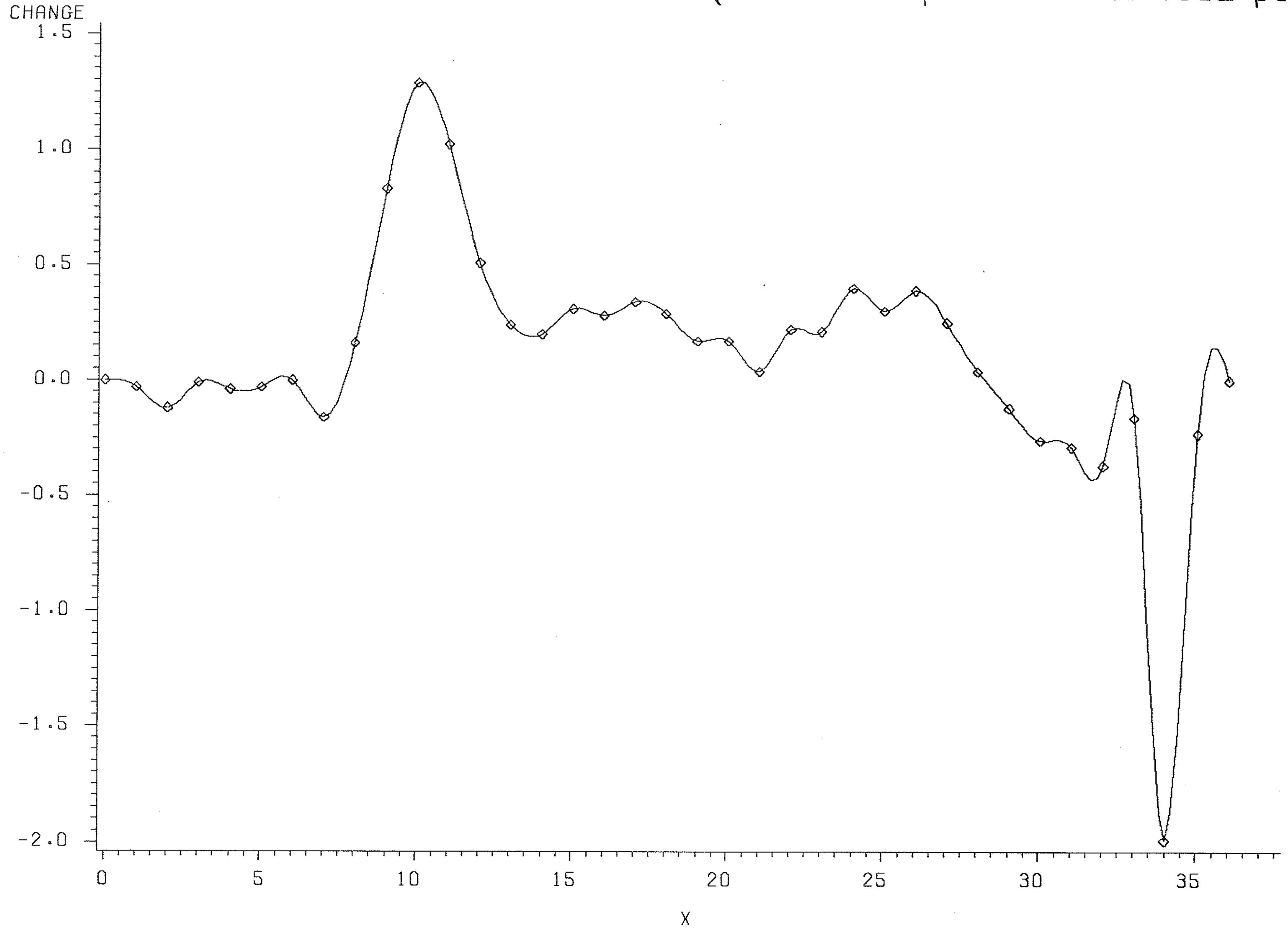
GRAVEL CREEK CHANNEL CHANGE A-REACH (A-12 1981 post-flood to 1982 post



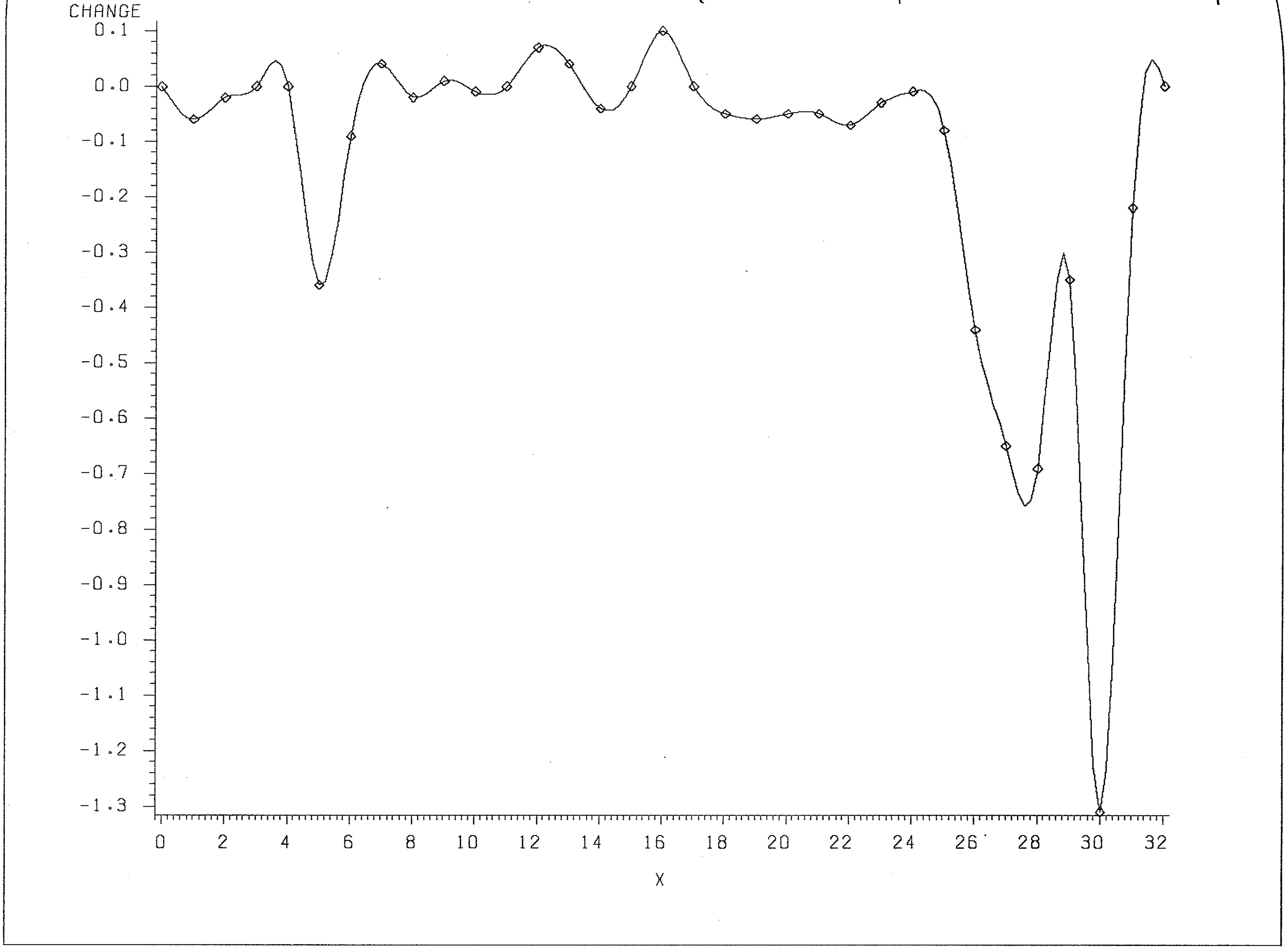
GRAVEL CREEK CHANNEL CHANGE A–REACH (A–13 1981 post–flood to 1982 post



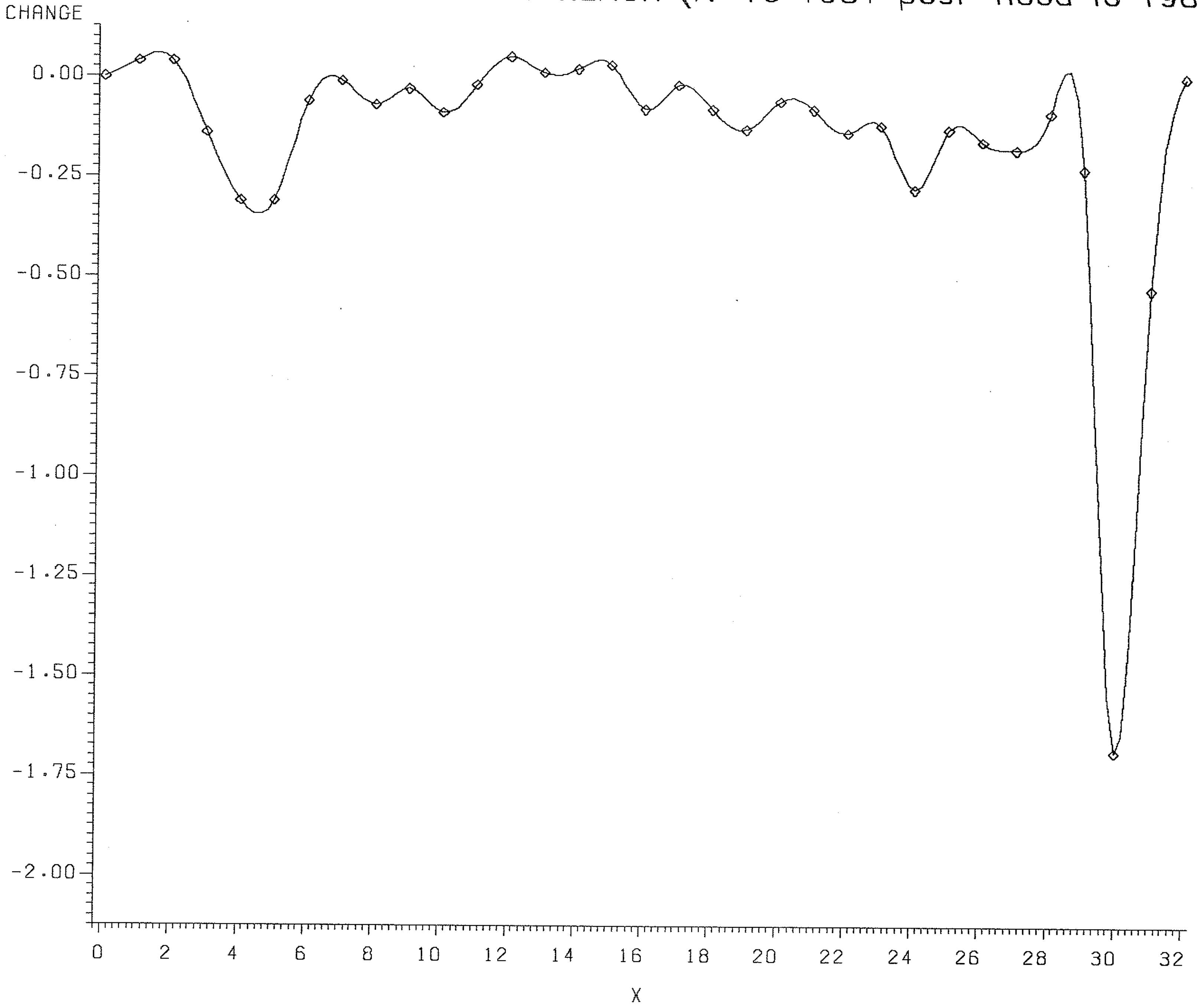
GRAVEL CREEK CHANNEL CHANGE A-REACH (A-14 1981 post-flood to 1982 post



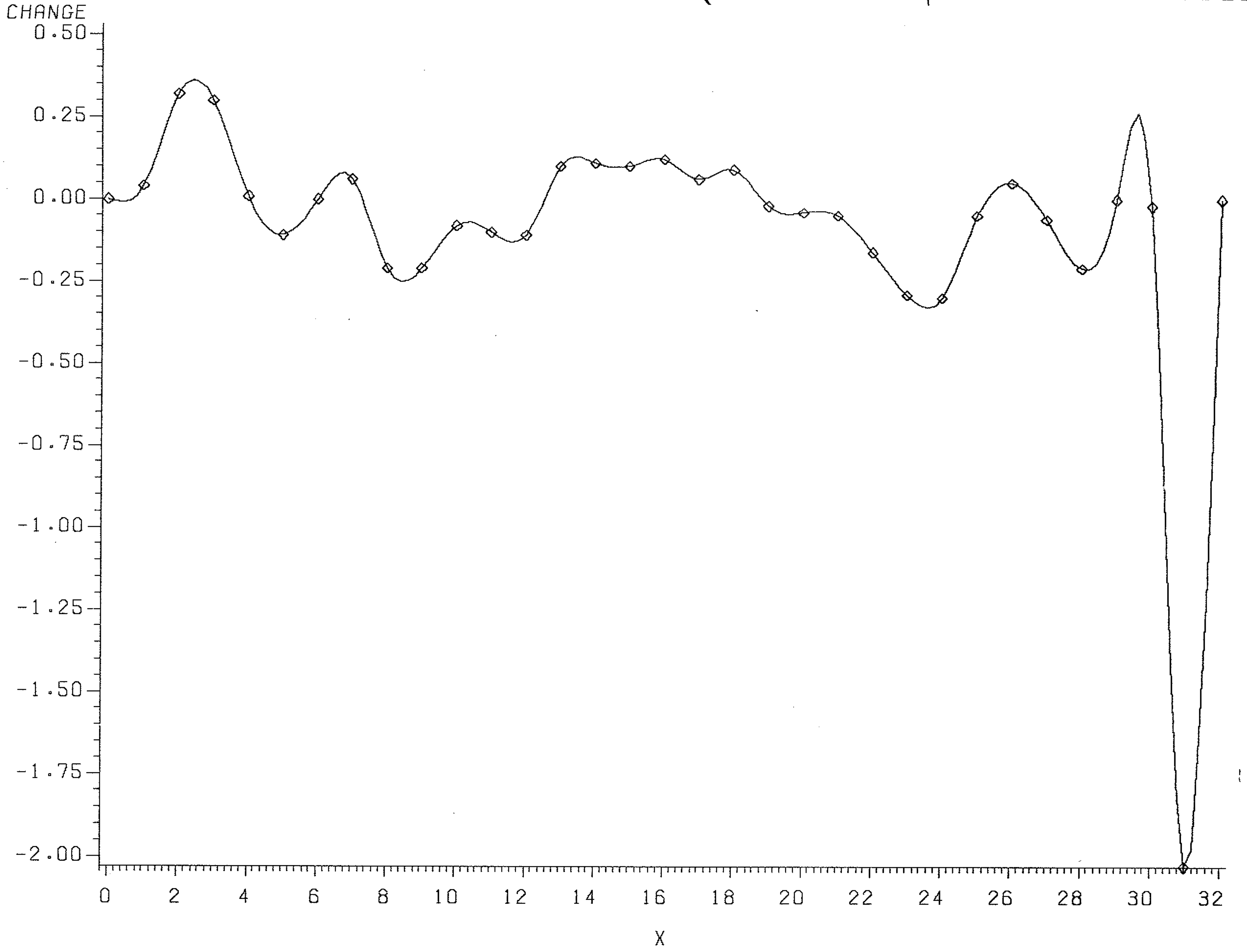
GRAVEL CREEK CHANNEL CHANGE A-REACH (A-15 1981 post-flood to 1982 post



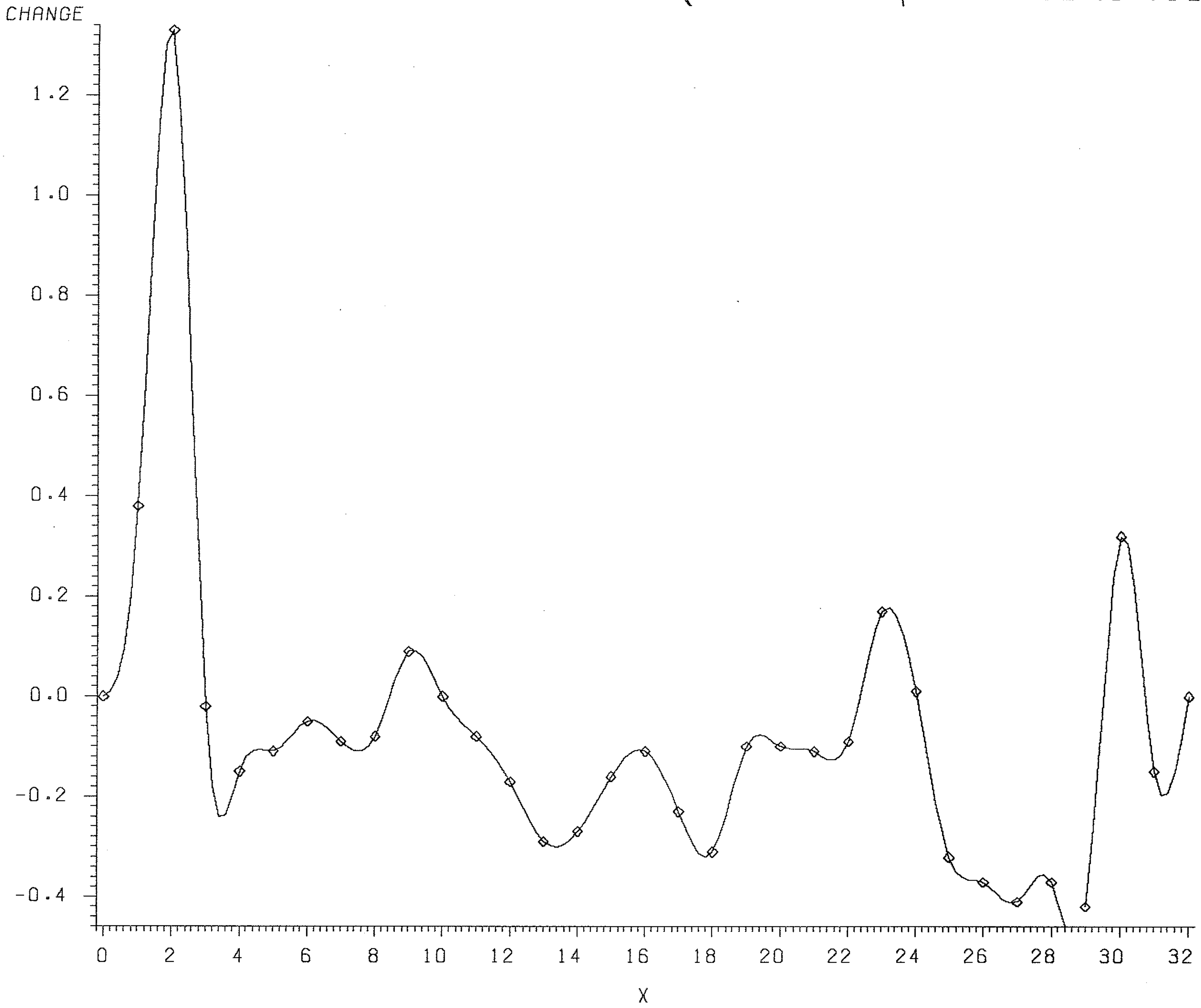
GRAVEL CREEK CHANNEL CHANGE A–REACH (A–16 1981 post–flood to 1982 post



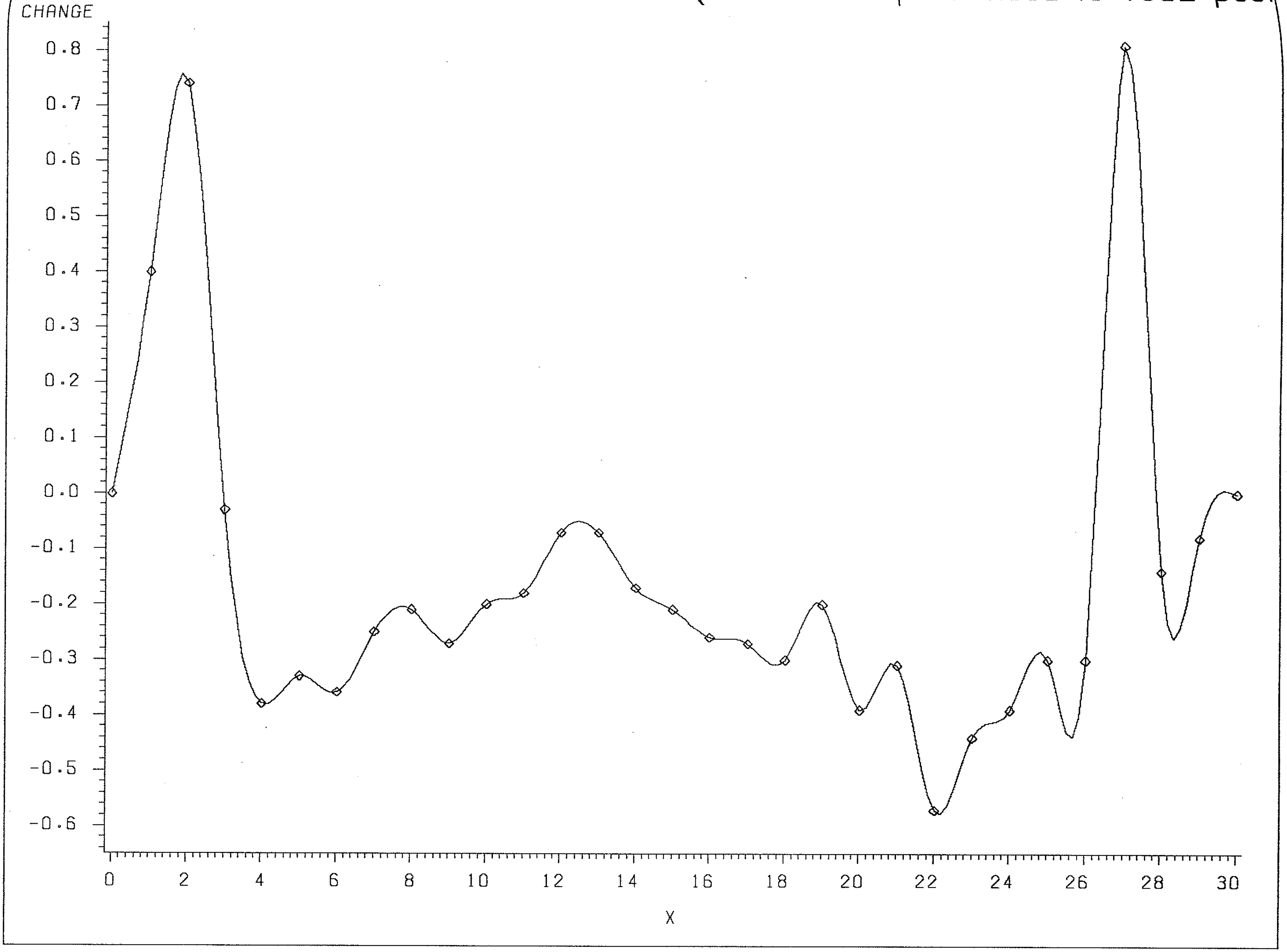
GRAVEL CREEK CHANNEL CHANGE A–REACH (A–17 1981 post–flood to 1982 post



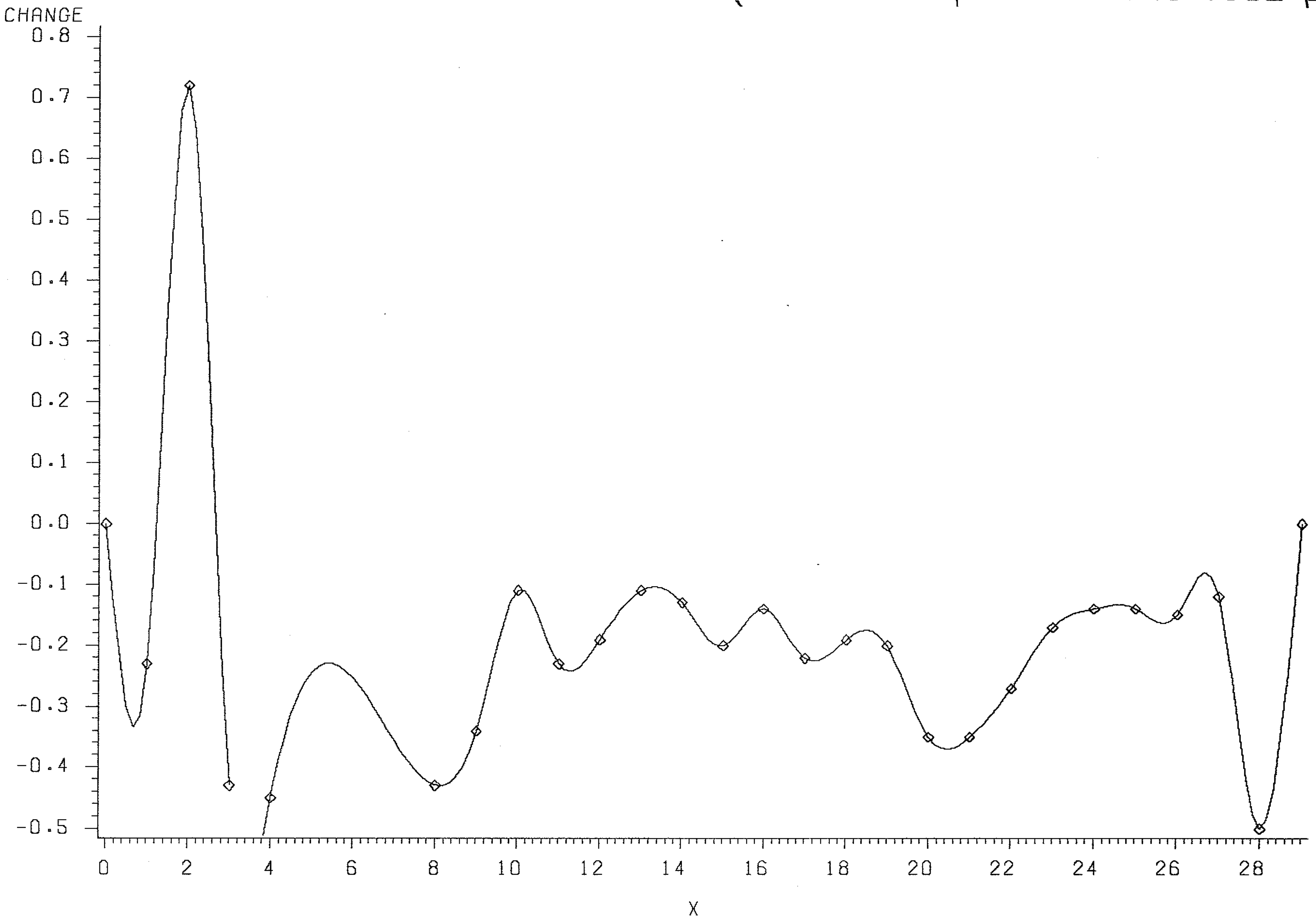
GRAVEL CREEK CHANNEL CHANGE A–REACH (A–18 1981 post–flood to 1982 post

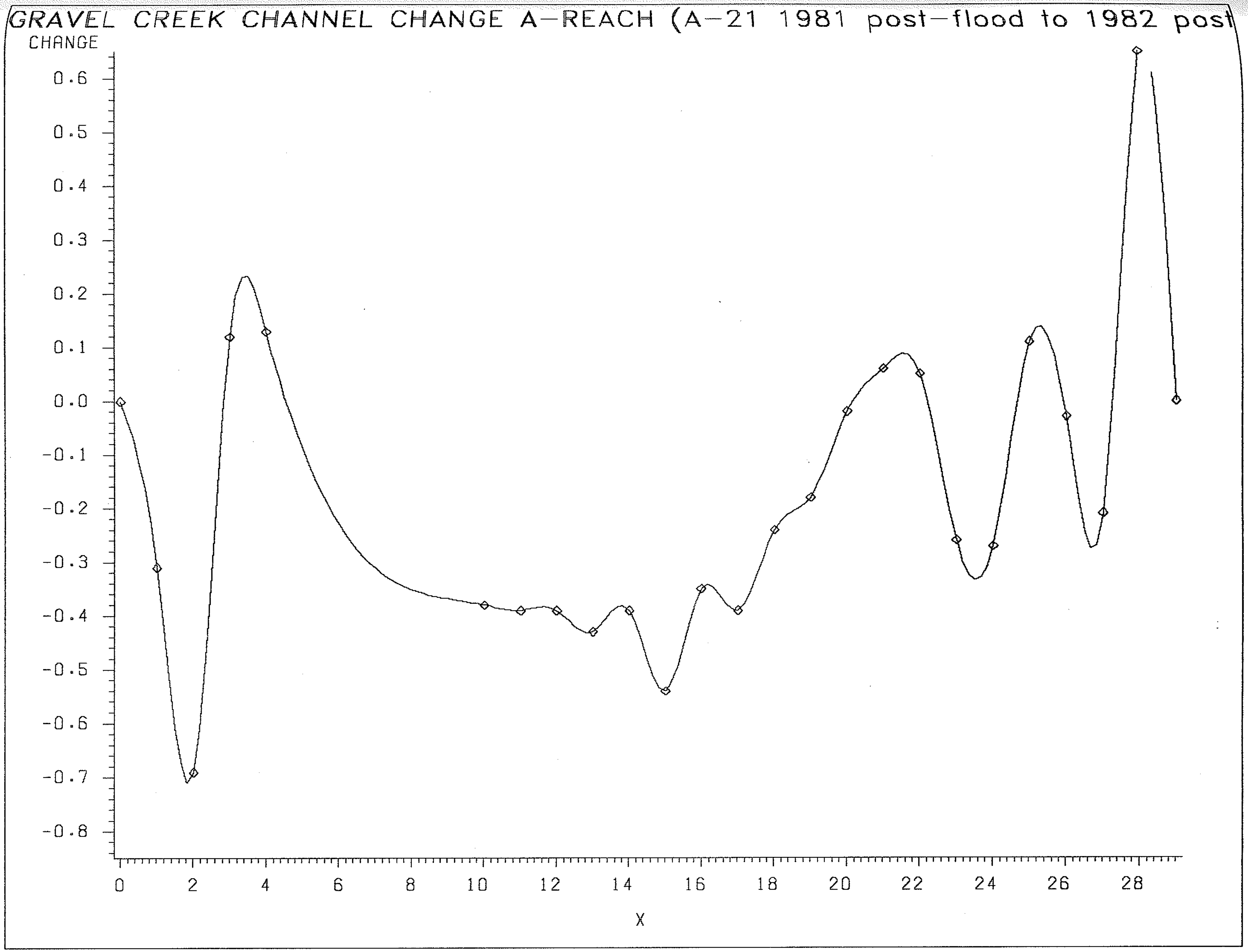


GRAVEL CREEK CHANNEL CHANGE A–REACH (A–19 1981 post–flood to 1982 post



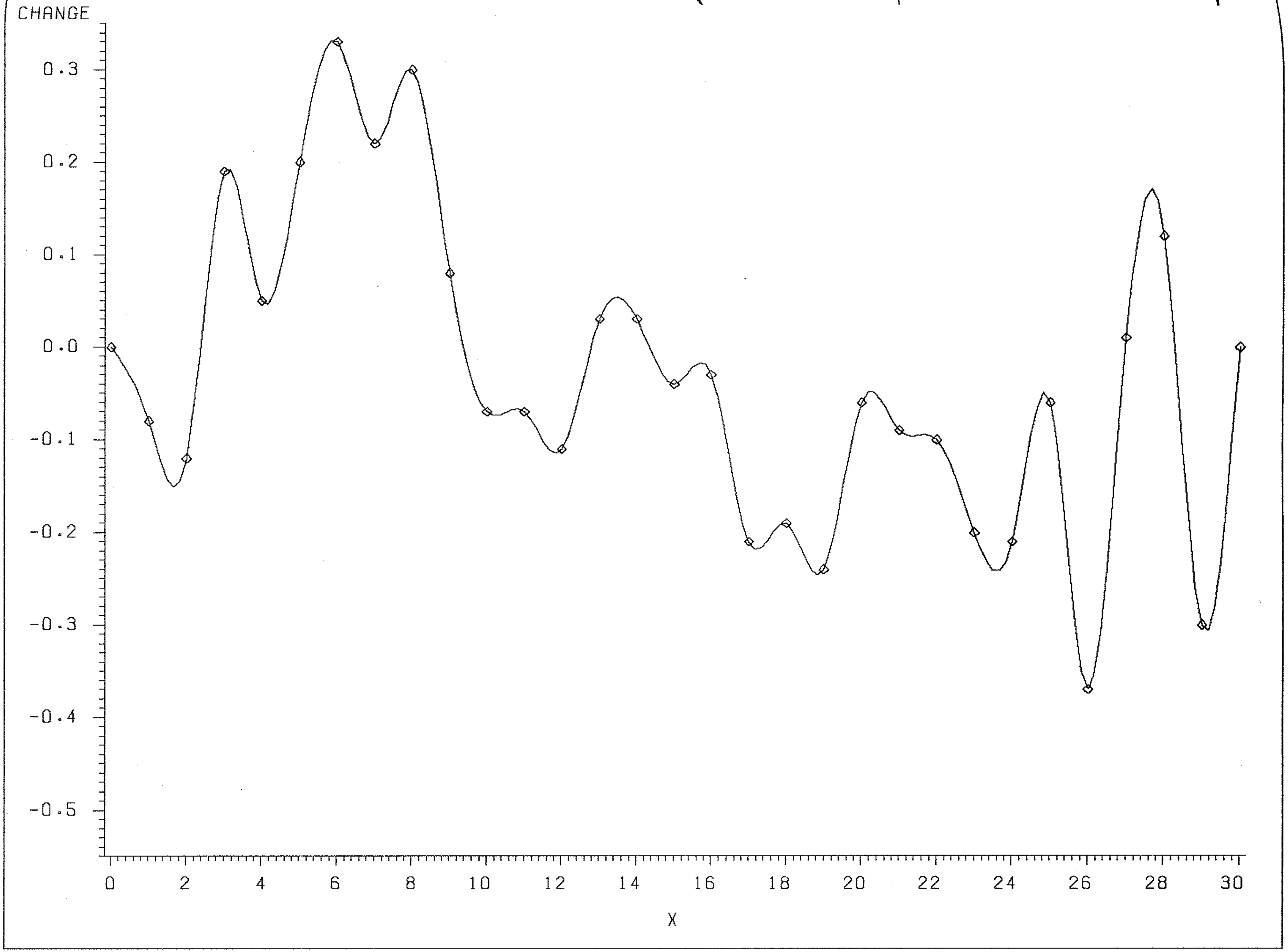
GRAVEL CREEK CHANNEL CHANGE A—REACH (A—20 1981 post—flood to 1982 post



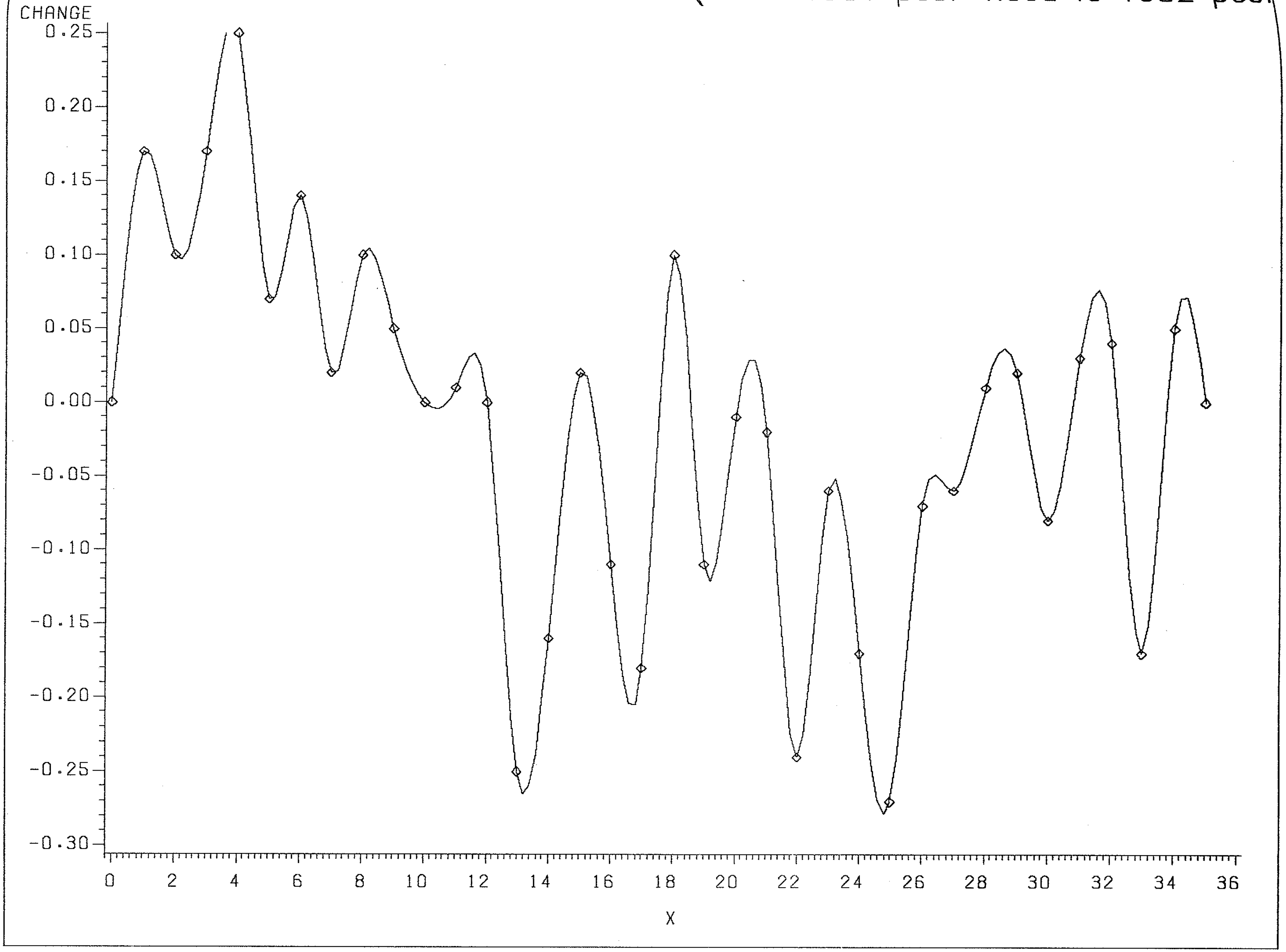


GRAVEL CREEK CHANNEL CHANGE A-REACH (A-21 1981 post-flood to 1982 post

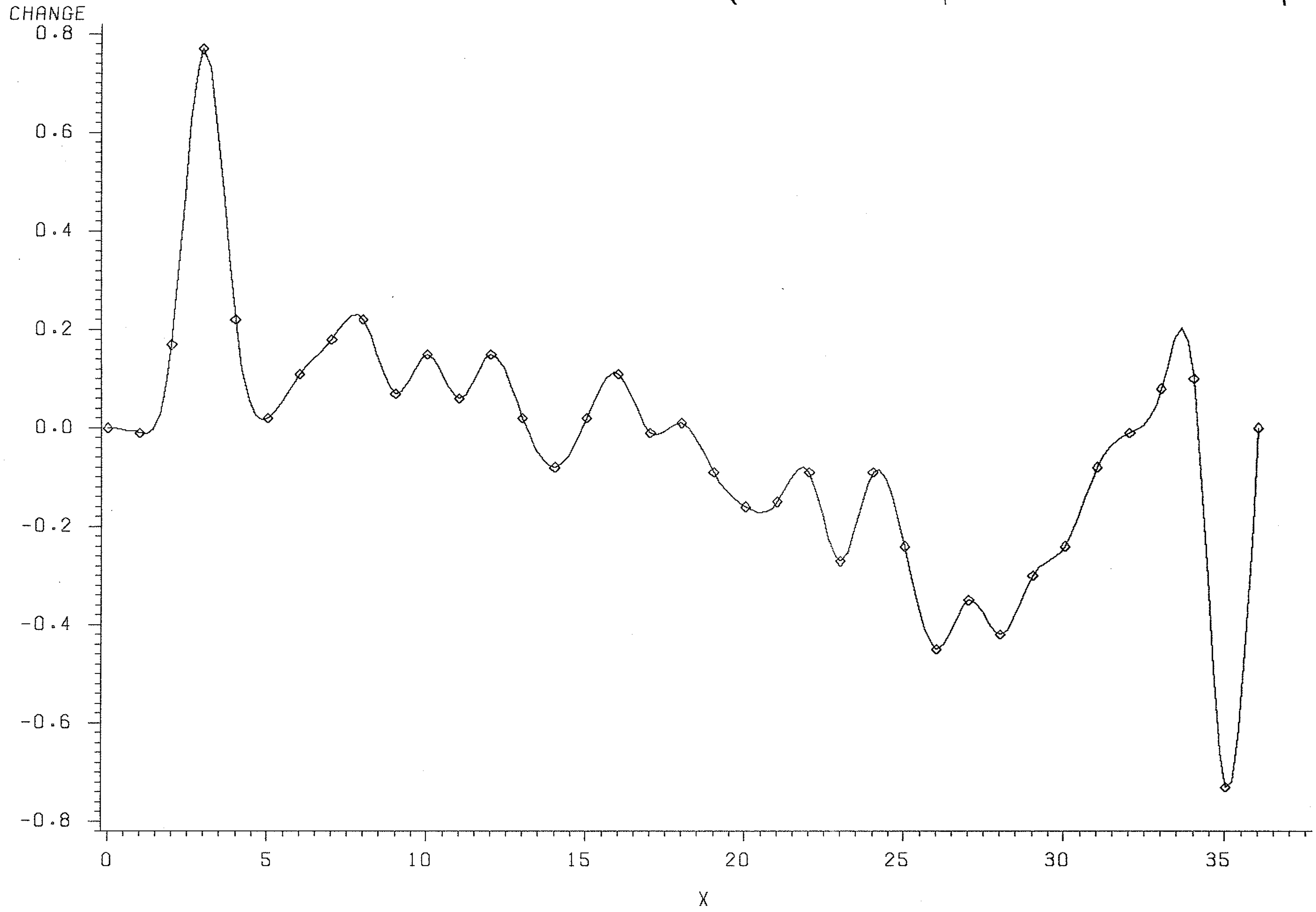
GRAVEL CREEK CHANNEL CHANGE A-REACH (A-22 1981 post-flood to 1982 post



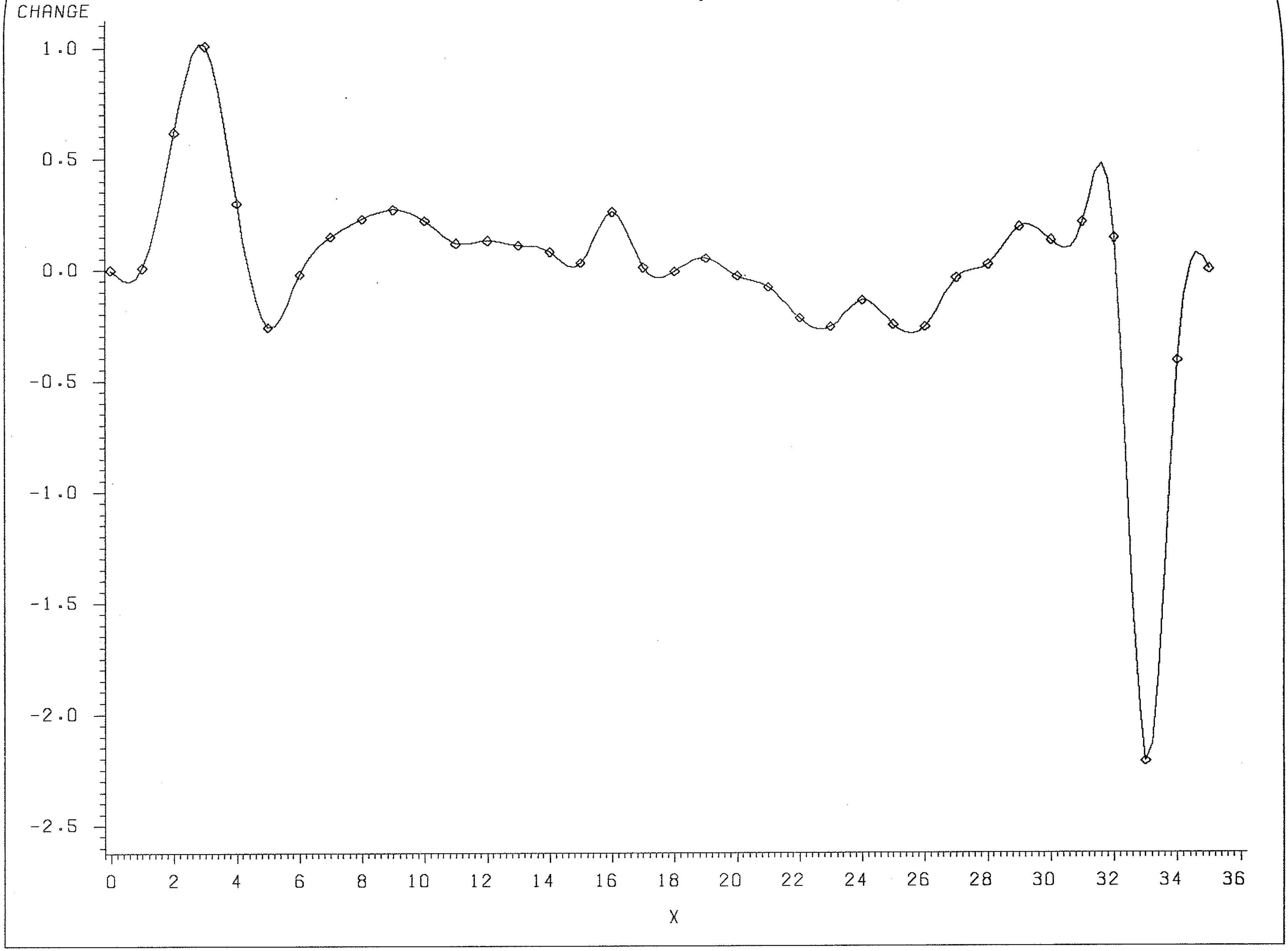
GRAVEL CREEK CHANNEL CHANGE A—REACH (A—23 1981 post—flood to 1982 post



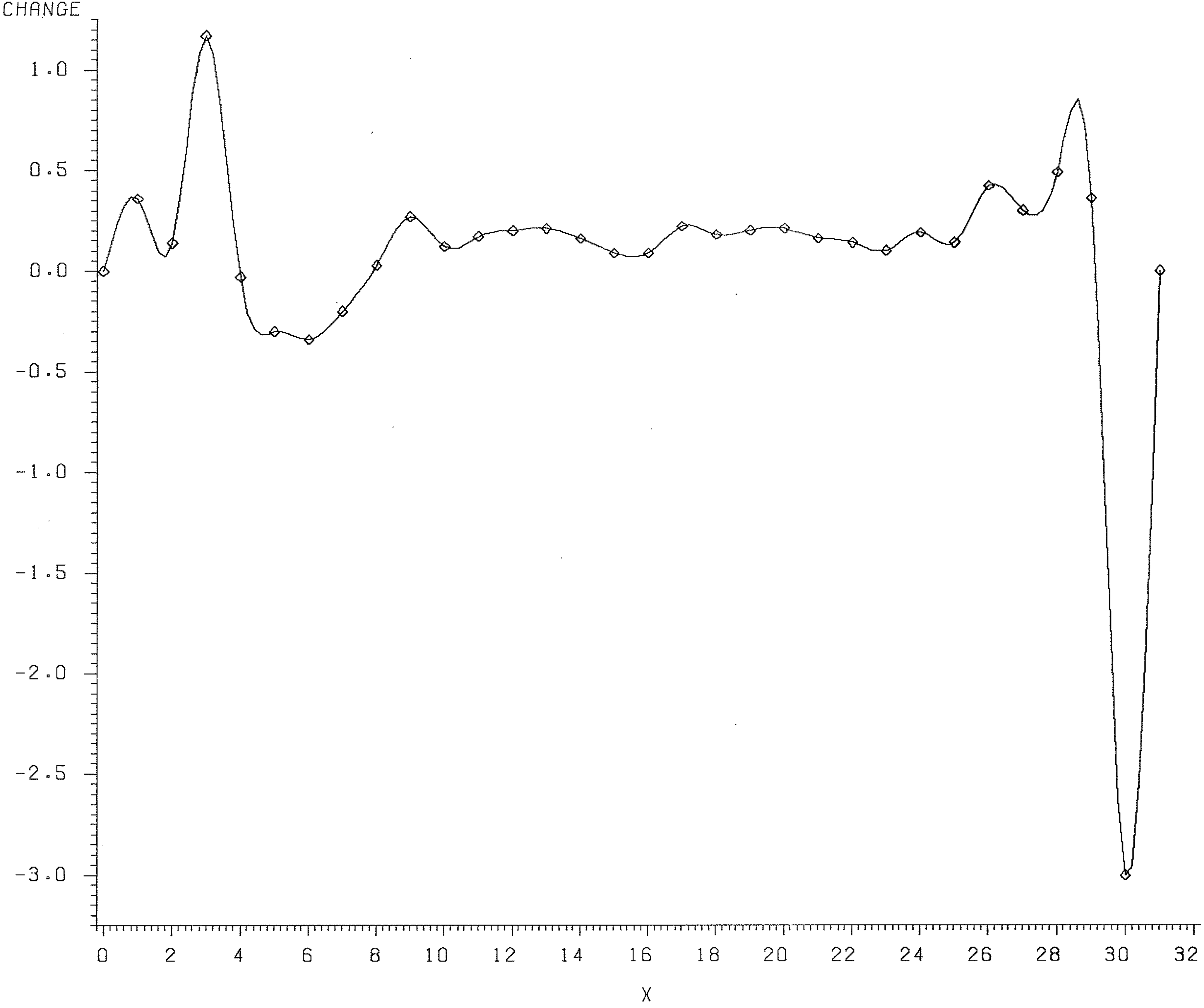
GRAVEL CREEK CHANNEL CHANGE A-REACH (A-24 1981 post-flood to 1982 post



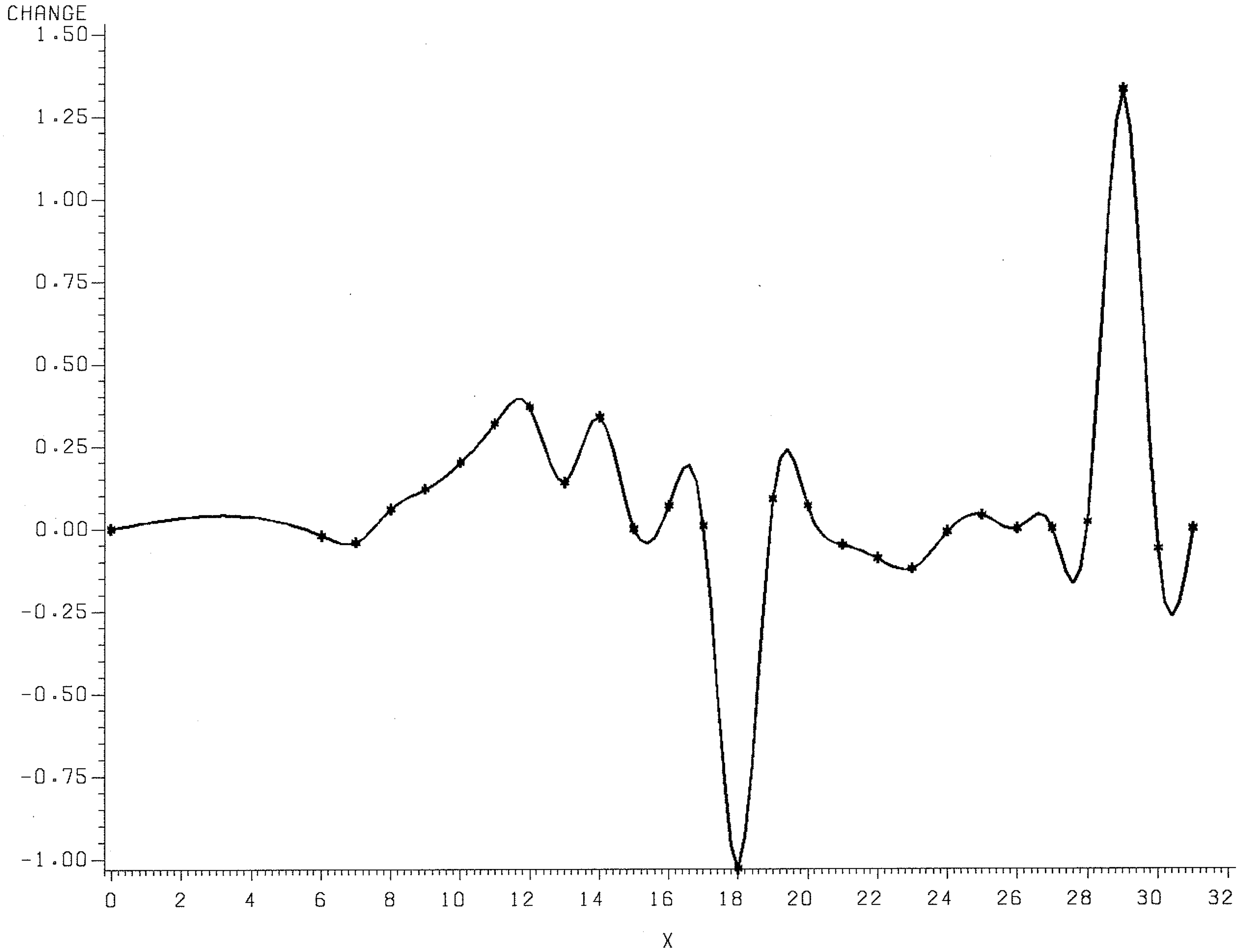
GRAVEL CREEK CHANNEL CHANGE A-REACH (A-25 1981 post-flood to 1982 post



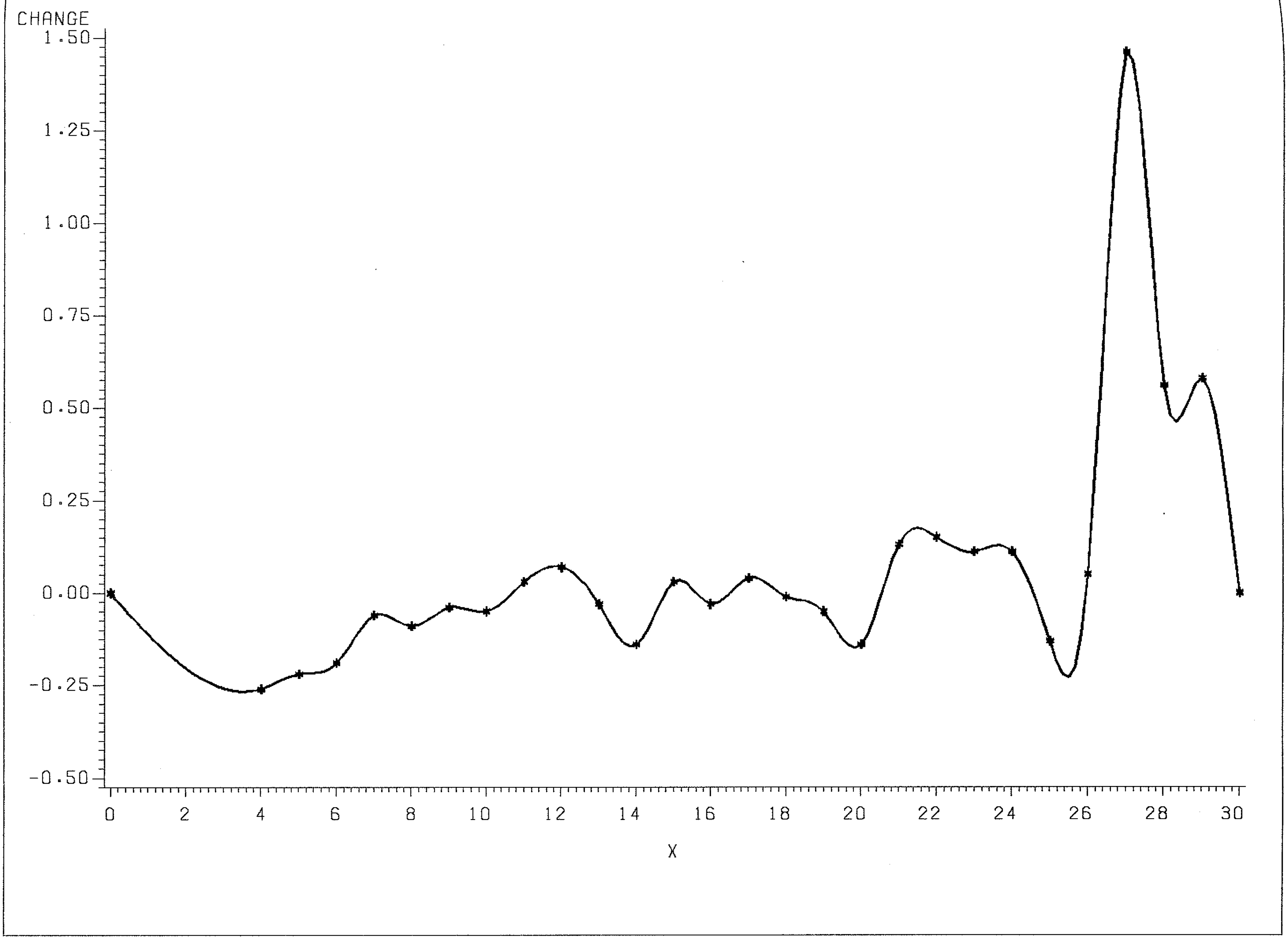
GRAVEL CREEK CHANNEL CHANGE A—REACH (A—26 1981 post—flood to 1982 post



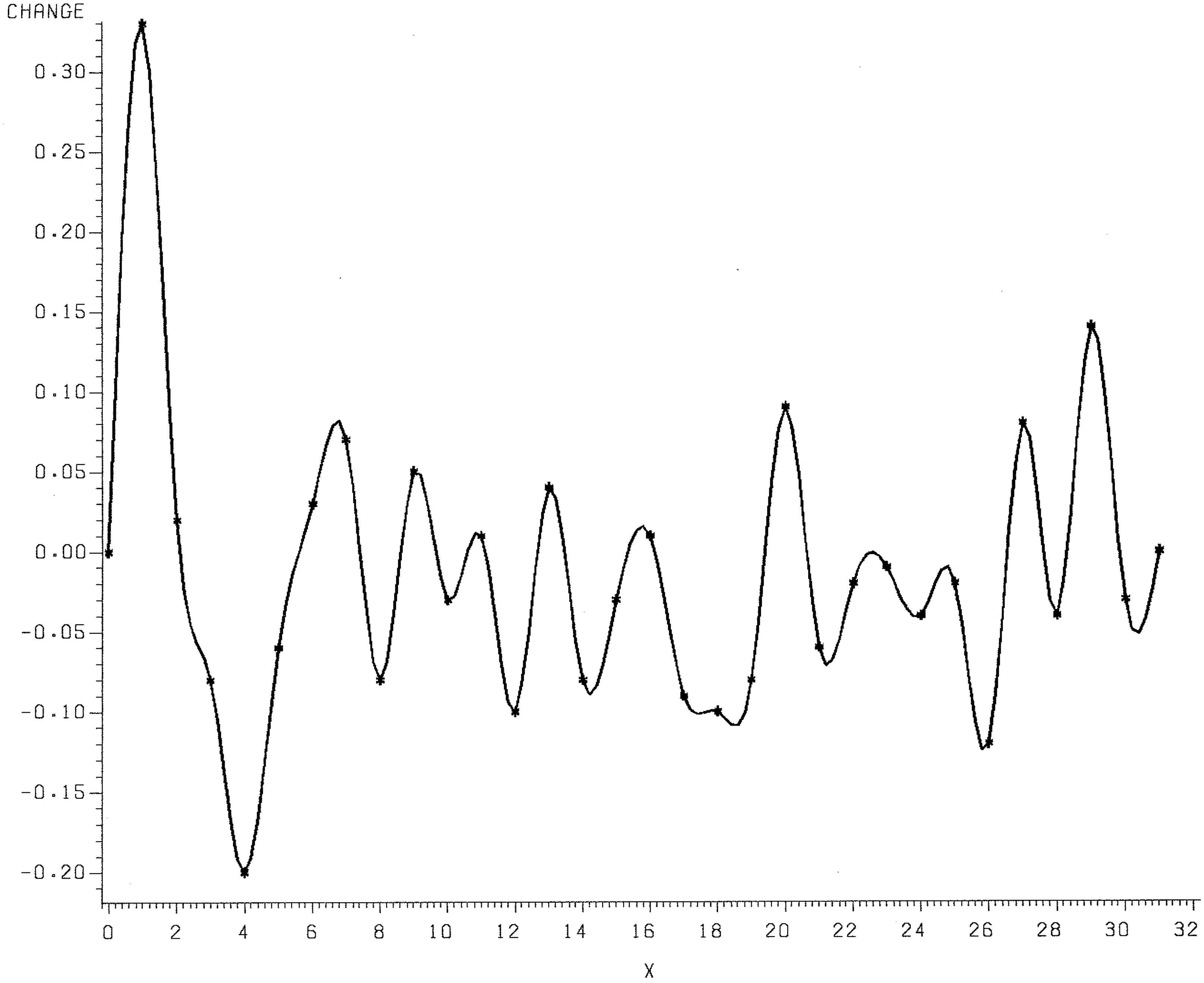
GRAVEL CREEK CHANNEL CHANGE B-1 (June,1981-post breakup May 1982)



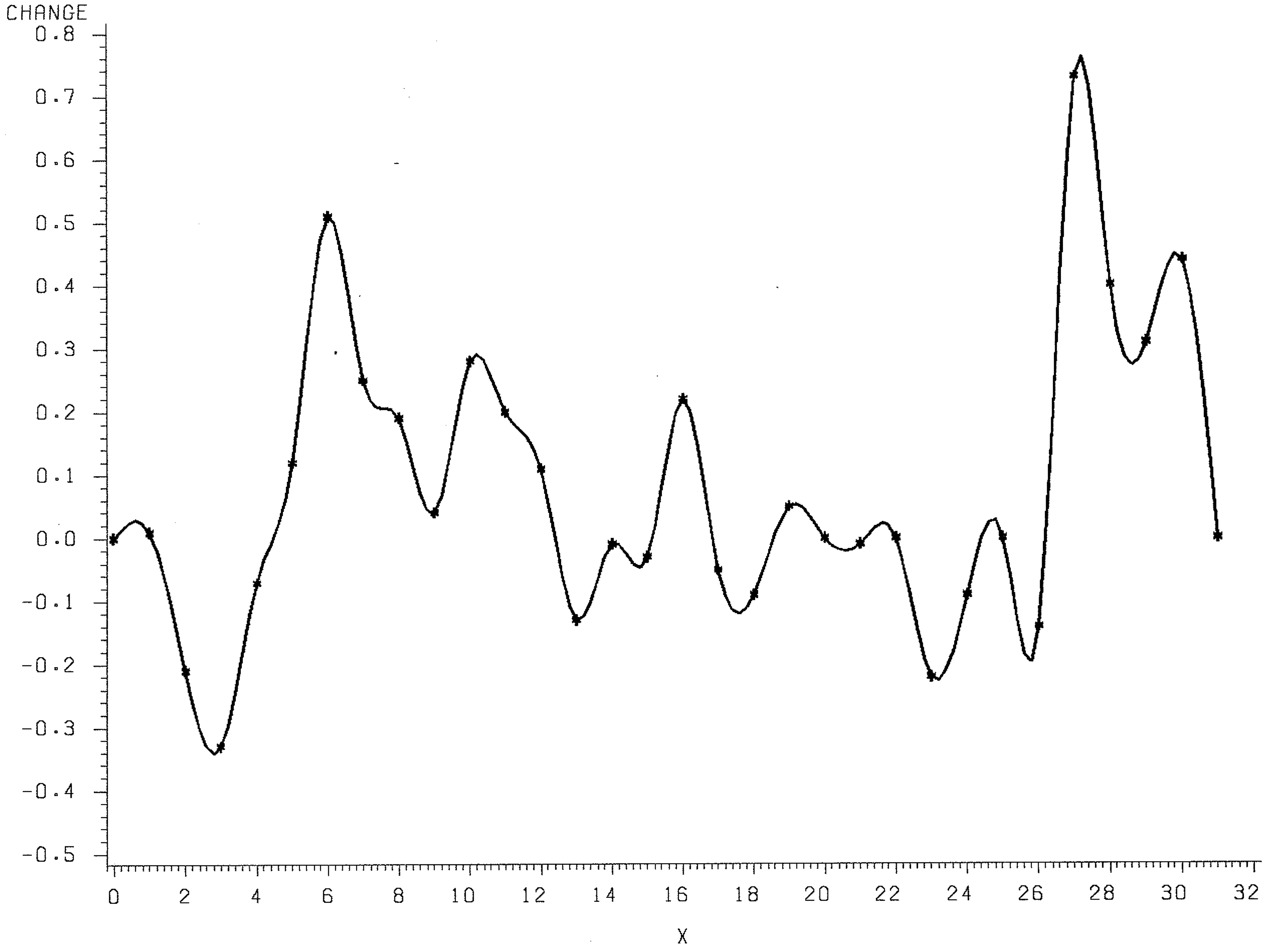
GRAVEL CREEK CHANNEL CHANGE B-2 (June,1981-post breakup May 1982)

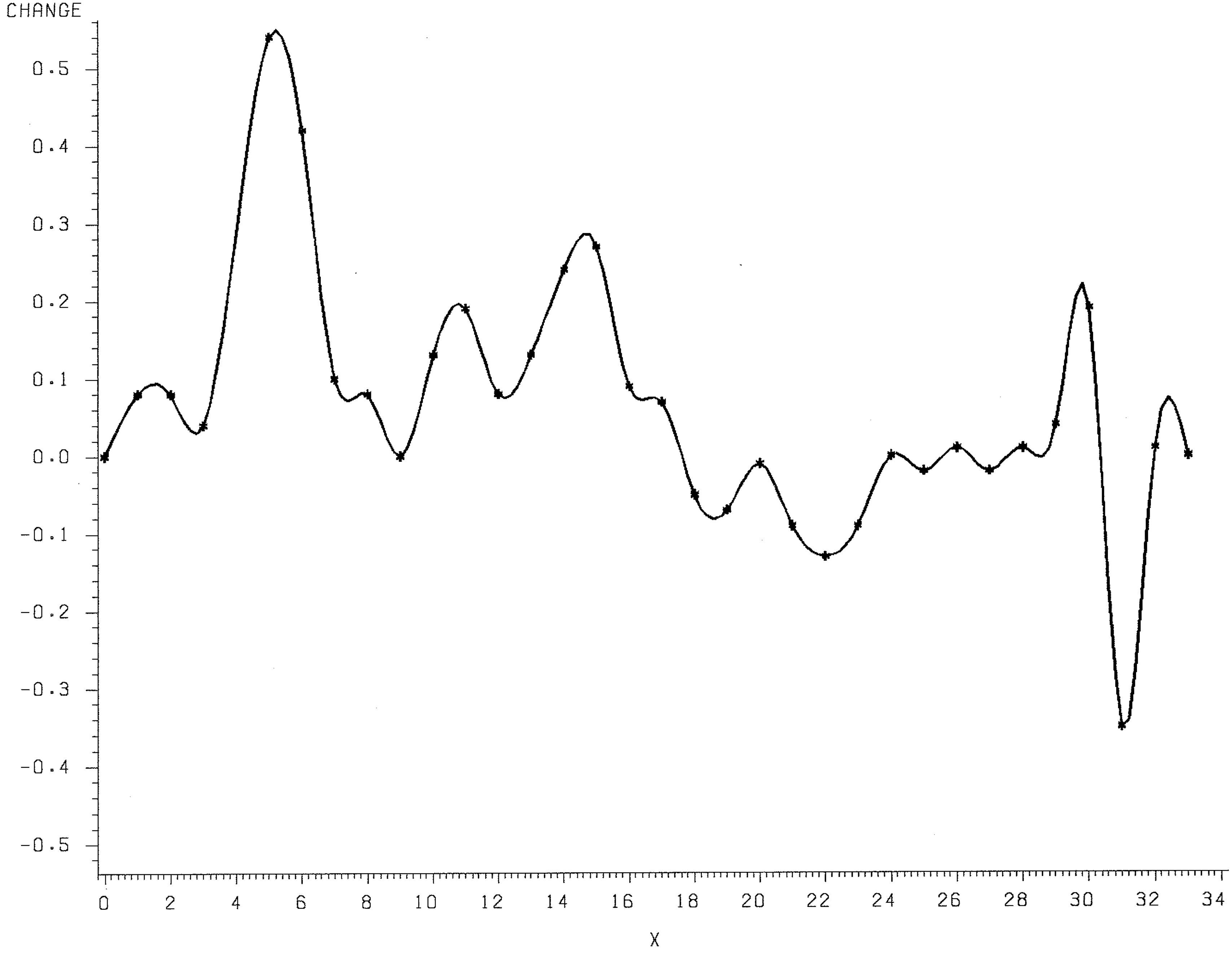


GRAVEL CREEK CHANNEL CHANGE B-3 (June,1981-post breakup May 1982)



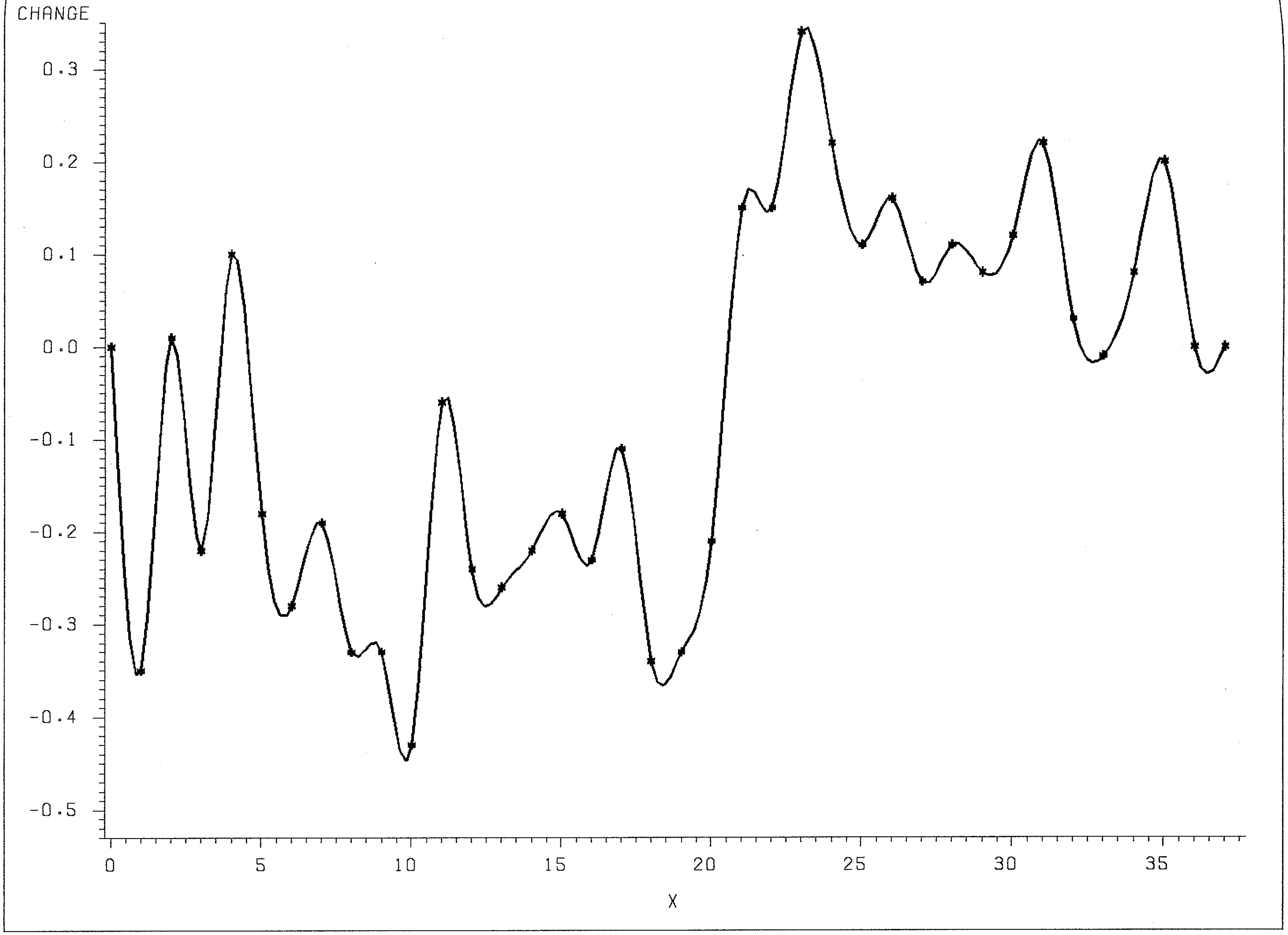
GRAVEL CREEK CHANNEL CHANGE B-4 (June,1981-post breakup May 1982)



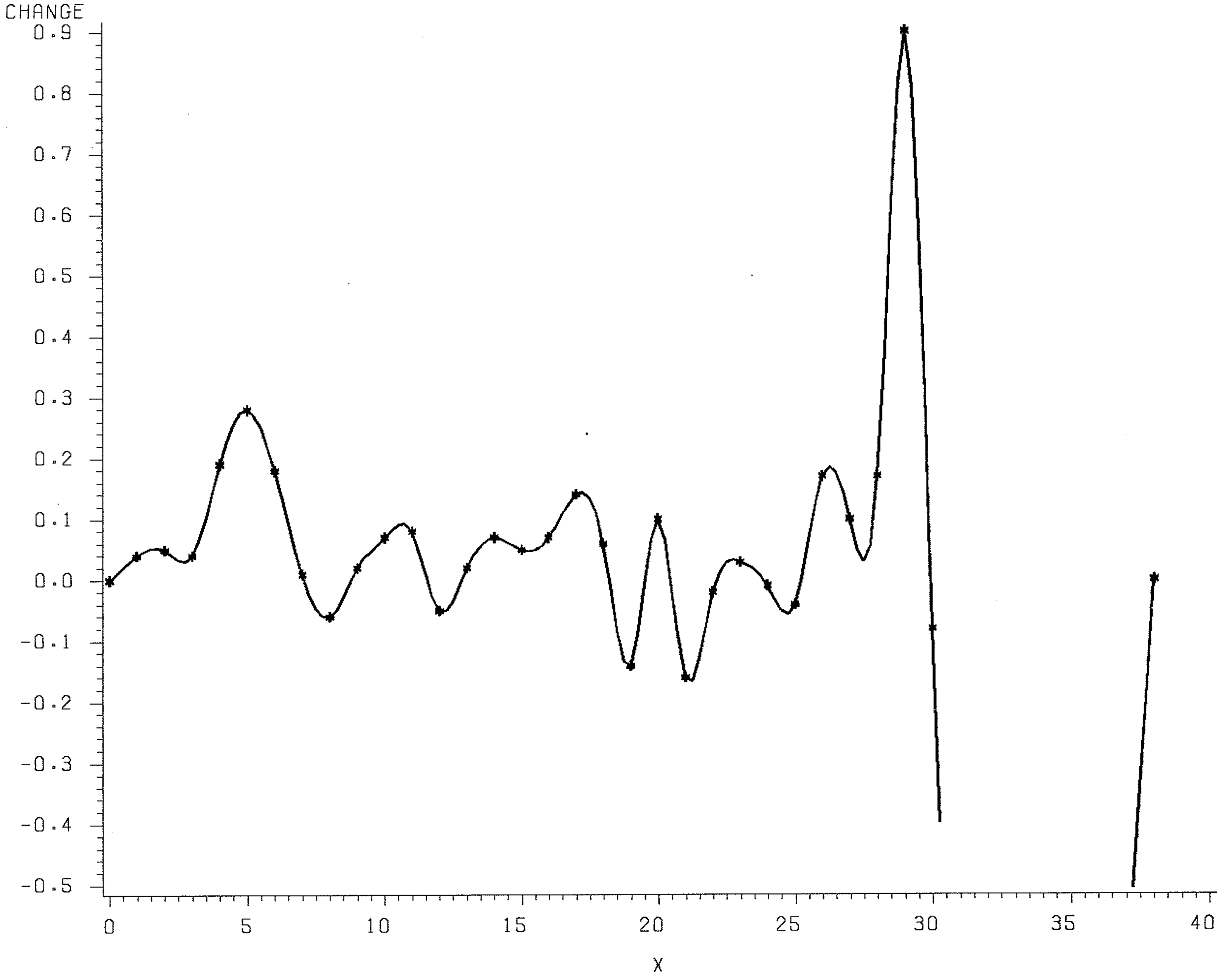


GRAVEL CREEK CHANNEL CHANGE B-5 (June,1981-post breakup May 1982)

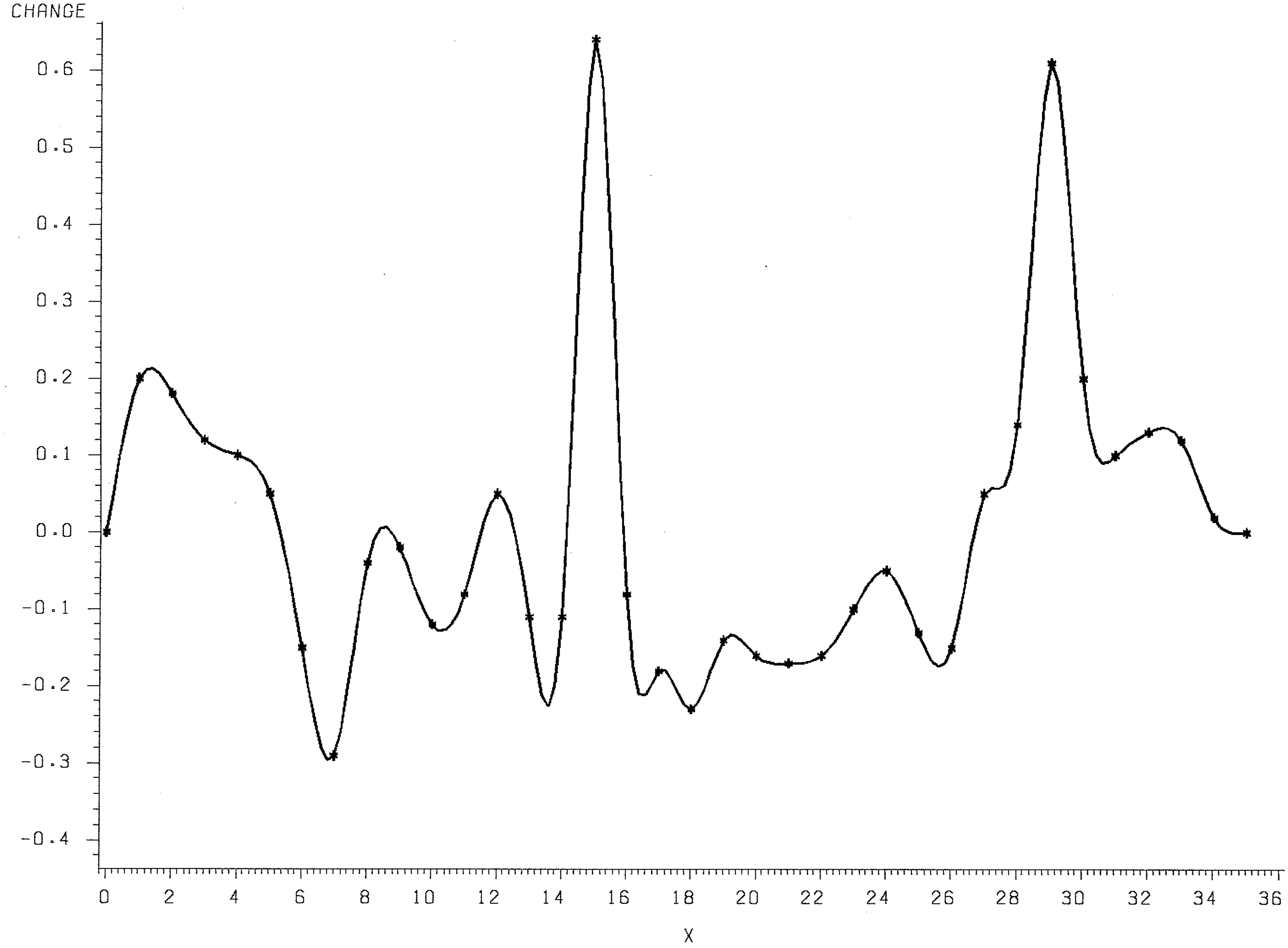
GRAVEL CREEK CHANNEL CHANGE B-6 (June,1981-post breakup May 1982)



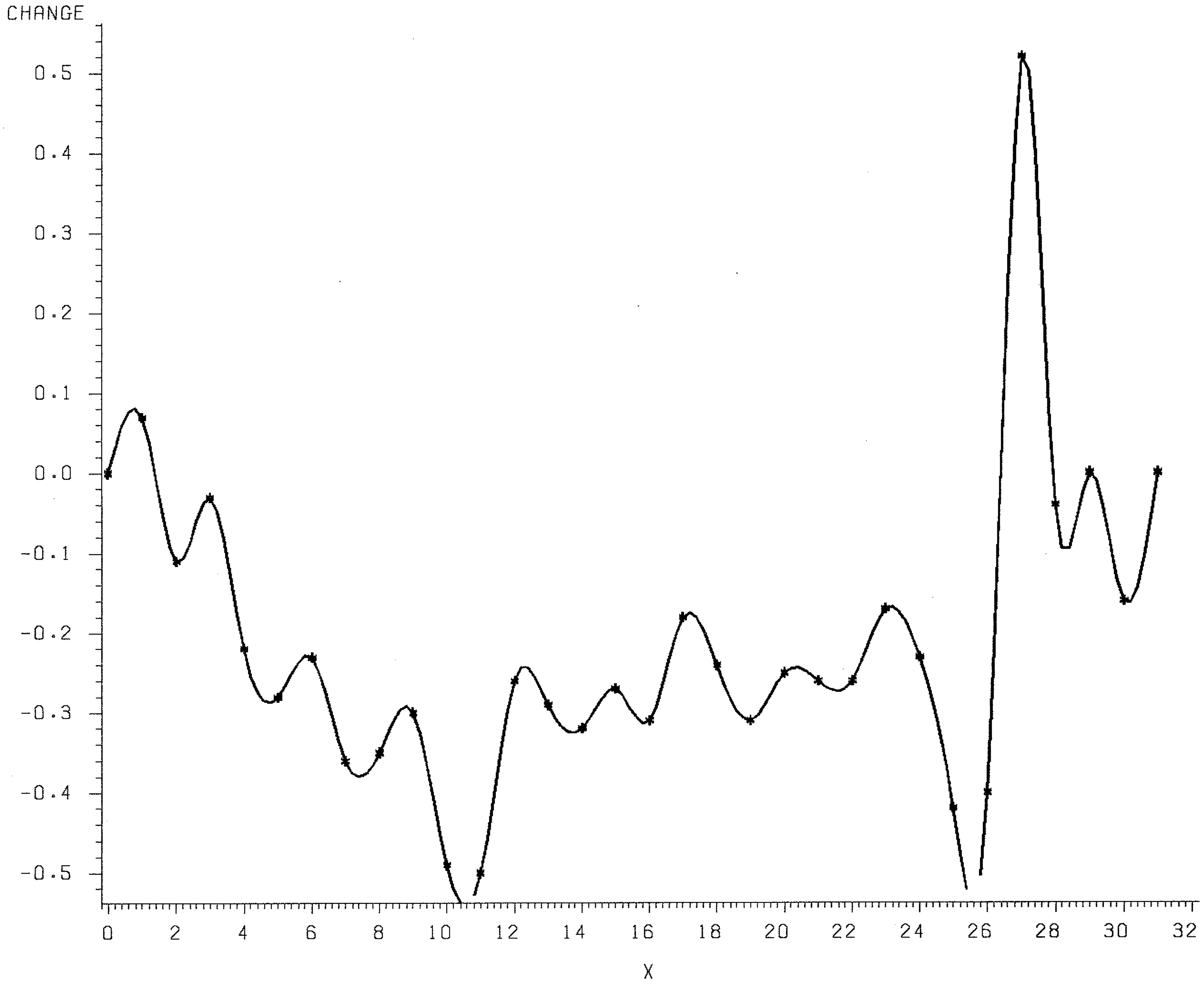
GRAVEL CREEK CHANNEL CHANGE B-7 (June,1981-post breakup May 1982)



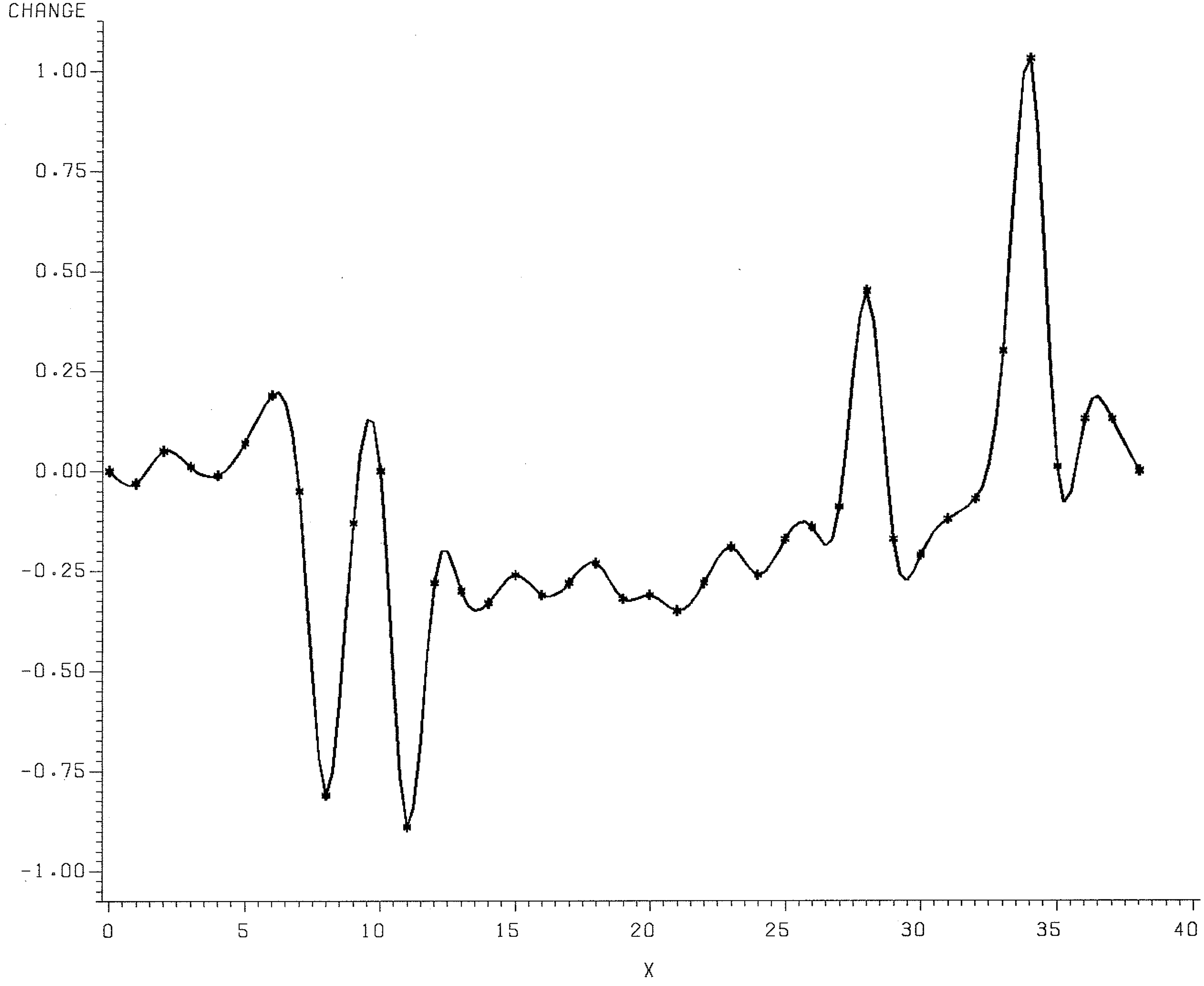
GRAVEL CREEK CHANNEL CHANGE B-8 (June, 1981-post breakup May 1982)



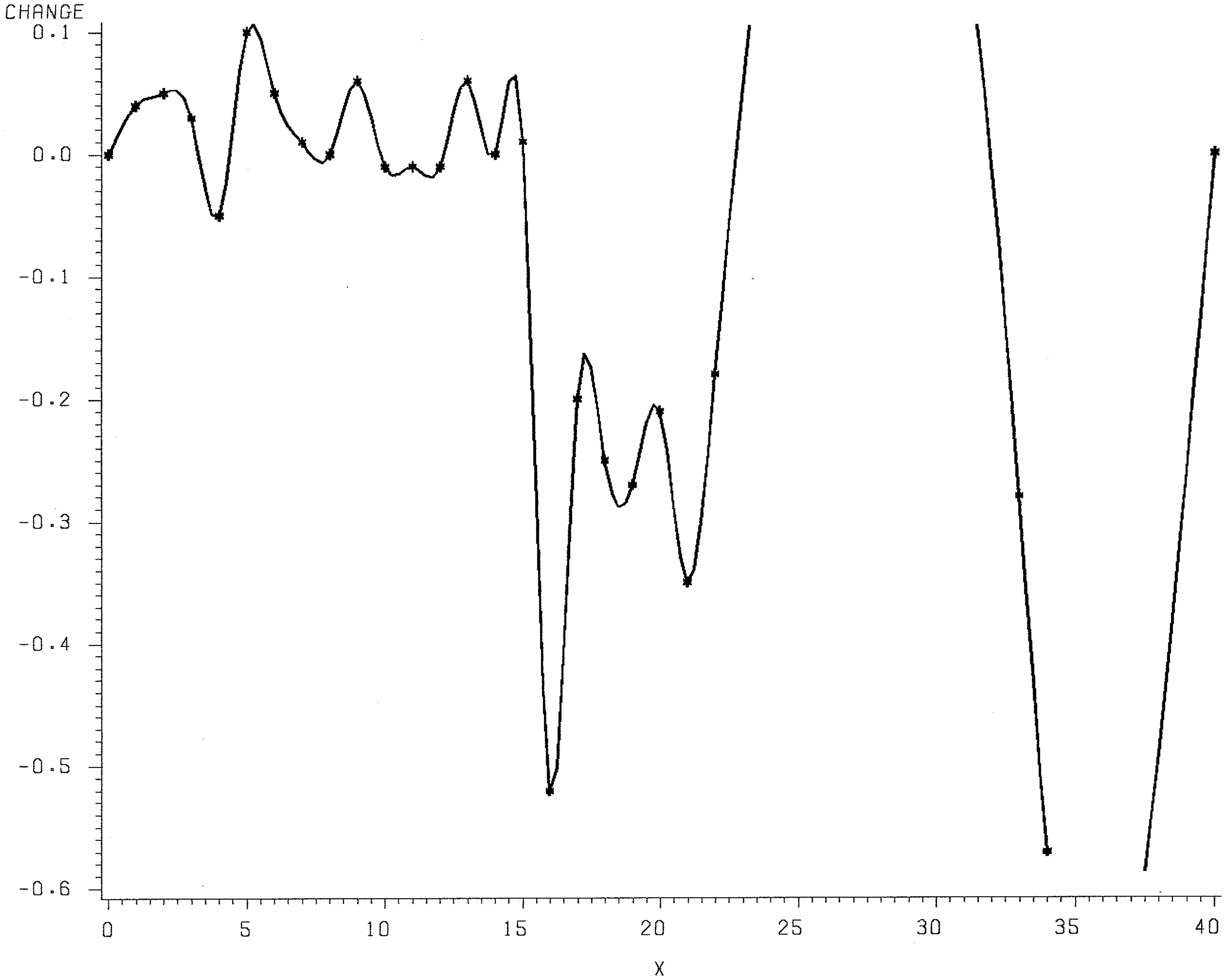
GRAVEL CREEK CHANNEL CHANGE B-9 (June,1981-post breakup May 1982)



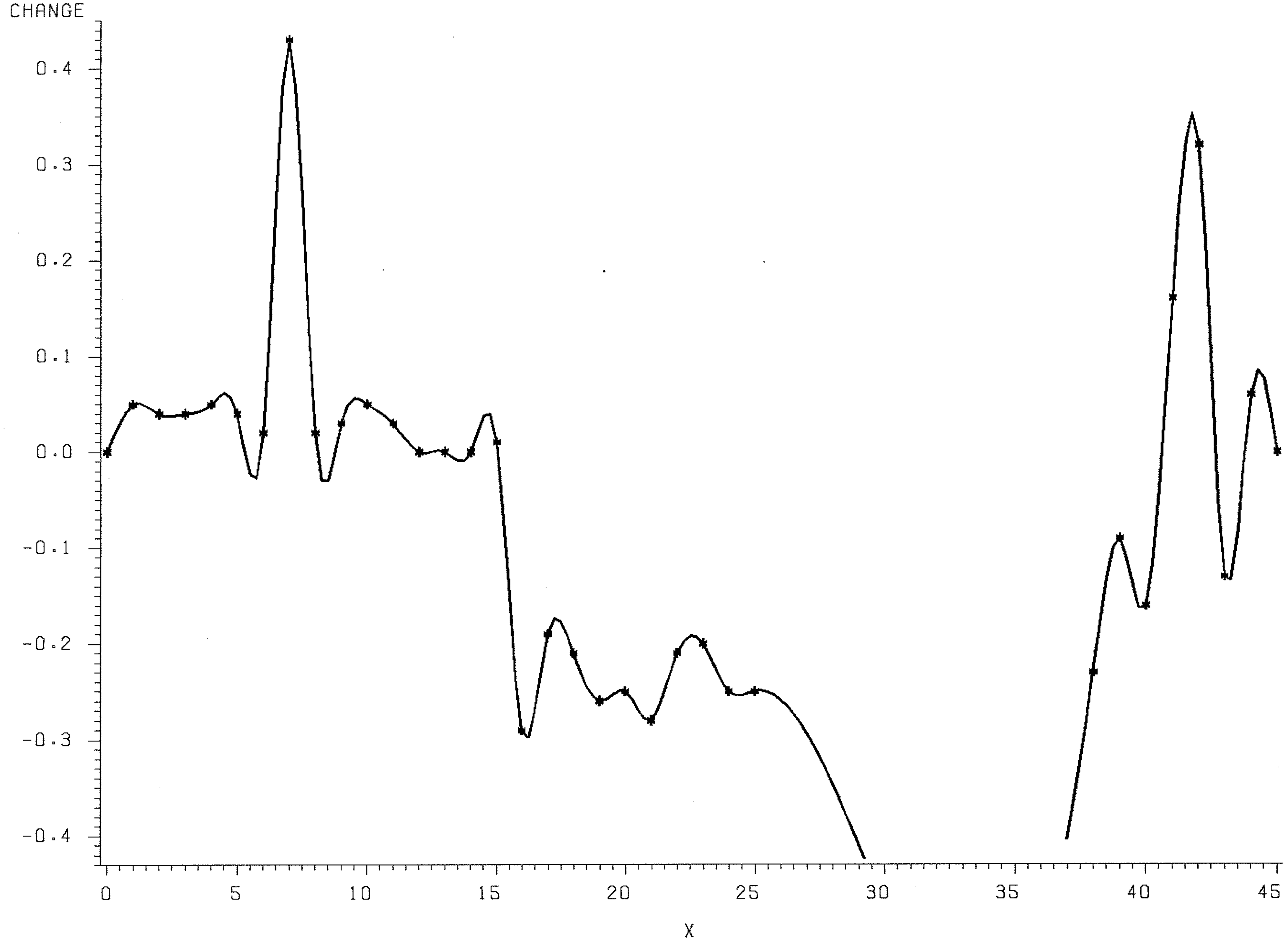
GRAVEL CREEK CHANNEL CHANGE B-10 (June,1981-post breakup May 1982)



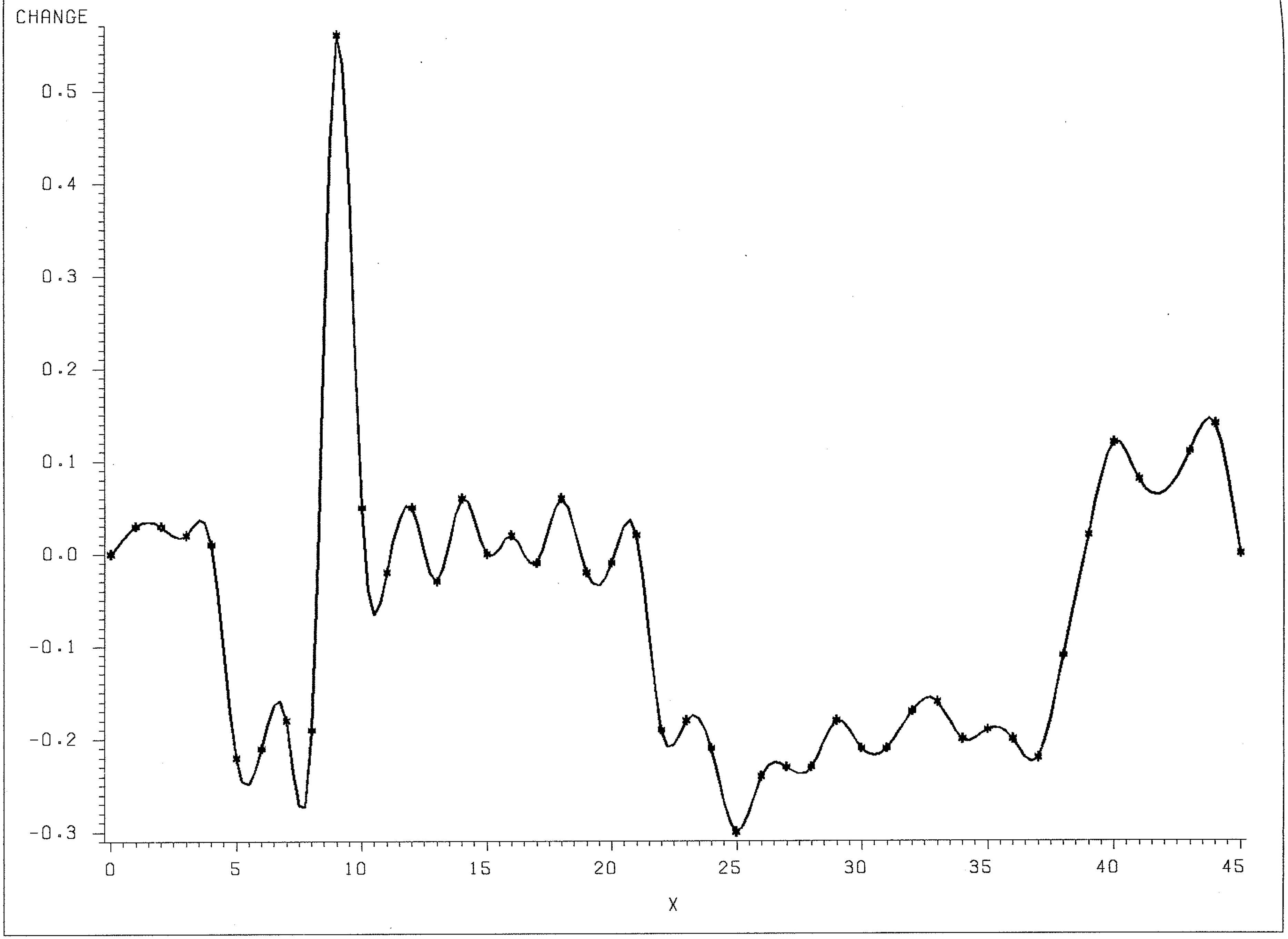
GRAVEL CREEK CHANNEL CHANGE B-12 (June,1981–post breakup May 1982)



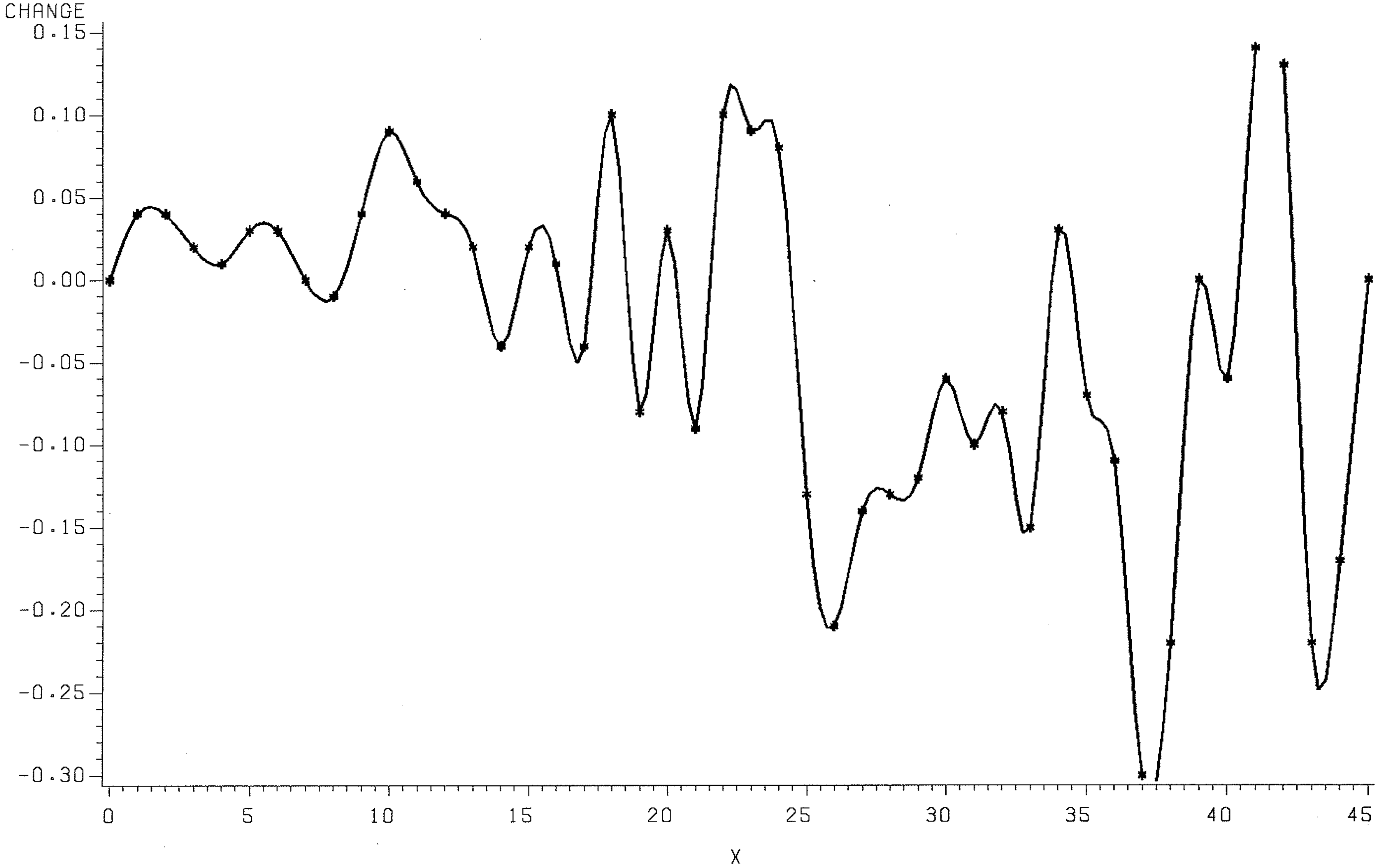
GRAVEL CREEK CHANNEL CHANGE B-13 (June,1981-post breakup May 1982)



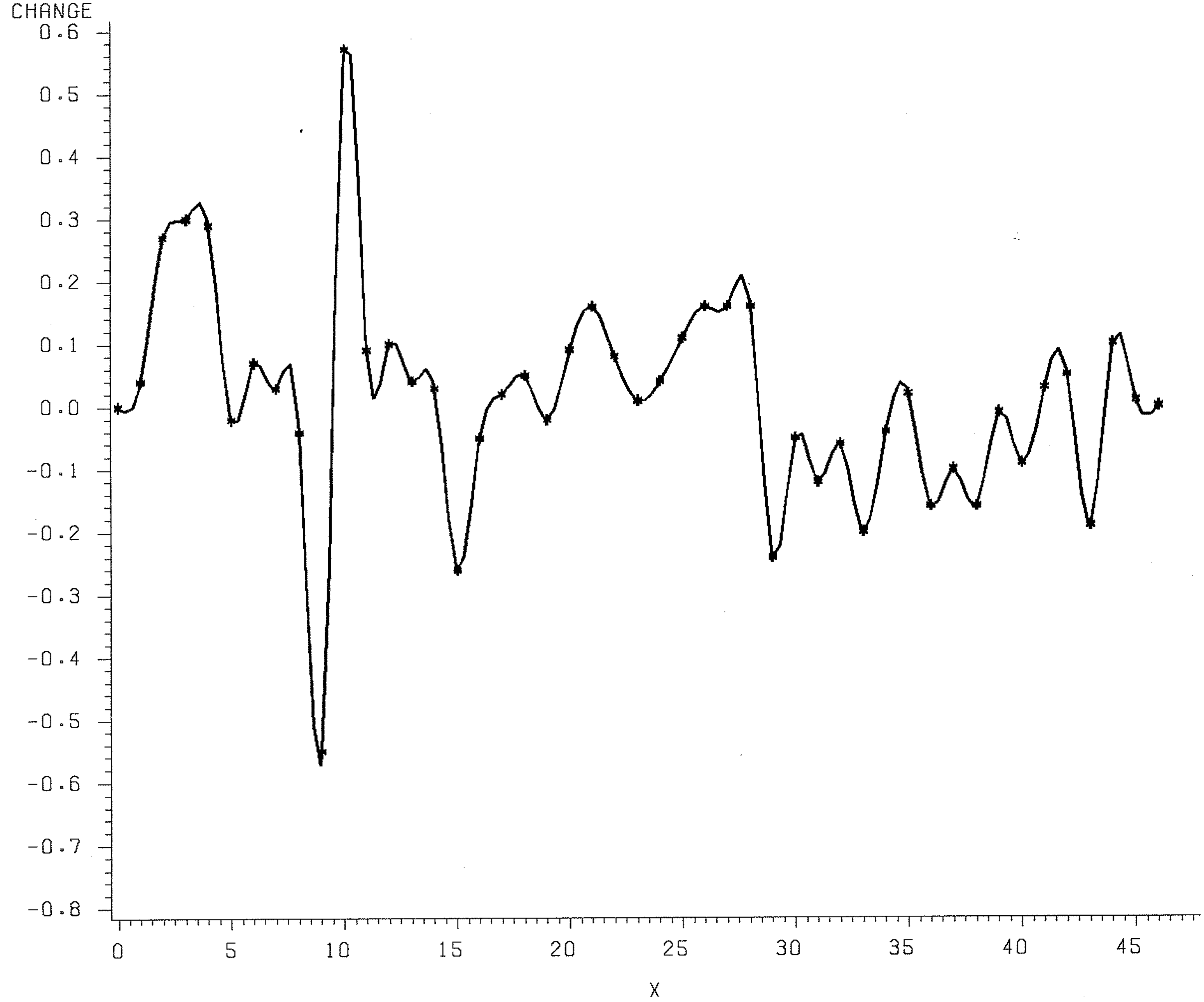
GRAVEL CREEK CHANNEL CHANGE B-14 (June,1981-post breakup May 1982)



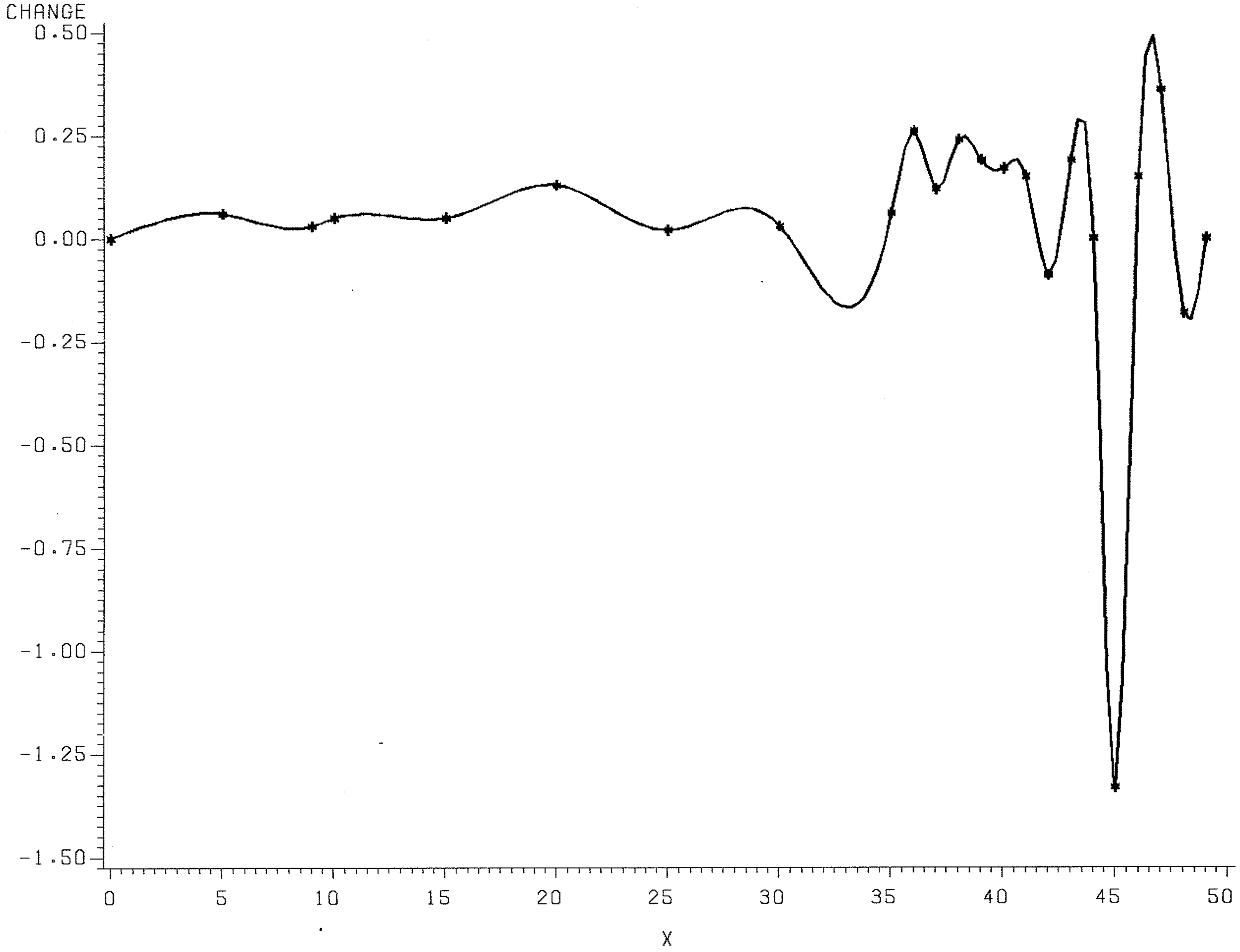
GRAVEL CREEK CHANNEL CHANGE B-15 (June,1981-post breakup May 1982)



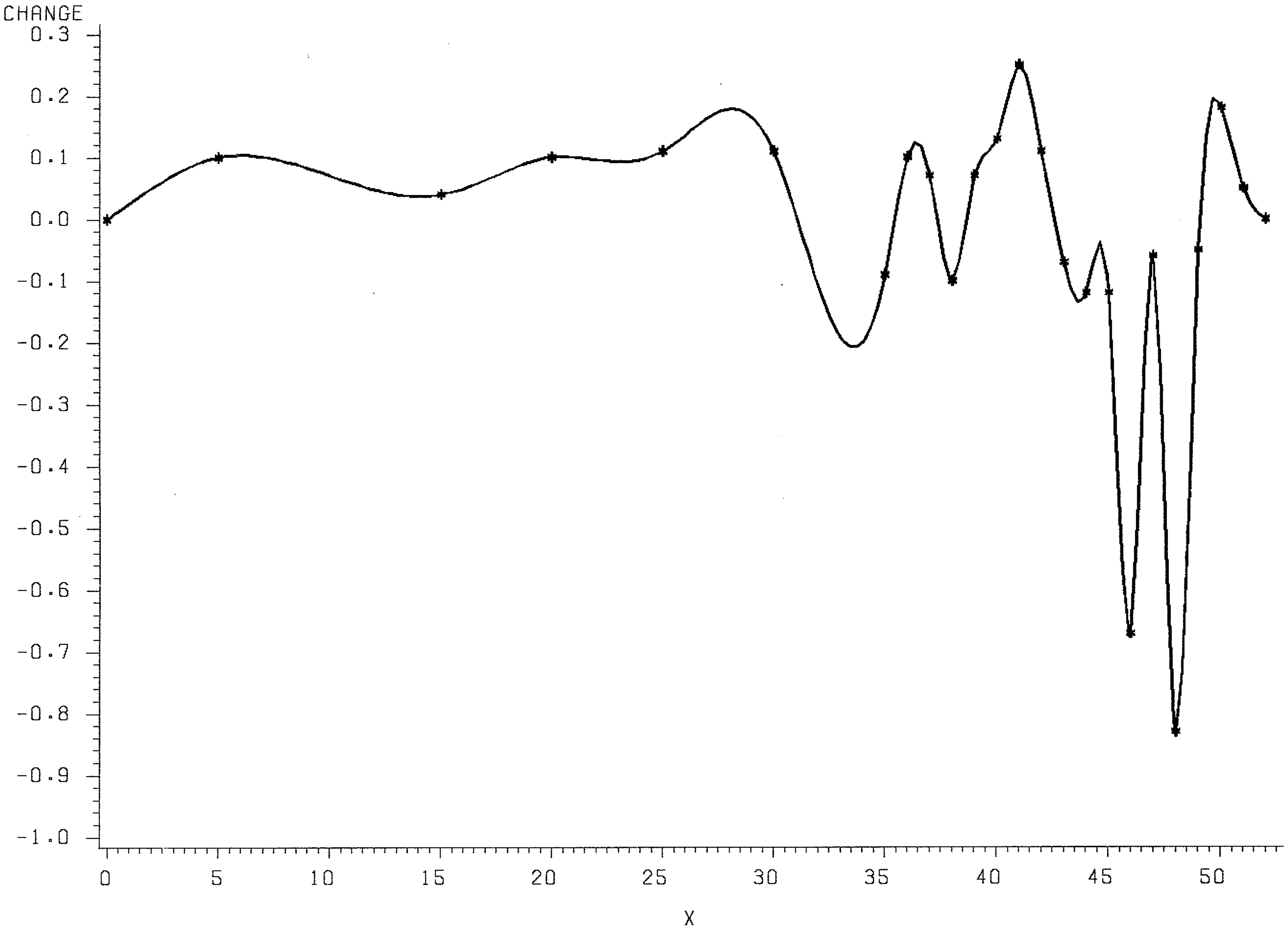
GRAVEL CREEK CHANNEL CHANGE B-16 (June,1981-post breakup May 1982)



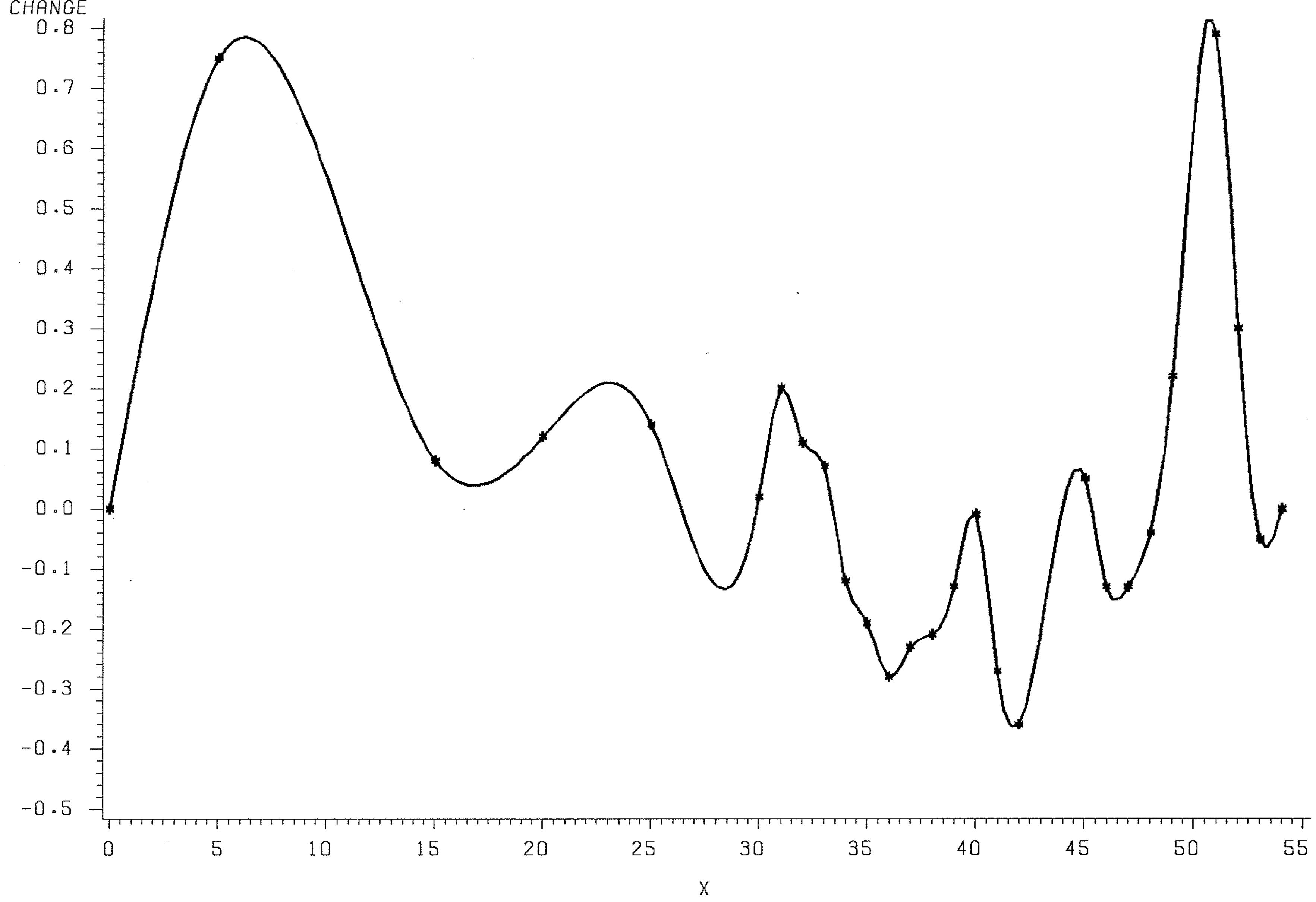
GRAVEL CREEK CHANNEL CHANGE B-17 (June,1981-post breakup May 1982)



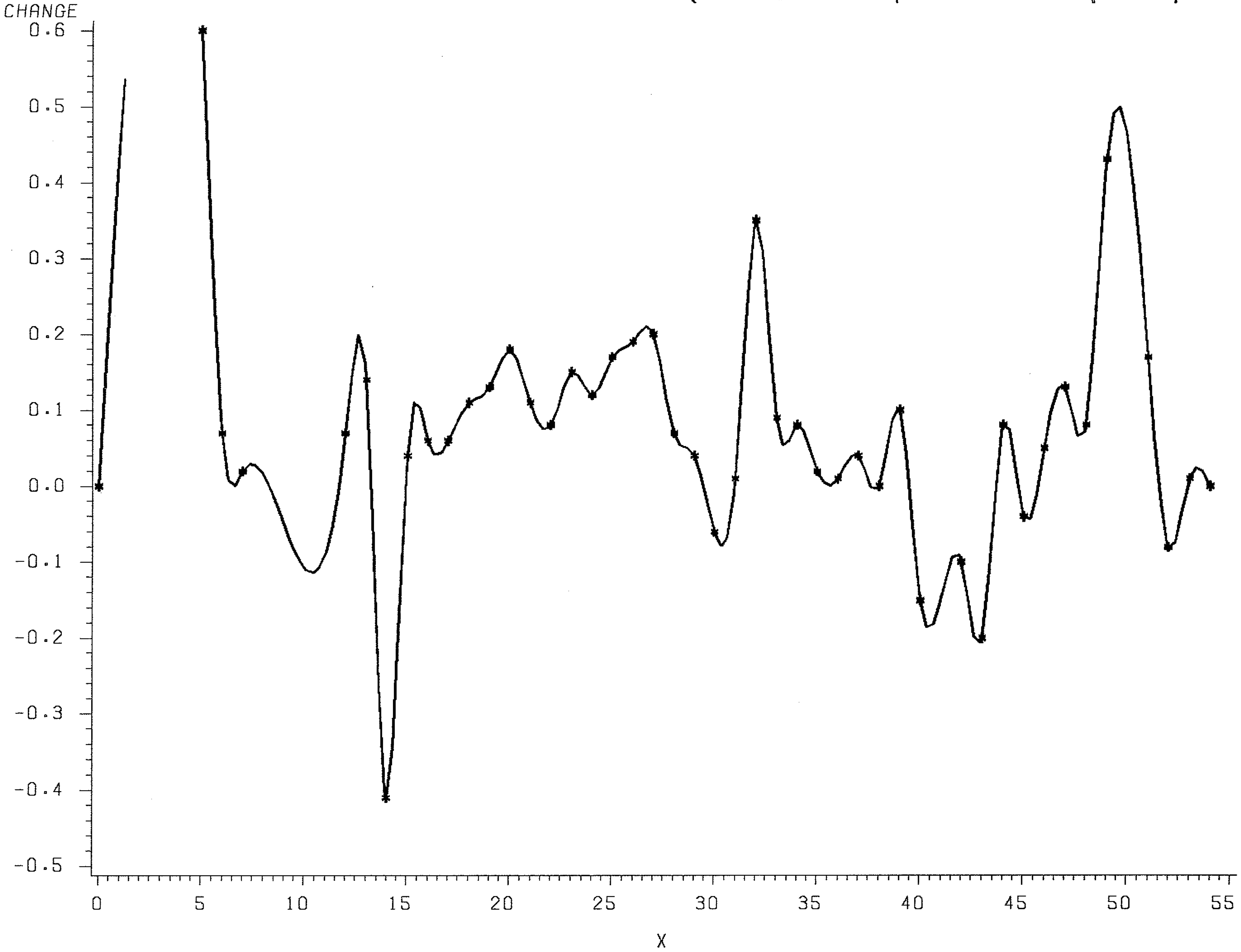
GRAVEL CREEK CHANNEL CHANGE B-18 (June,1981-post breakup May 1982)



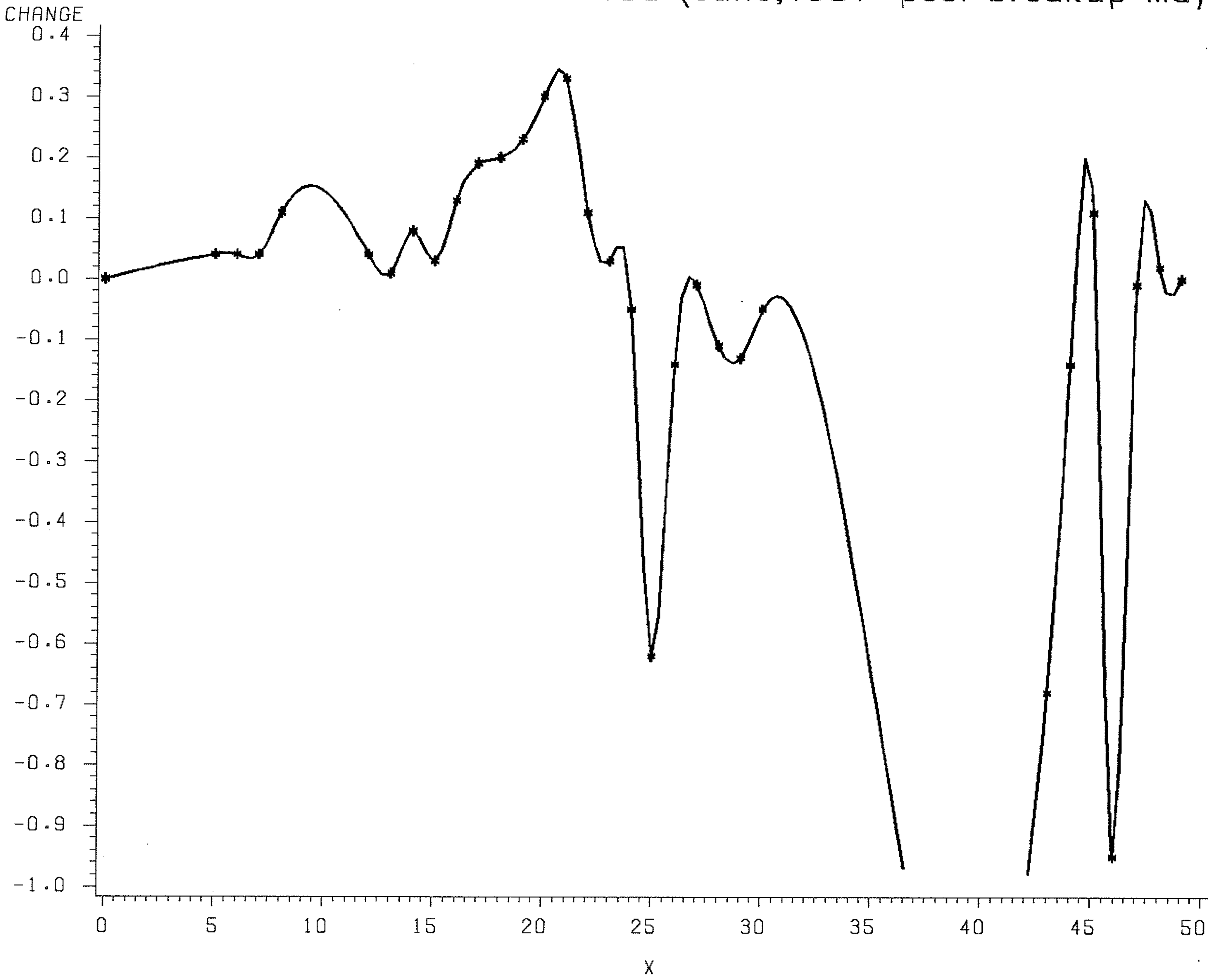
GRAVEL CREEK CHANNEL CHANGE B-18b (June,1981-post breakup May 1982)

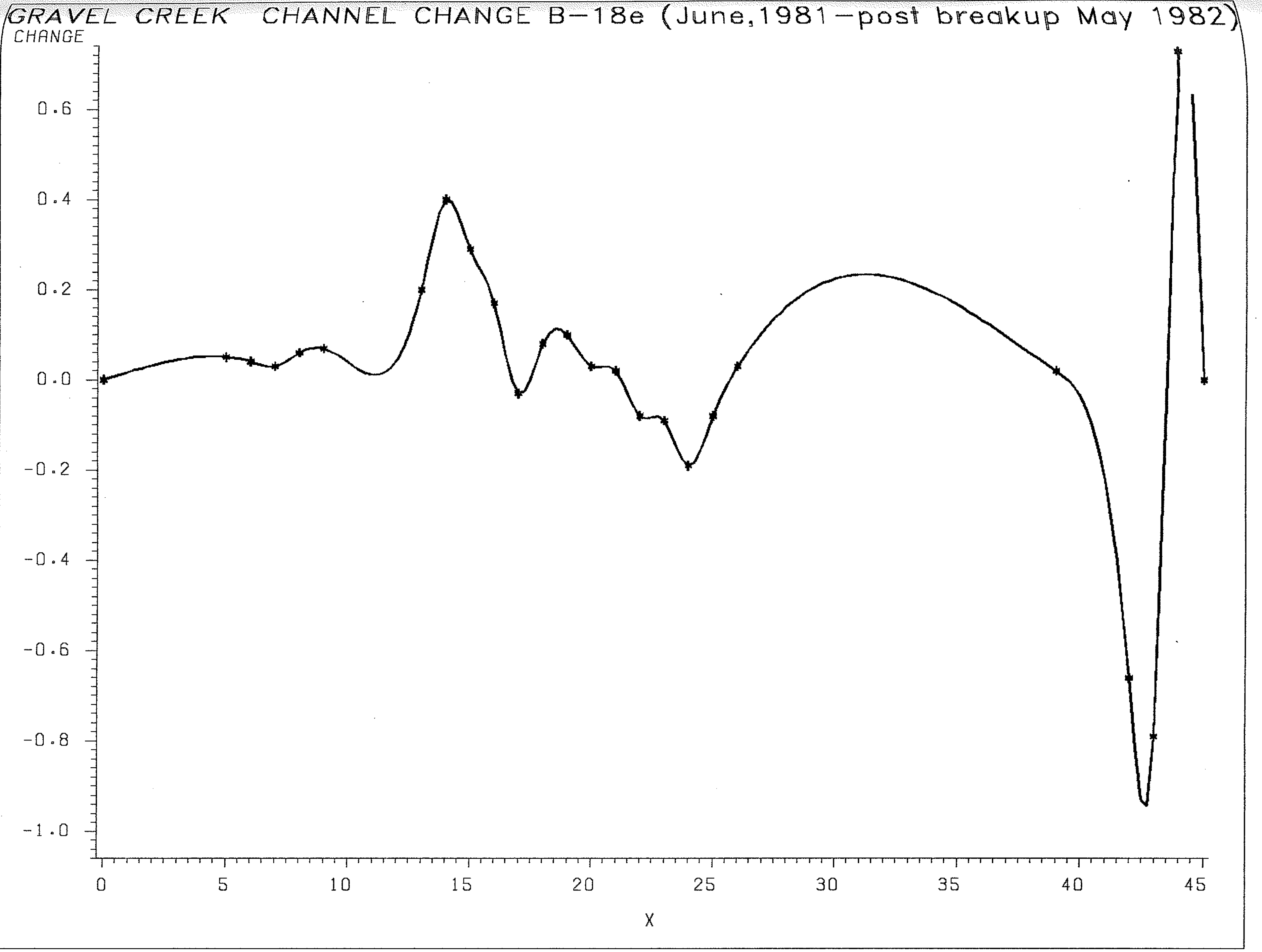


GRAVEL CREEK CHANNEL CHANGE B–18c (June,1981–post breakup May 1982)

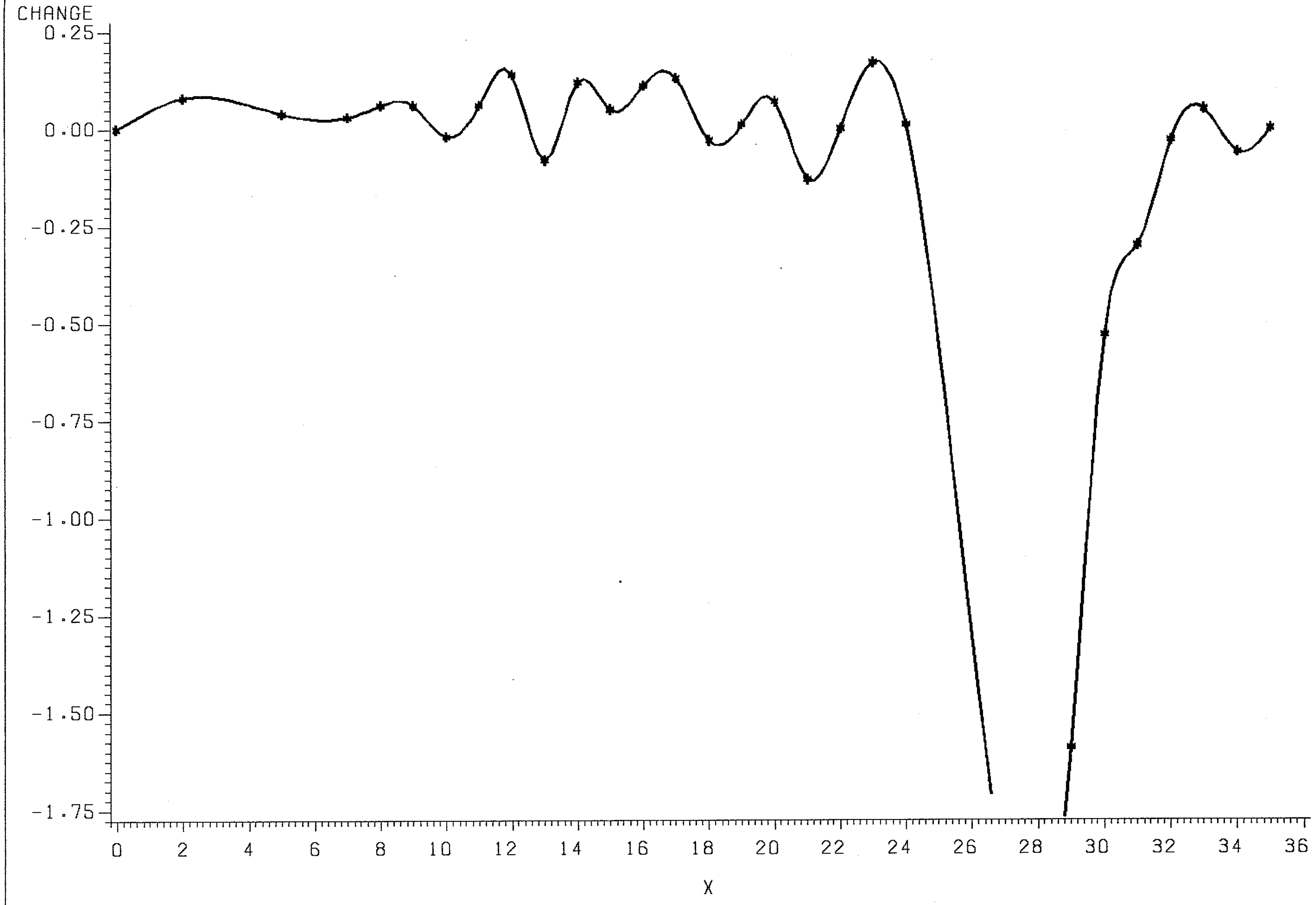


GRAVEL CREEK CHANNEL CHANGE B-18d (June,1981-post breakup May 1982)

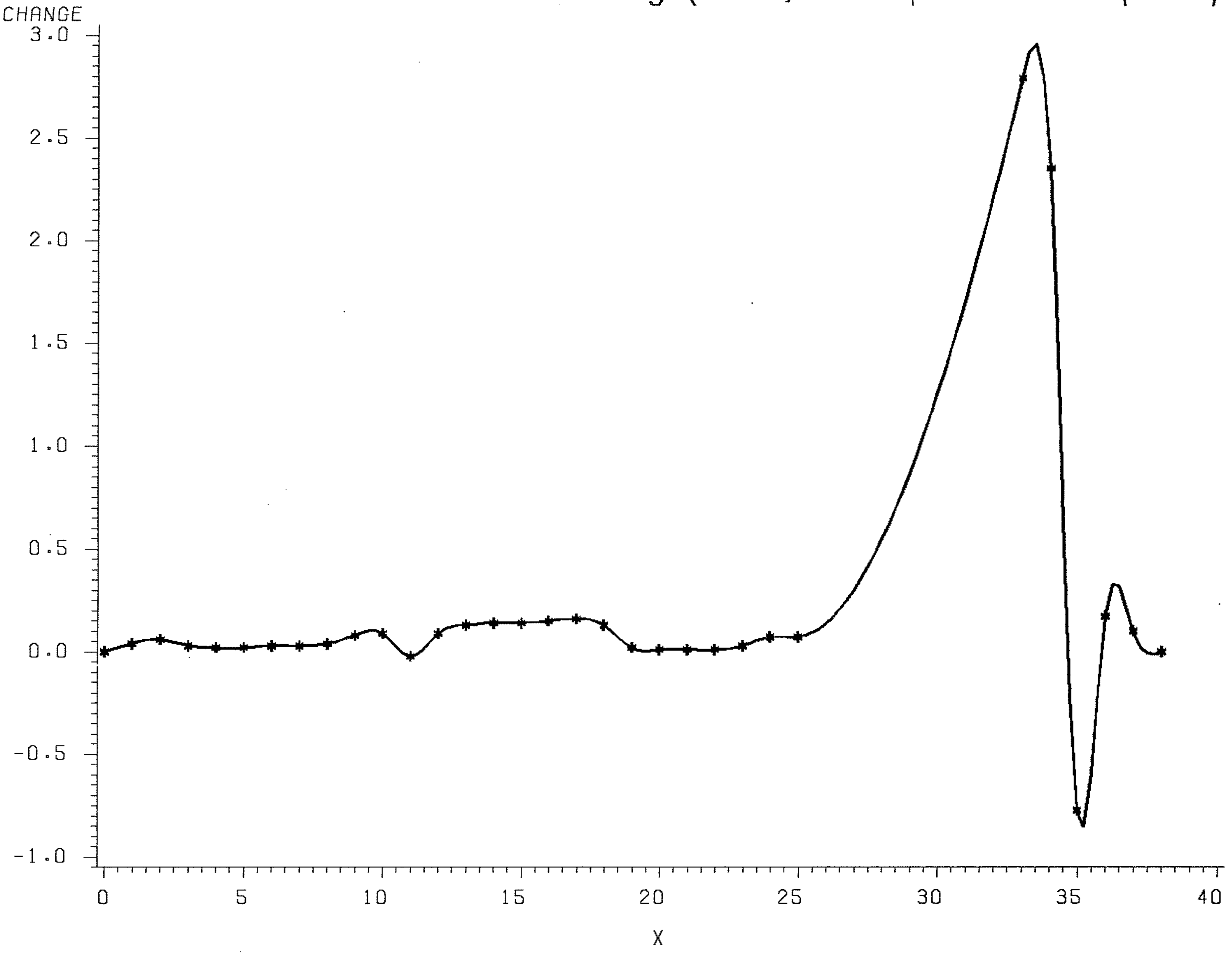



GRAVEL CREEK CHANNEL CHANGE B-18e (June,1981-post breakup May 1982)
CHANGE
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0
5
10
15
20
25
30
35
40
45
X

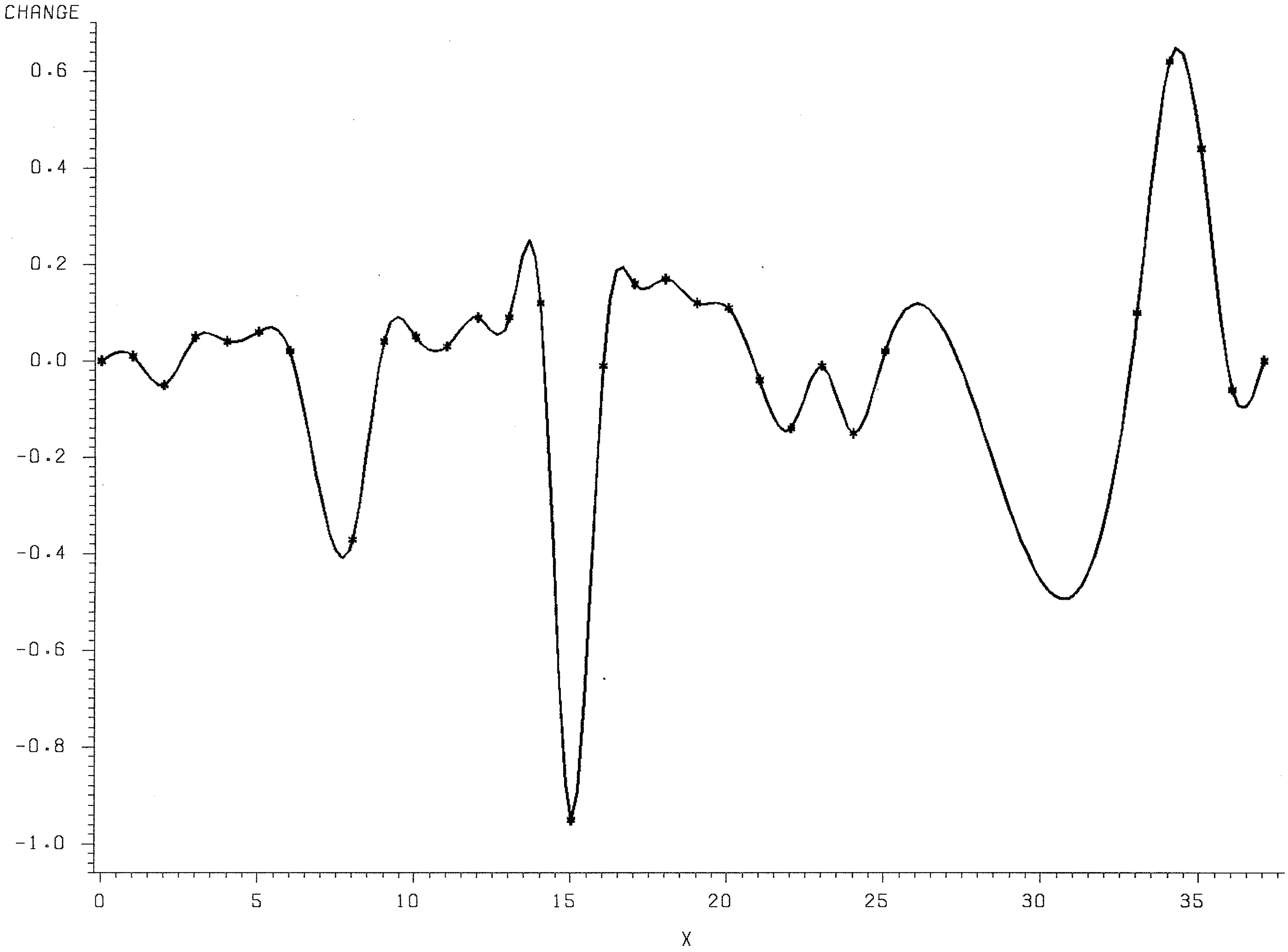
GRAVEL CREEK CHANNEL CHANGE B–18f (June,1981–post breakup May 1982)



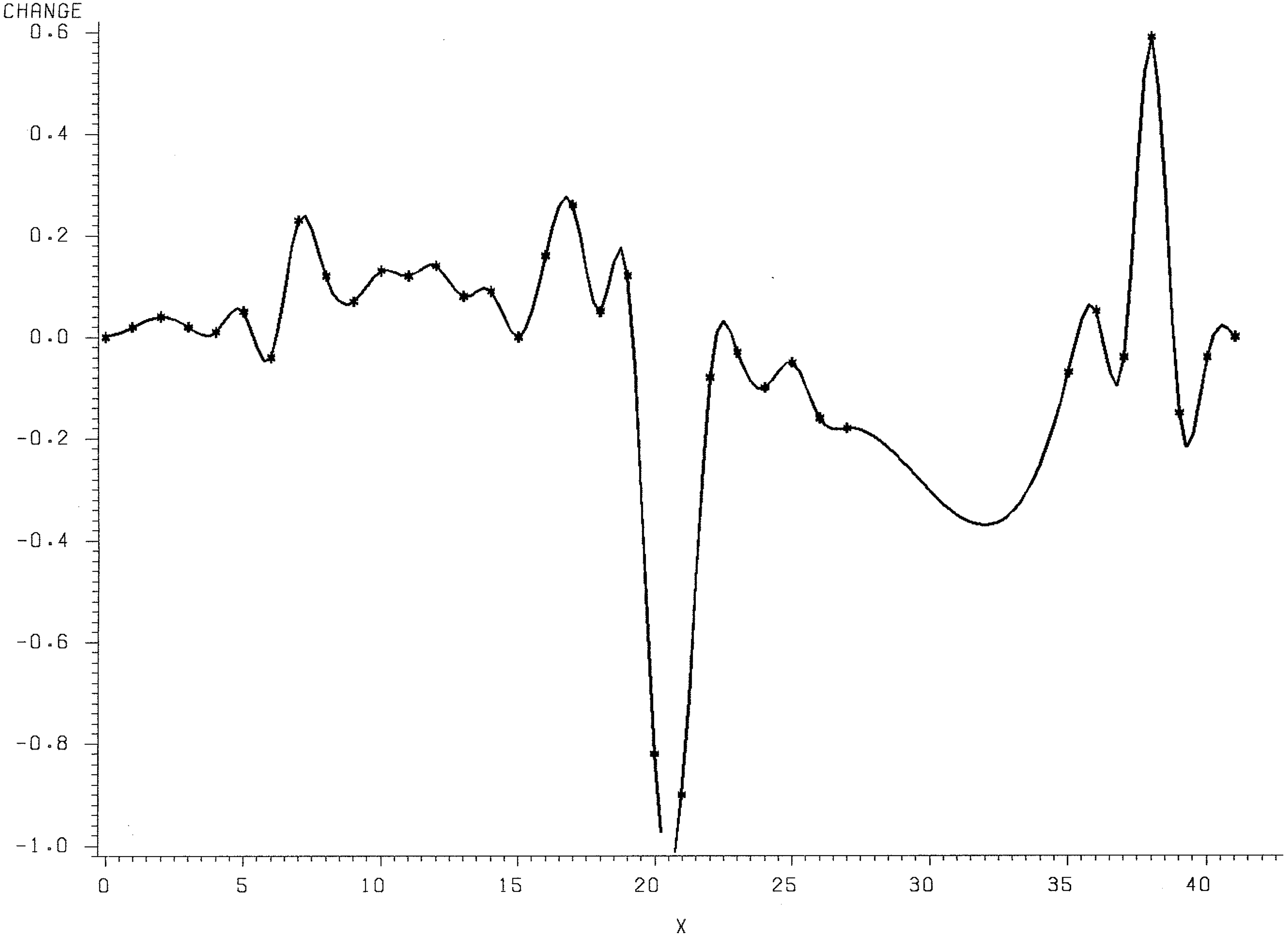
GRAVEL CREEK CHANNEL CHANGE B-18g (June,1981-post breakup May 1982)



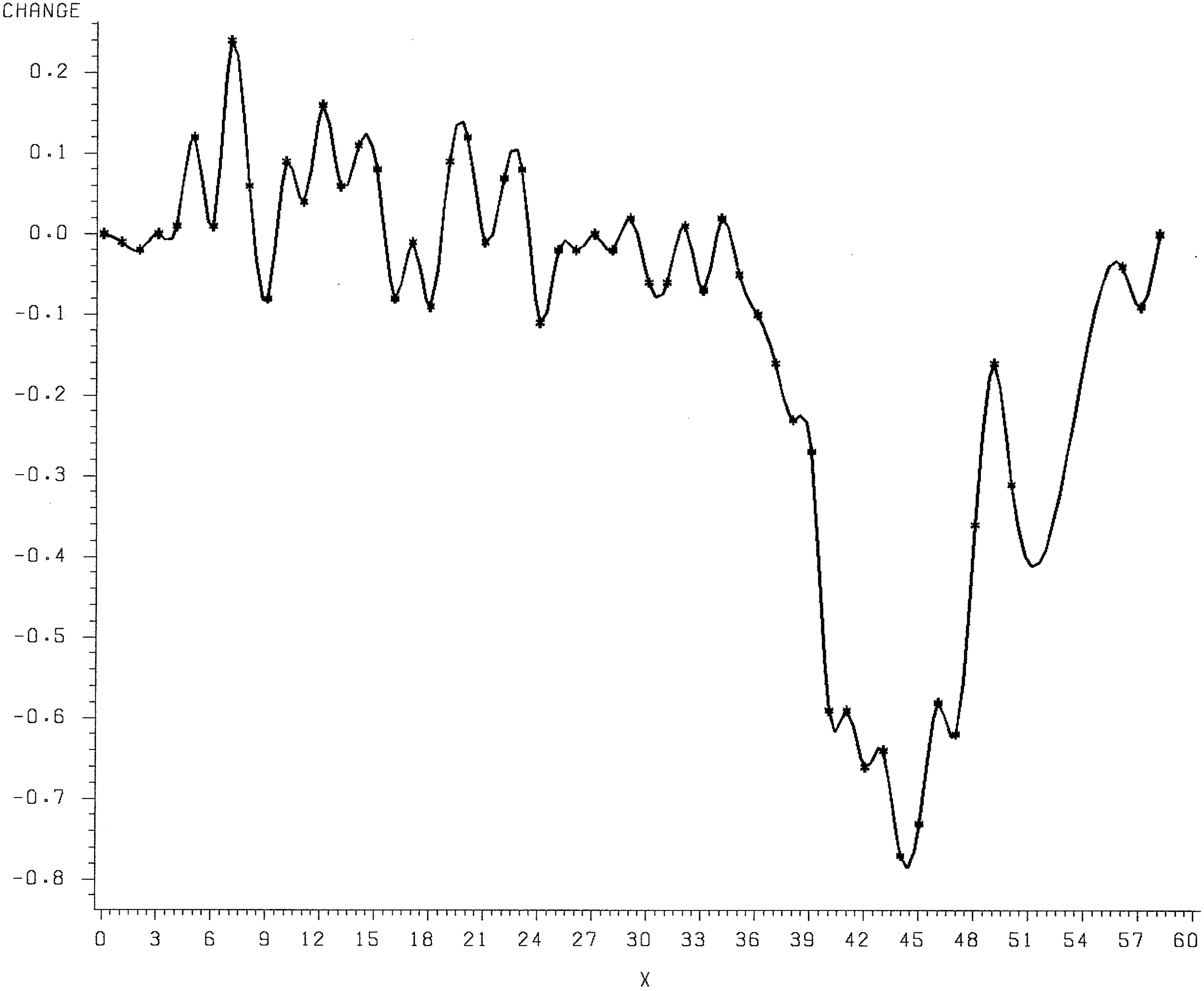
GRAVEL CREEK CHANNEL CHANGE B-19 (June,1981-post breakup May 1982)

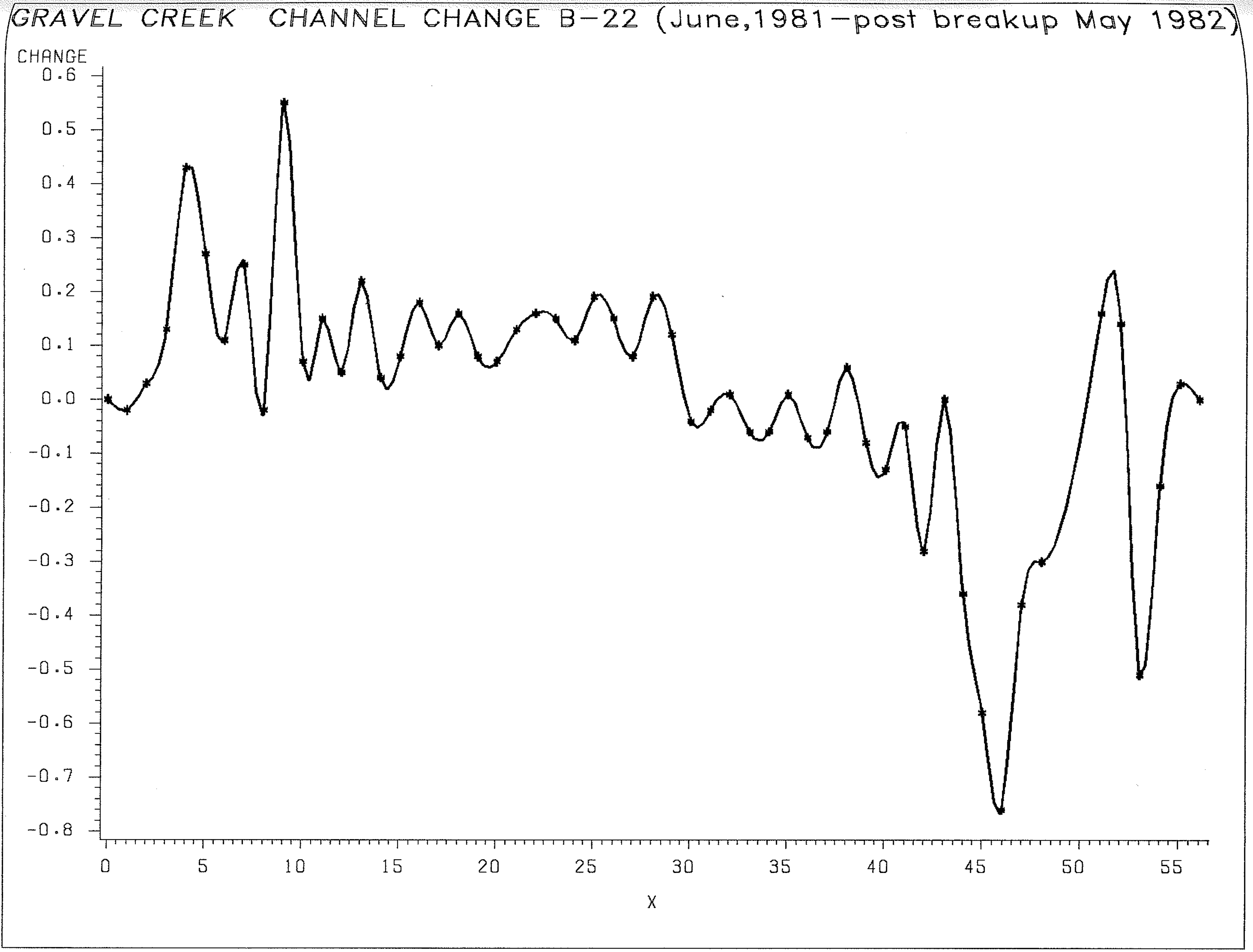


GRAVEL CREEK CHANNEL CHANGE B-20 (June,1981-post breakup May 1982)

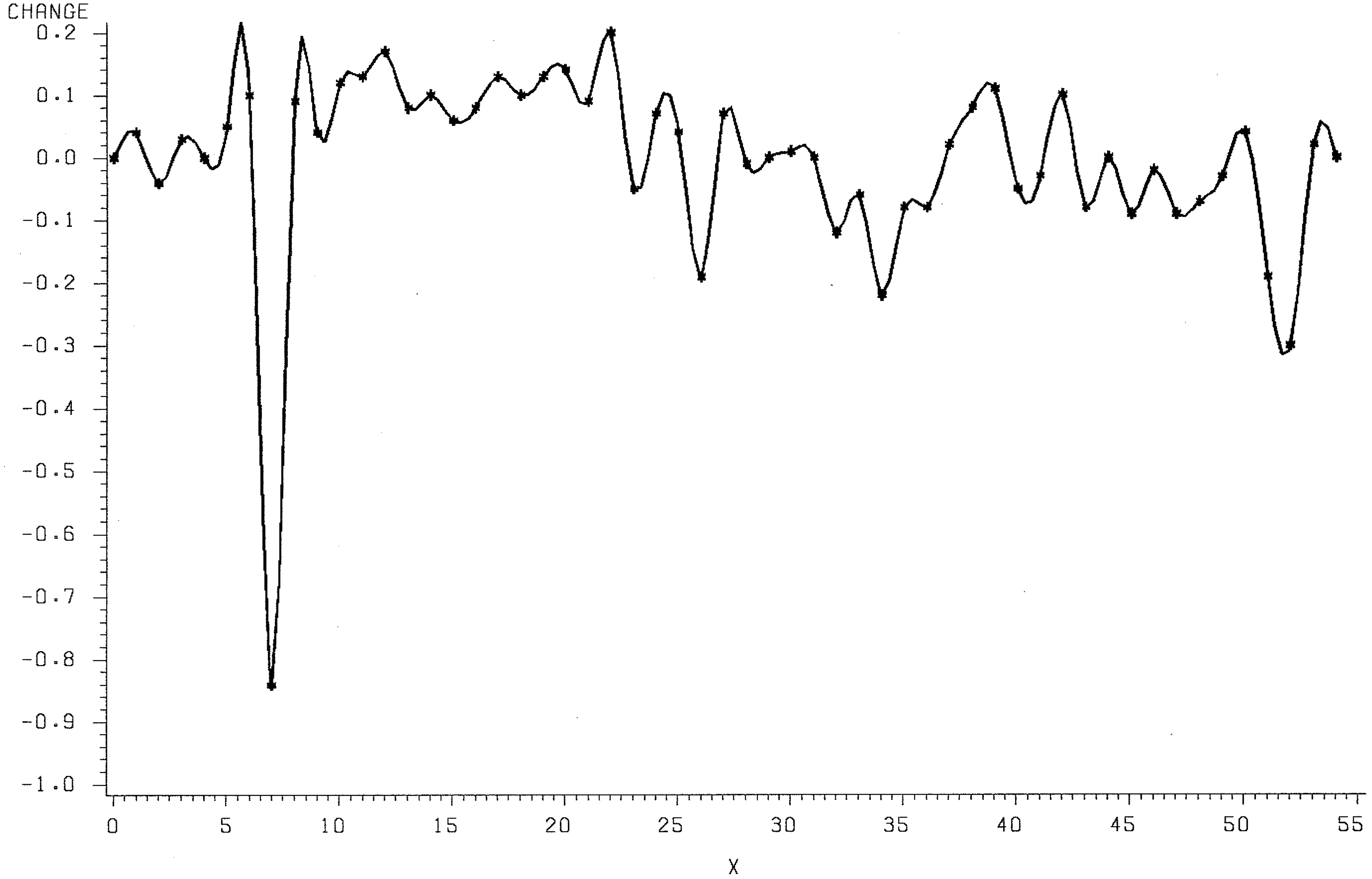


GRAVEL CREEK CHANNEL CHANGE B-21 (June,1981-post breakup May 1982)

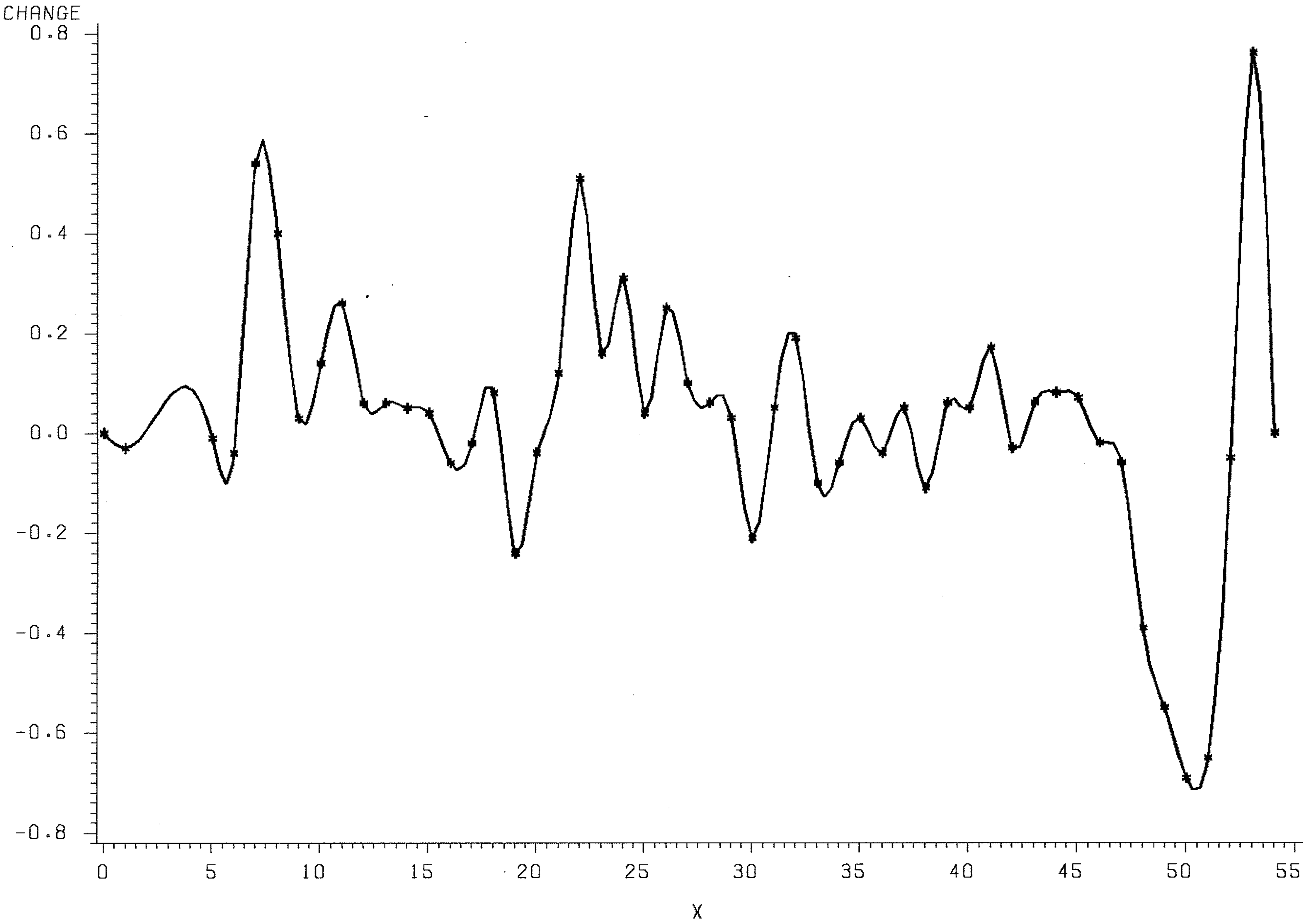



GRAVEL CREEK CHANNEL CHANGE B-22 (June,1981-post breakup May 1982)
CHANGE
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
0
5
10
15
20
25
30
35
40
45
50
55
X

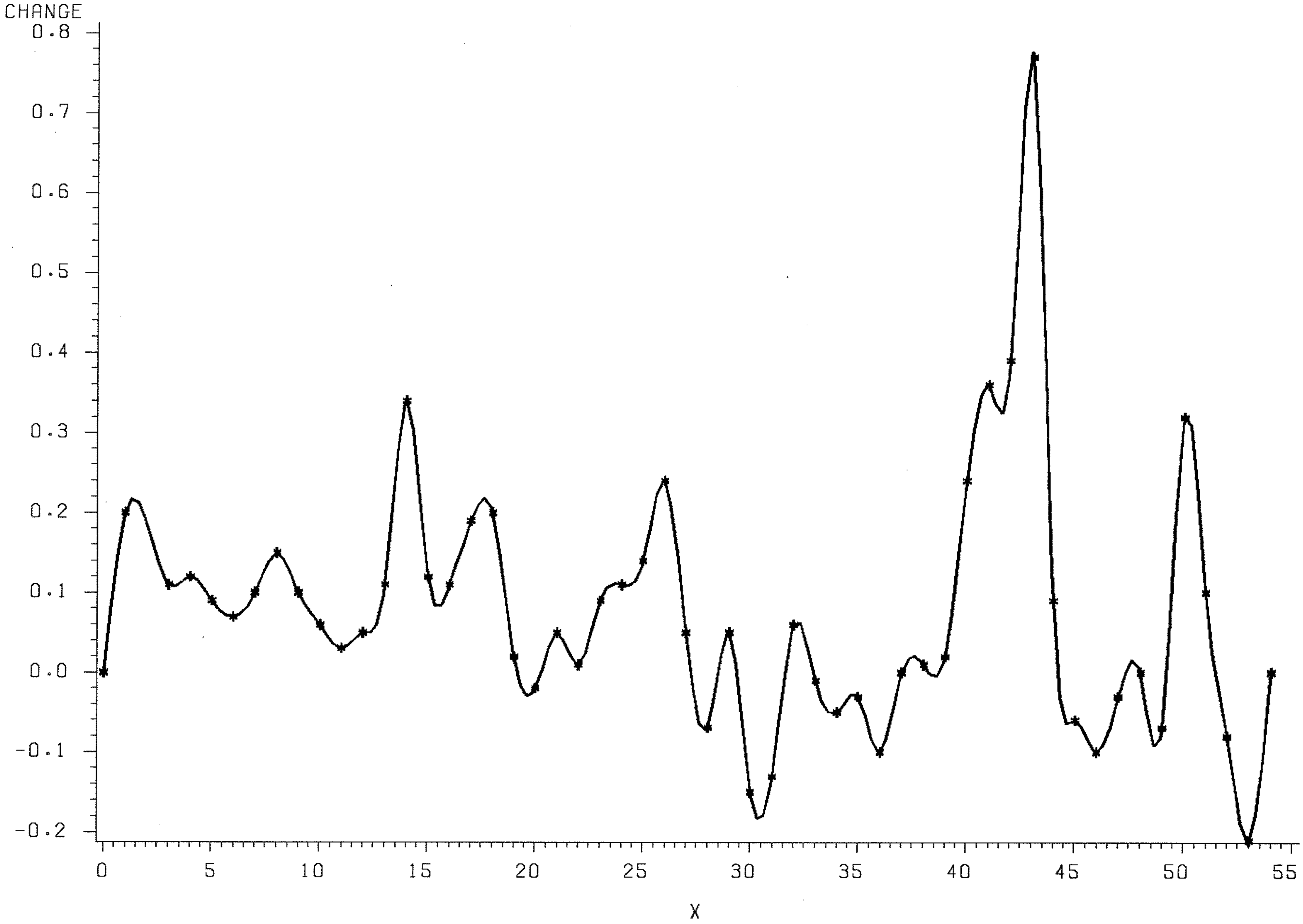
GRAVEL CREEK CHANNEL CHANGE B-23 (June,1981-post breakup May 1982)



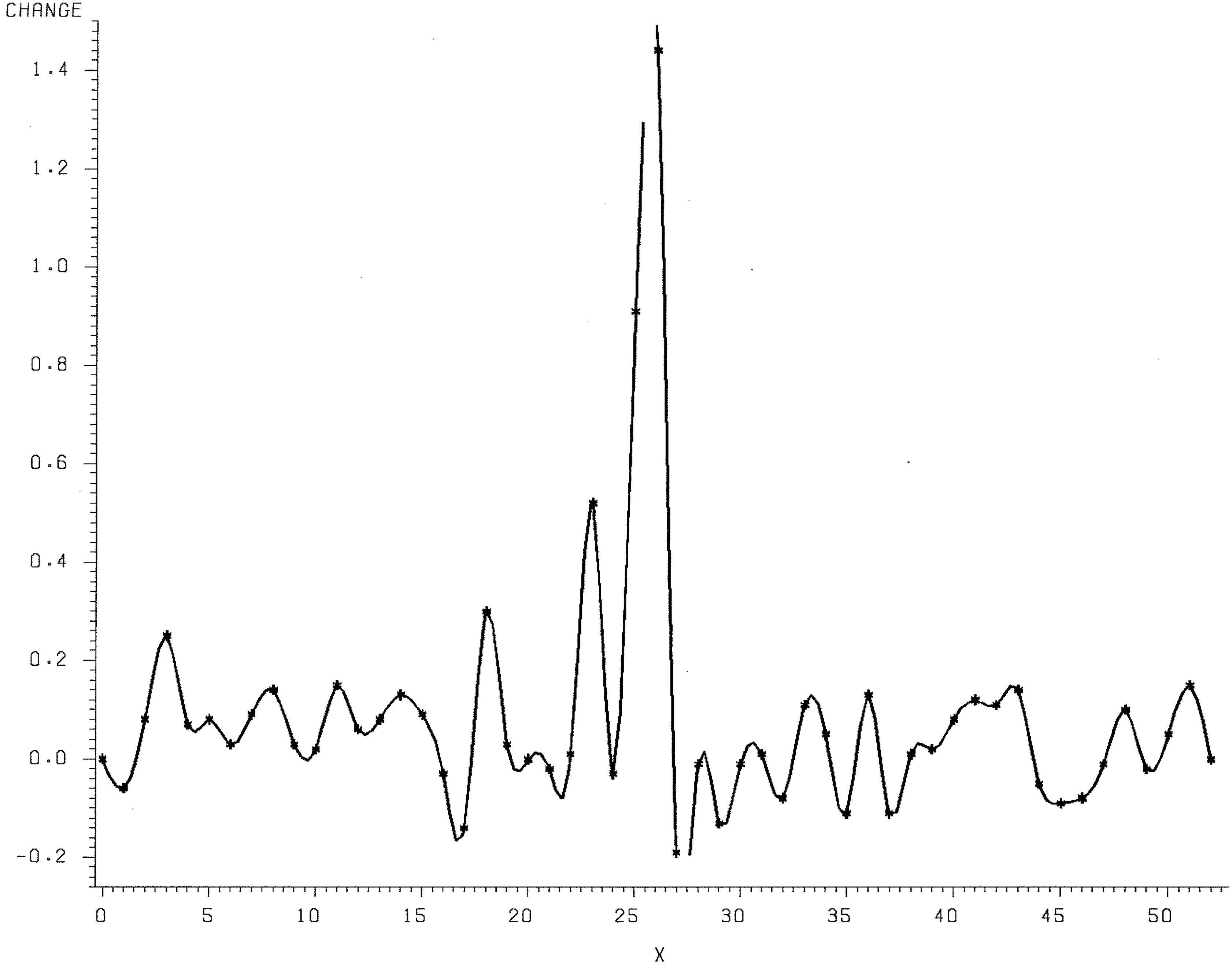
GRAVEL CREEK CHANNEL CHANGE B-24 (June,1981-post breakup May 1982)



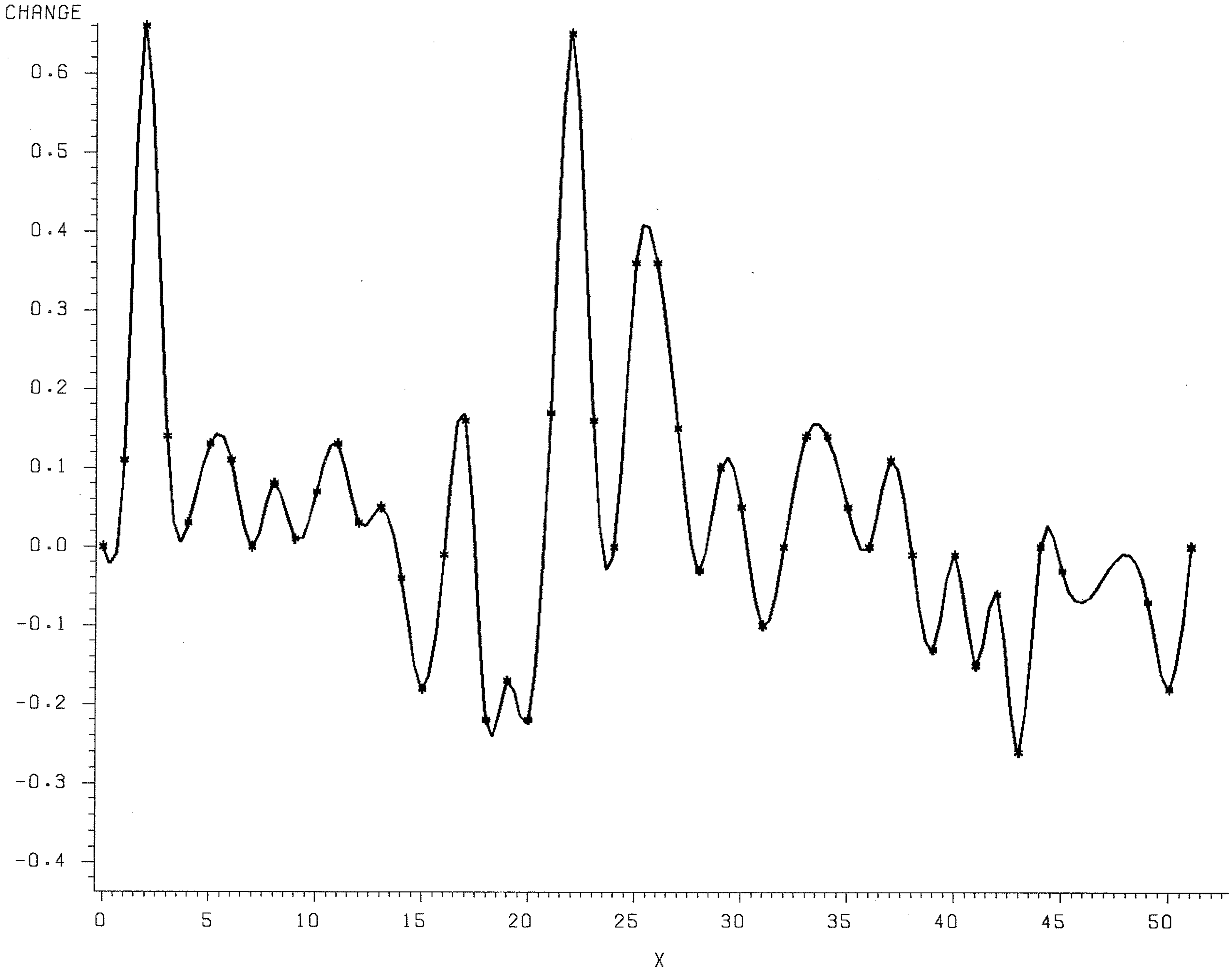
GRAVEL CREEK CHANNEL CHANGE B-25 (June,1981-post breakup May 1982)



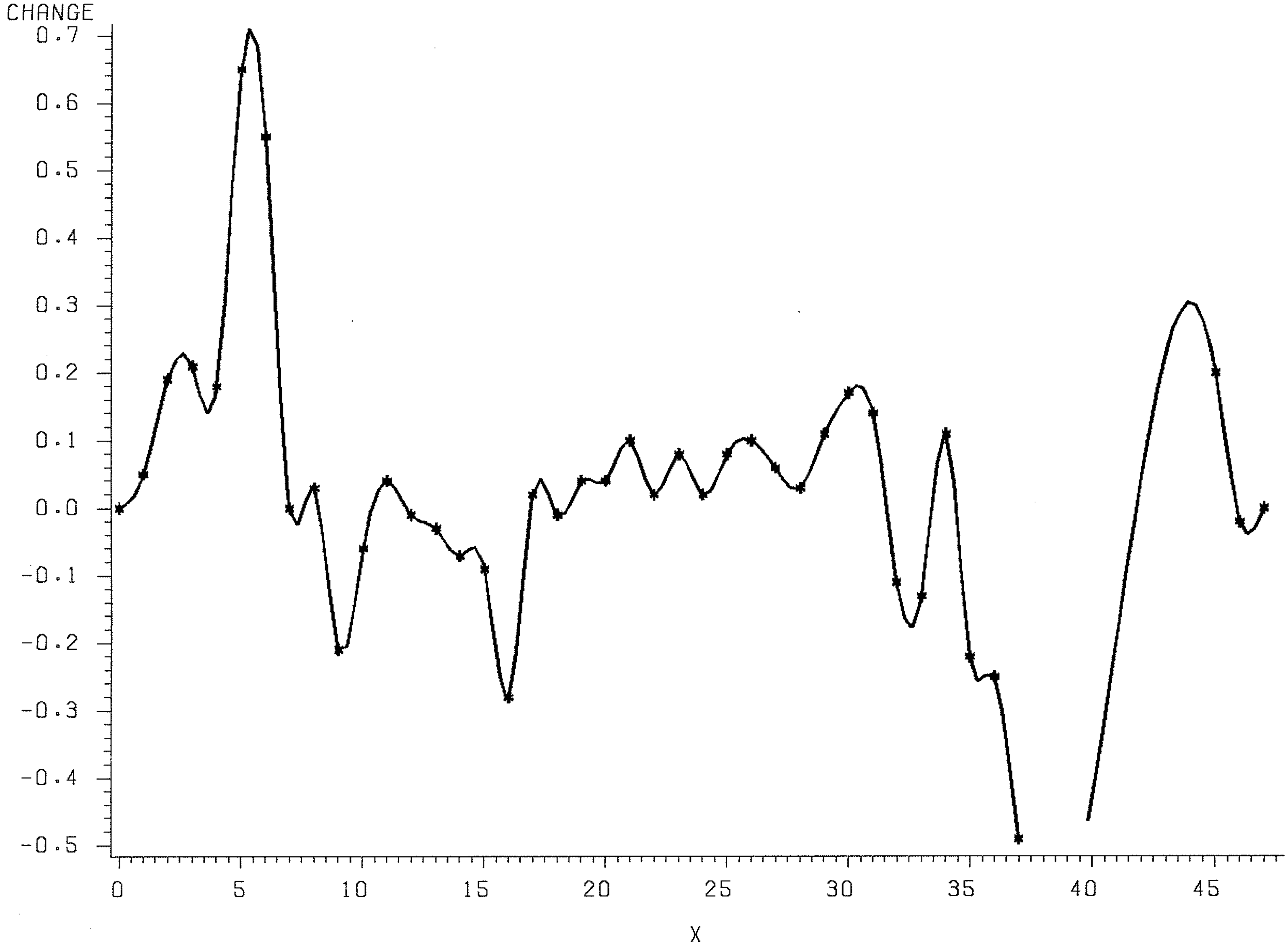
GRAVEL CREEK CHANNEL CHANGE B-26 (June,1981-post breakup May 1982)



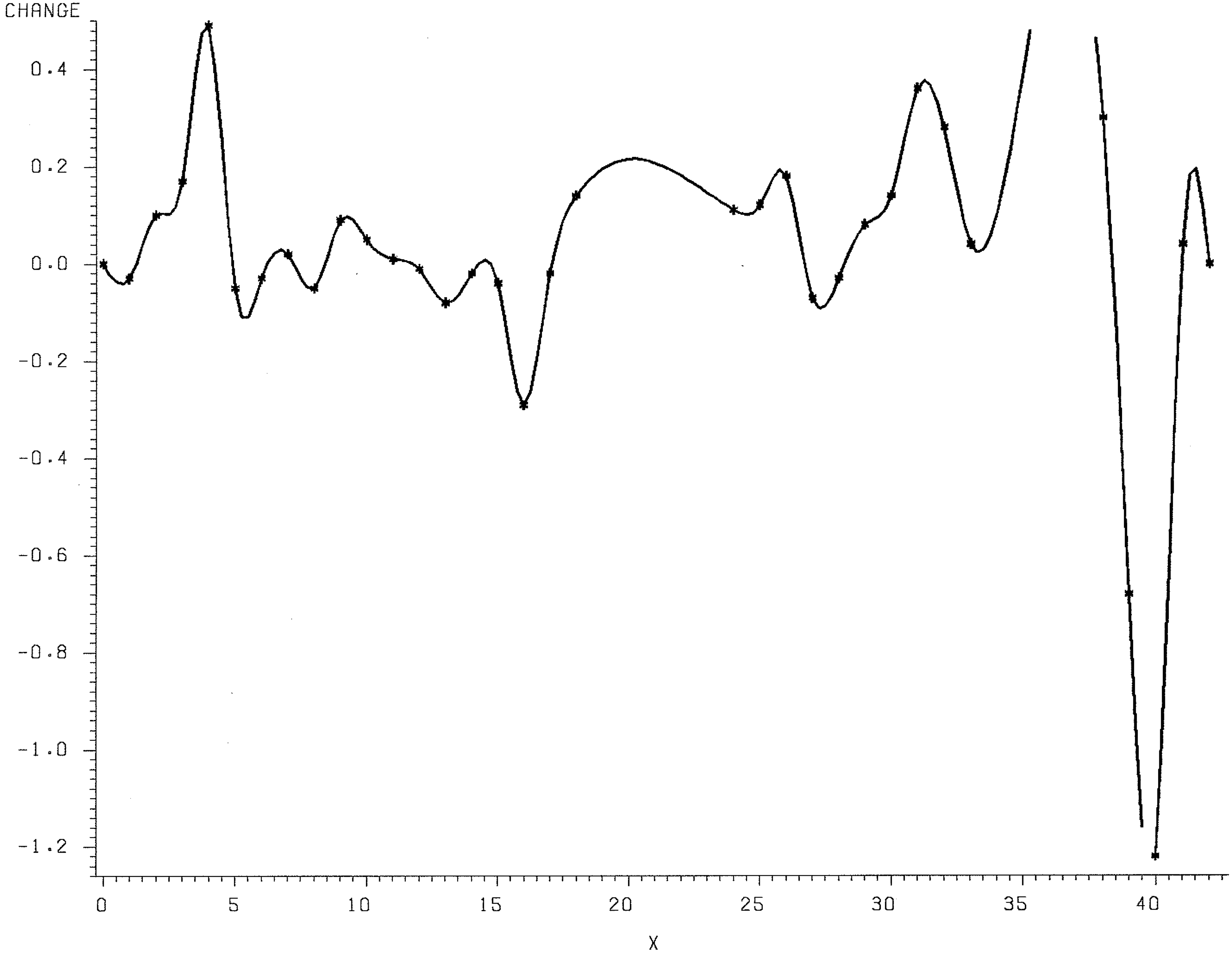
GRAVEL CREEK CHANNEL CHANGE B-27 (June,1981-post breakup May 1982)



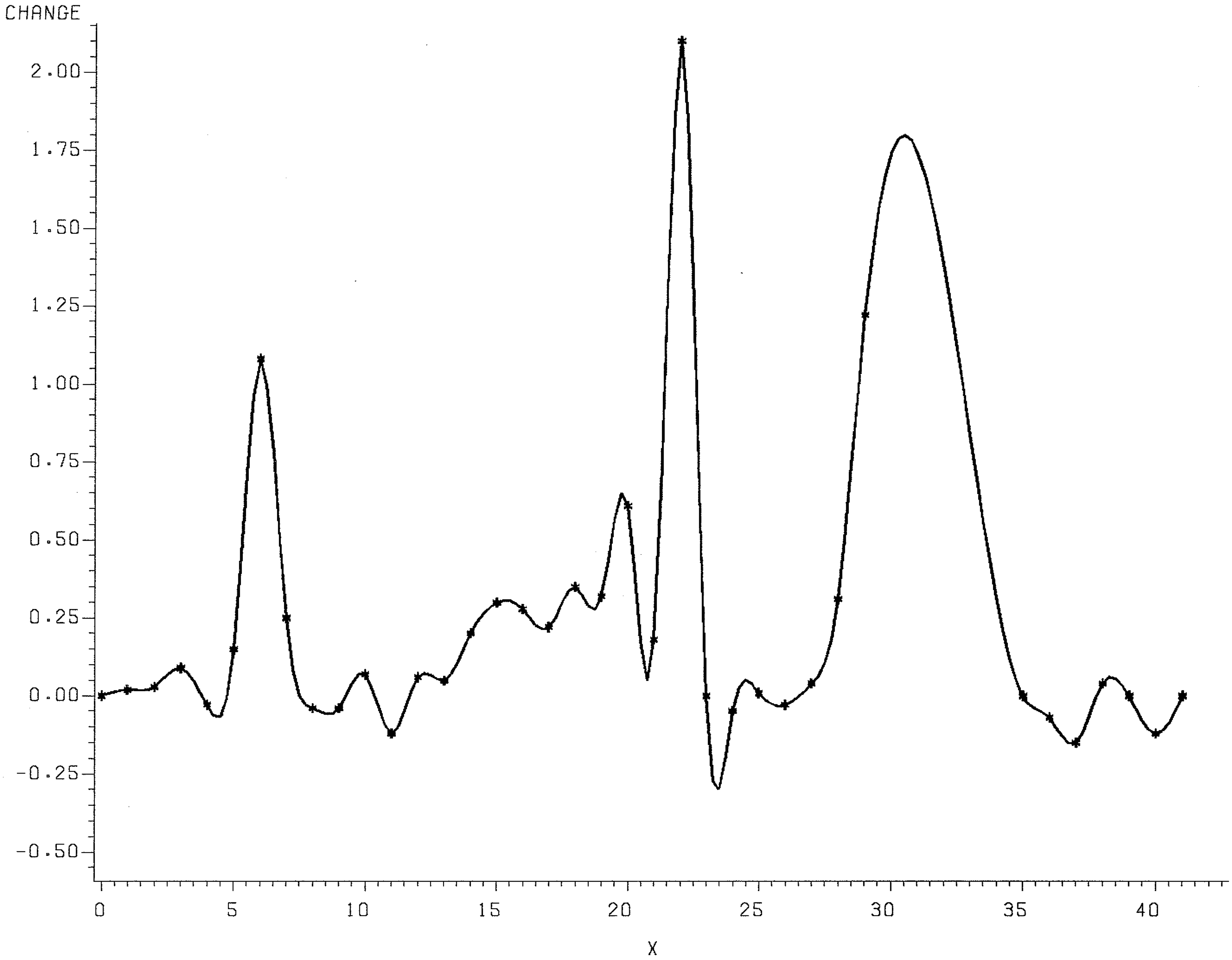
GRAVEL CREEK CHANNEL CHANGE B-28 (June,1981-post breakup May 1982)



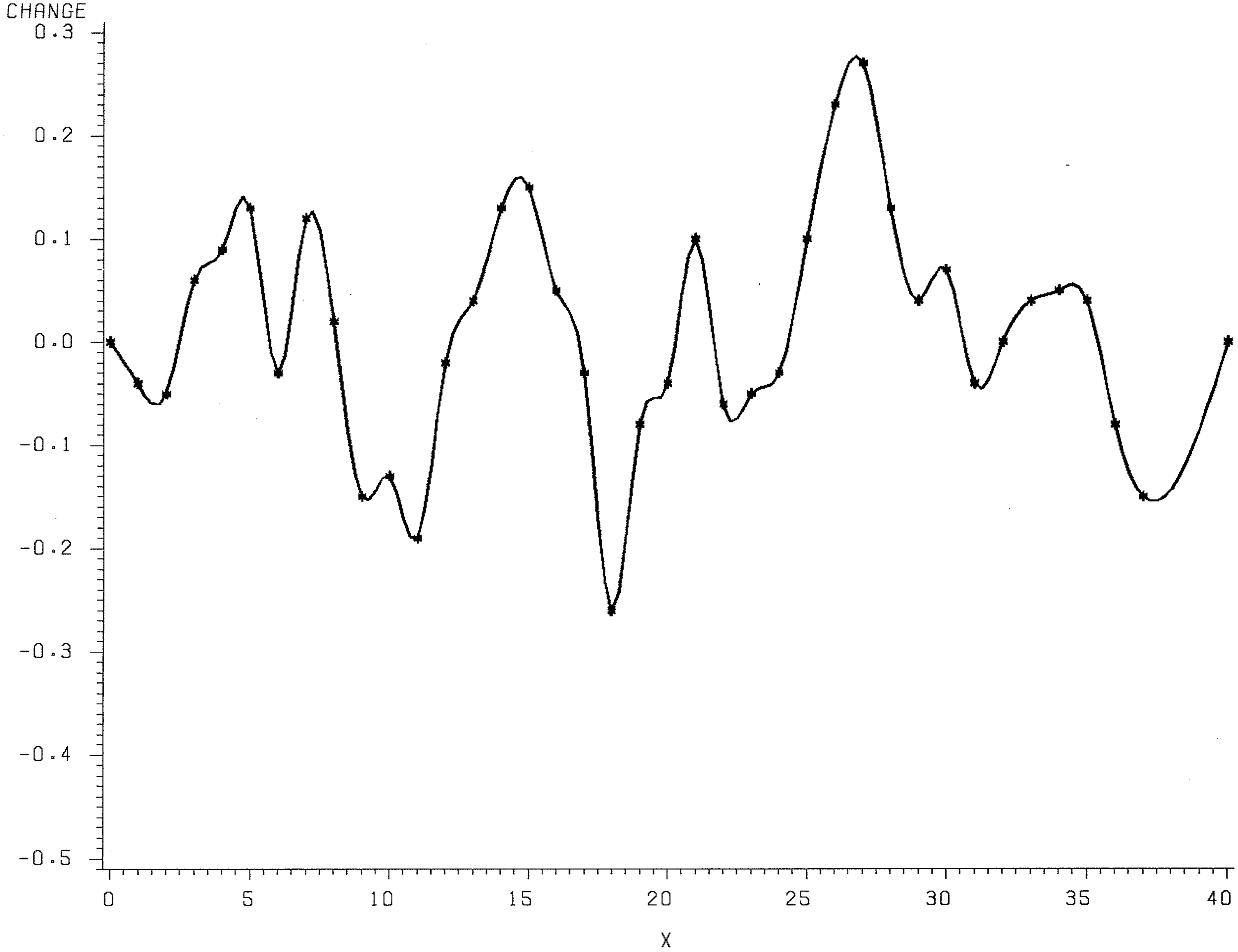
GRAVEL CREEK CHANNEL CHANGE B-29 (June,1981-post breakup May 1982)



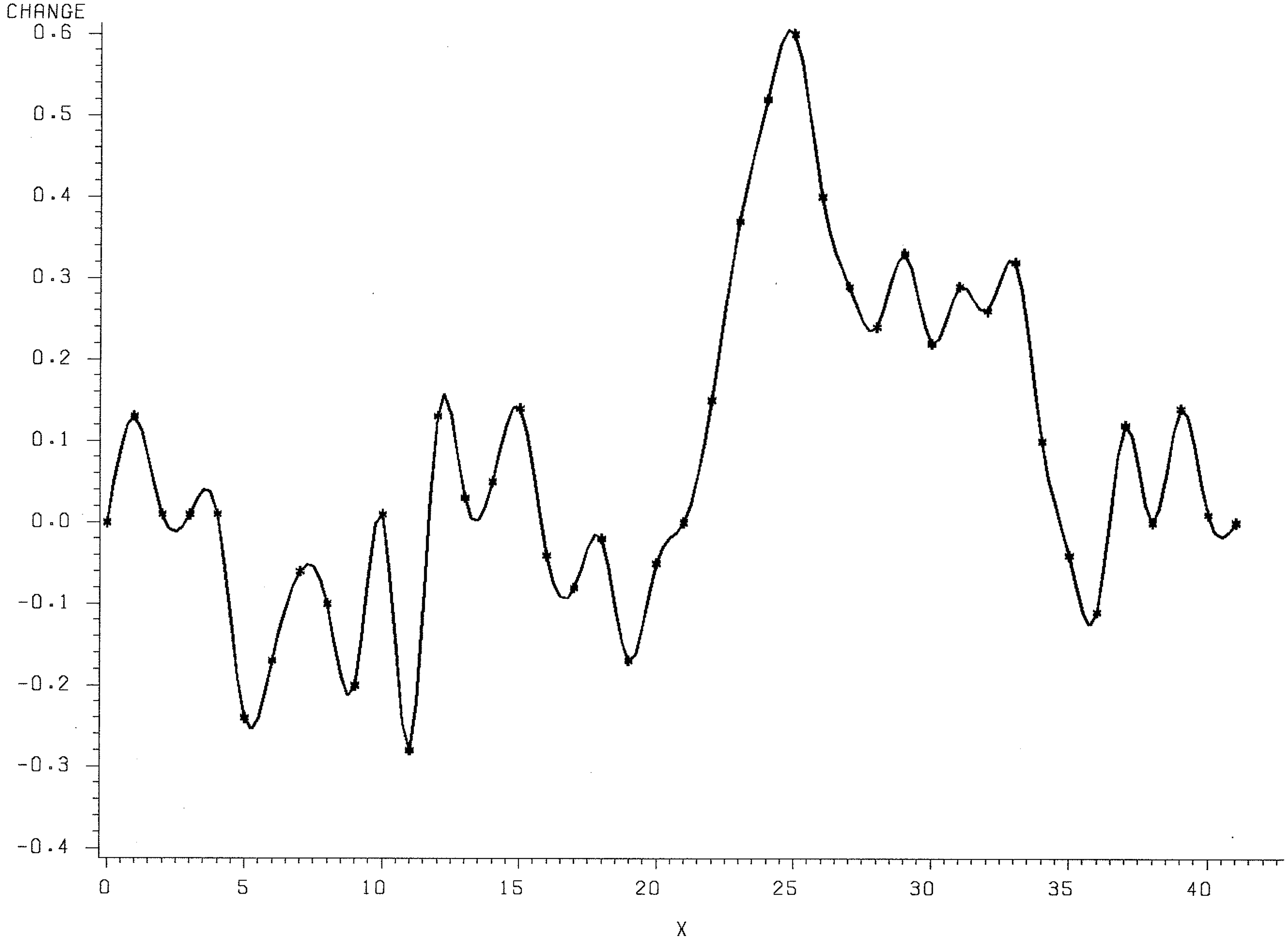
GRAVEL CREEK CHANNEL CHANGE B-30 (June,1981-post breakup May 1982)



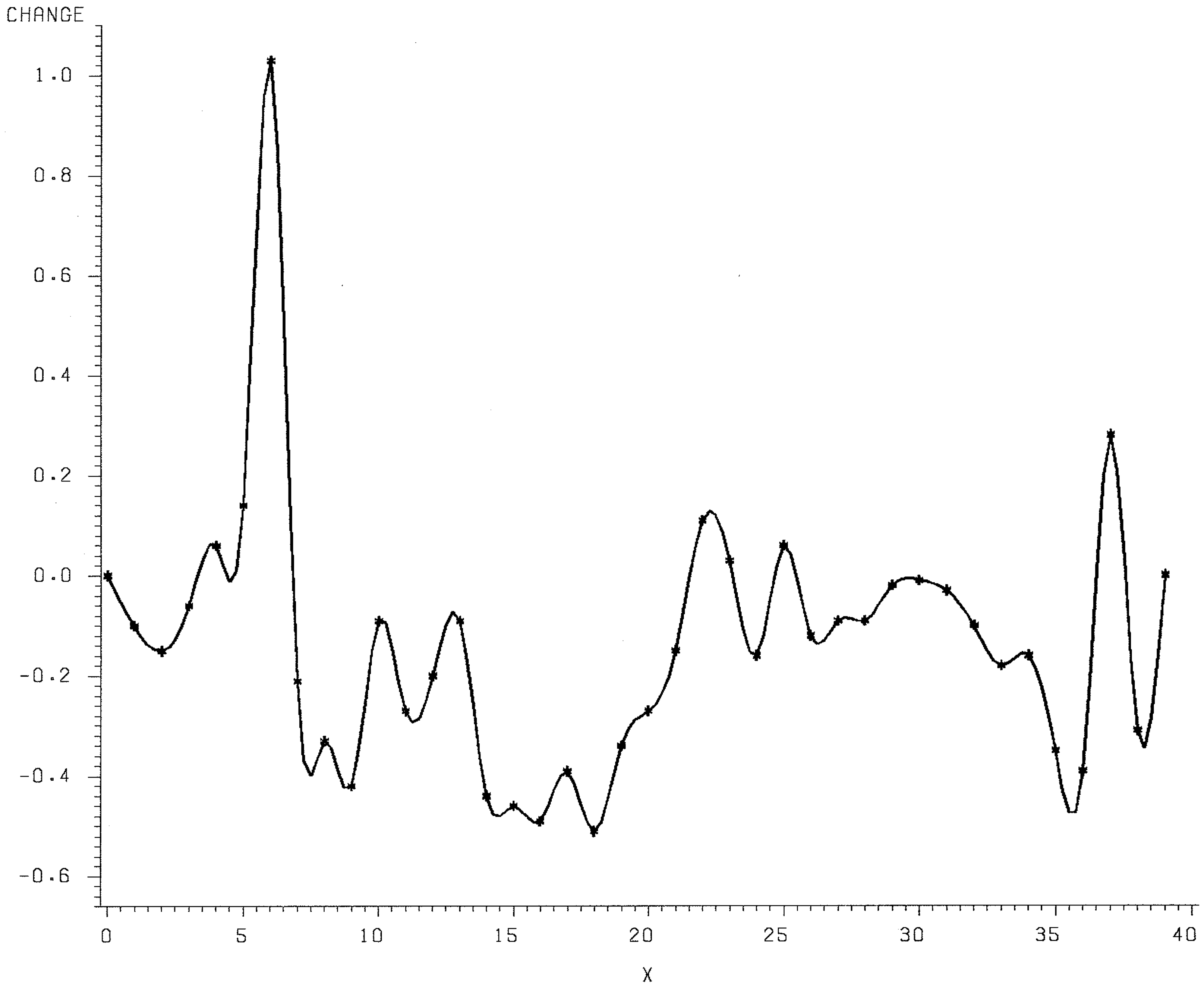
GRAVEL CREEK CHANNEL CHANGE B-31 (June,1981–post breakup May 1982)



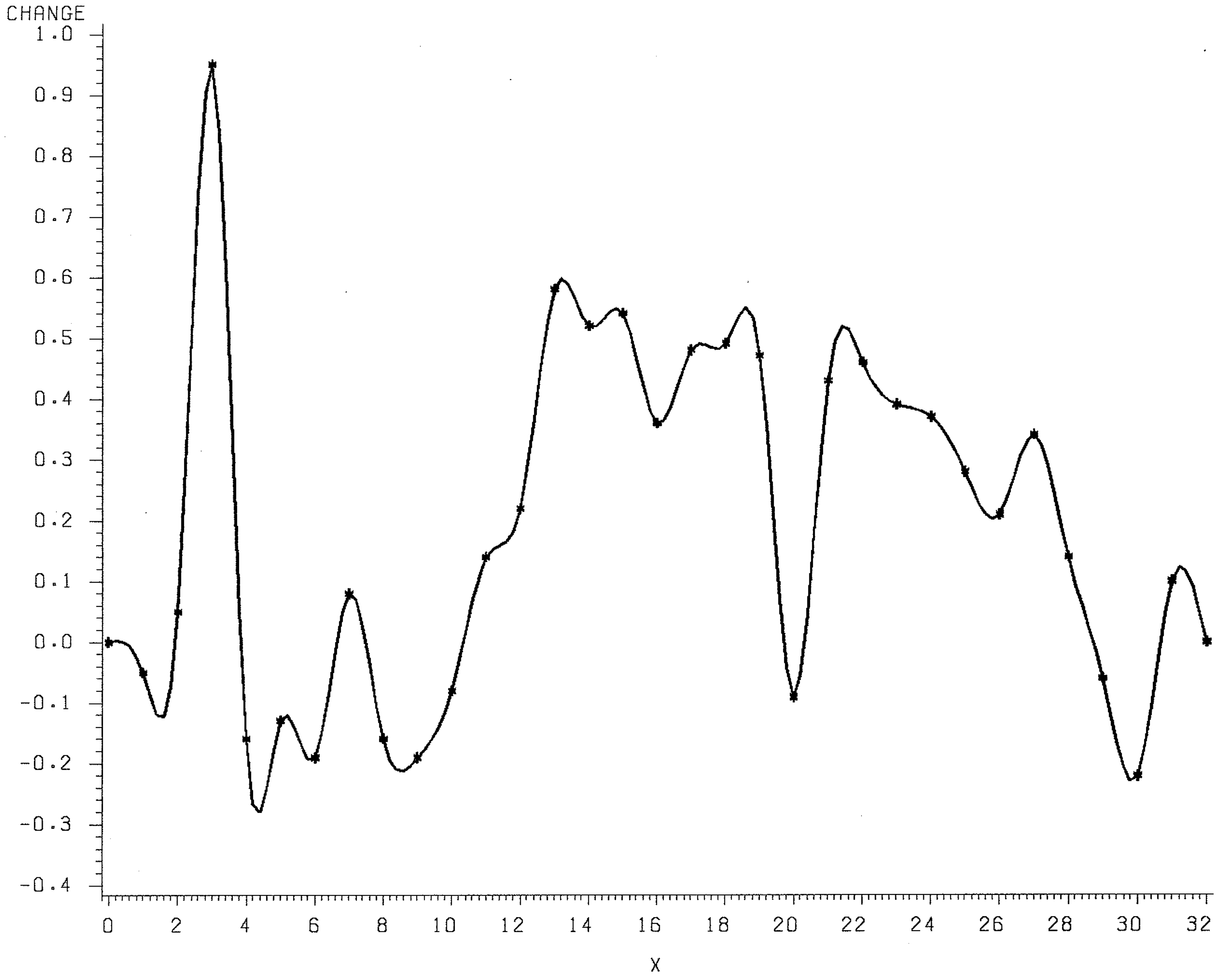
GRAVEL CREEK CHANNEL CHANGE B-32 (June,1981-post breakup May 1982)



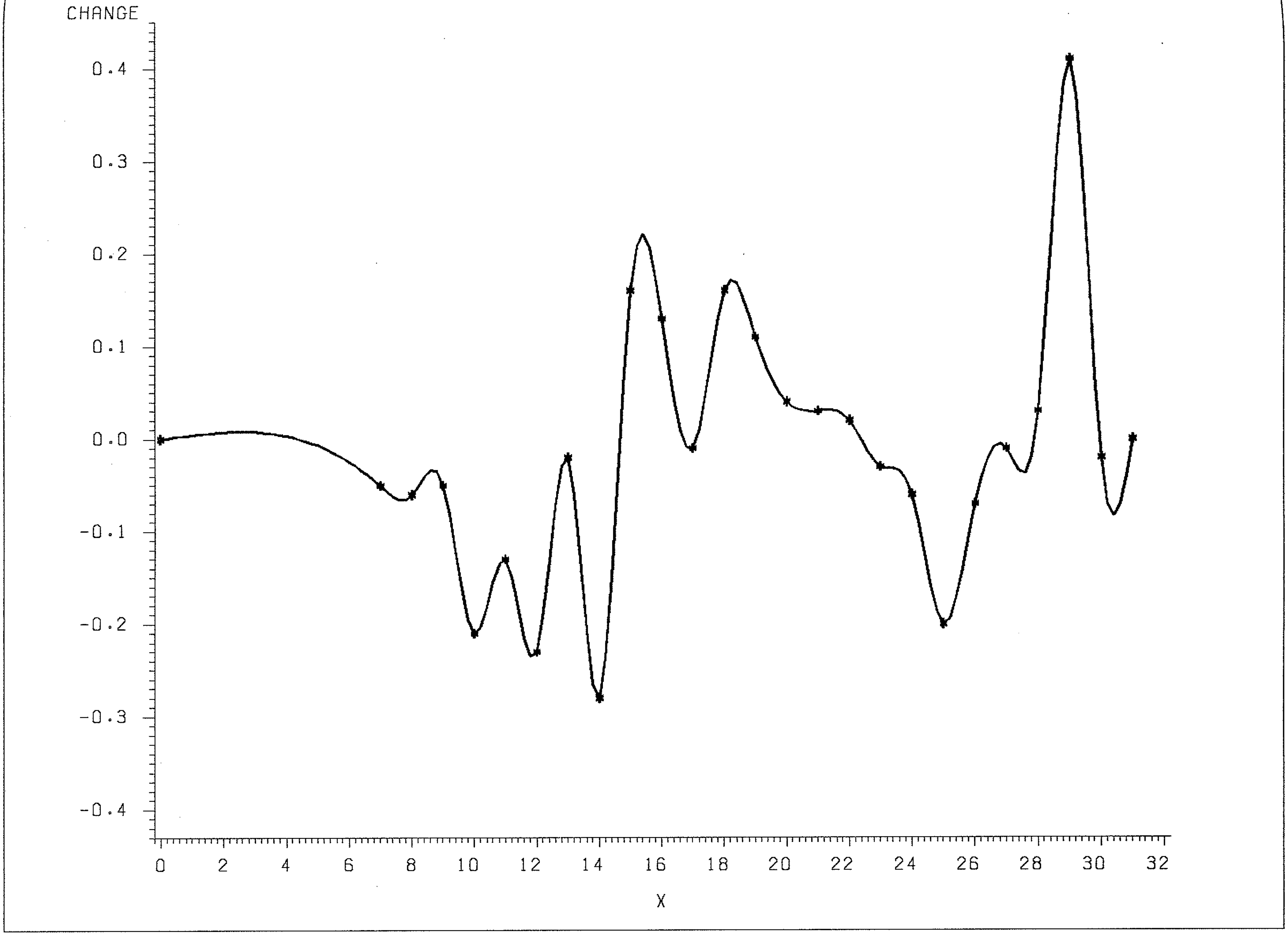
GRAVEL CREEK CHANNEL CHANGE B-33 (June,1981-post breakup May 1982)



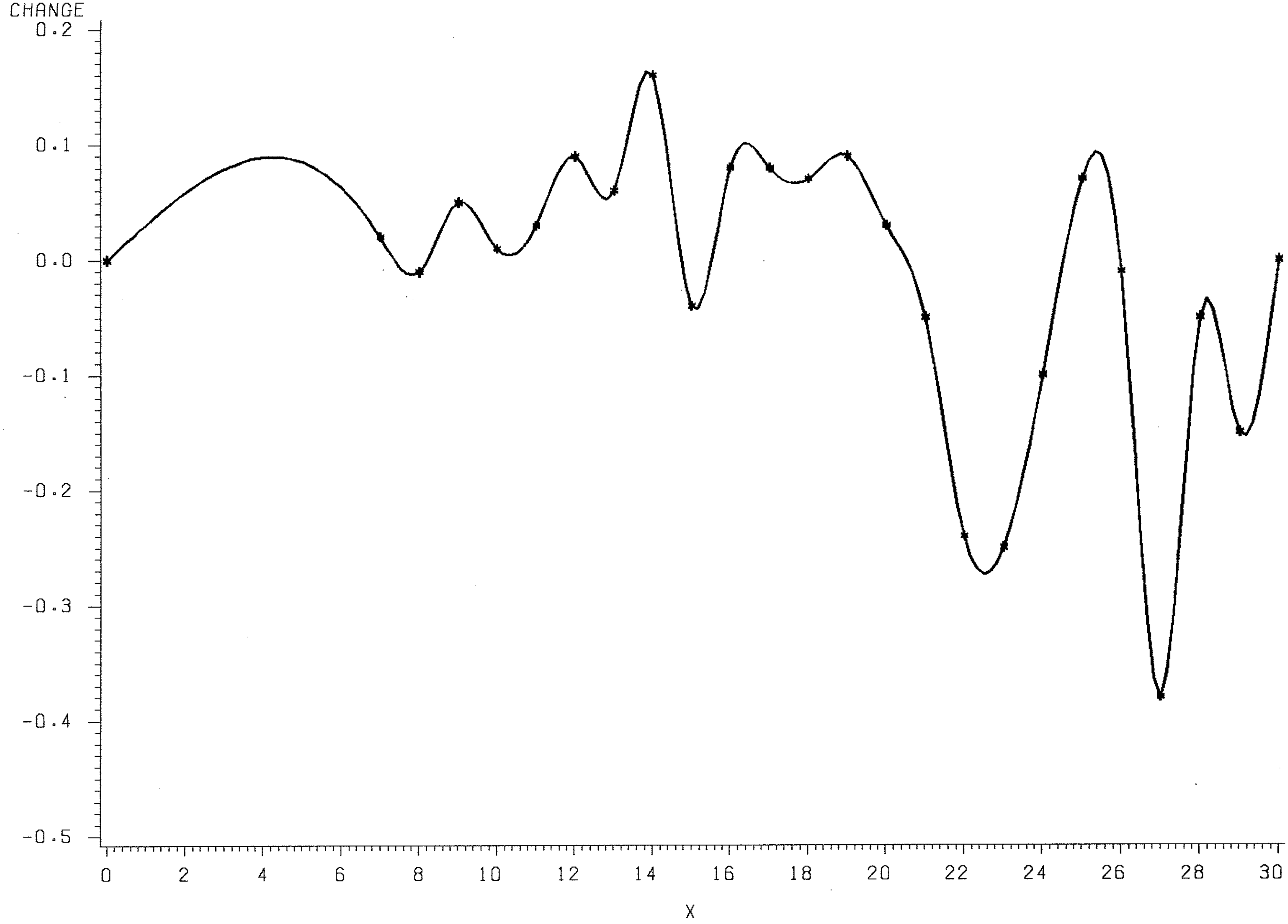
GRAVEL CREEK CHANNEL CHANGE B-34 (June,1981-post breakup May 1982)



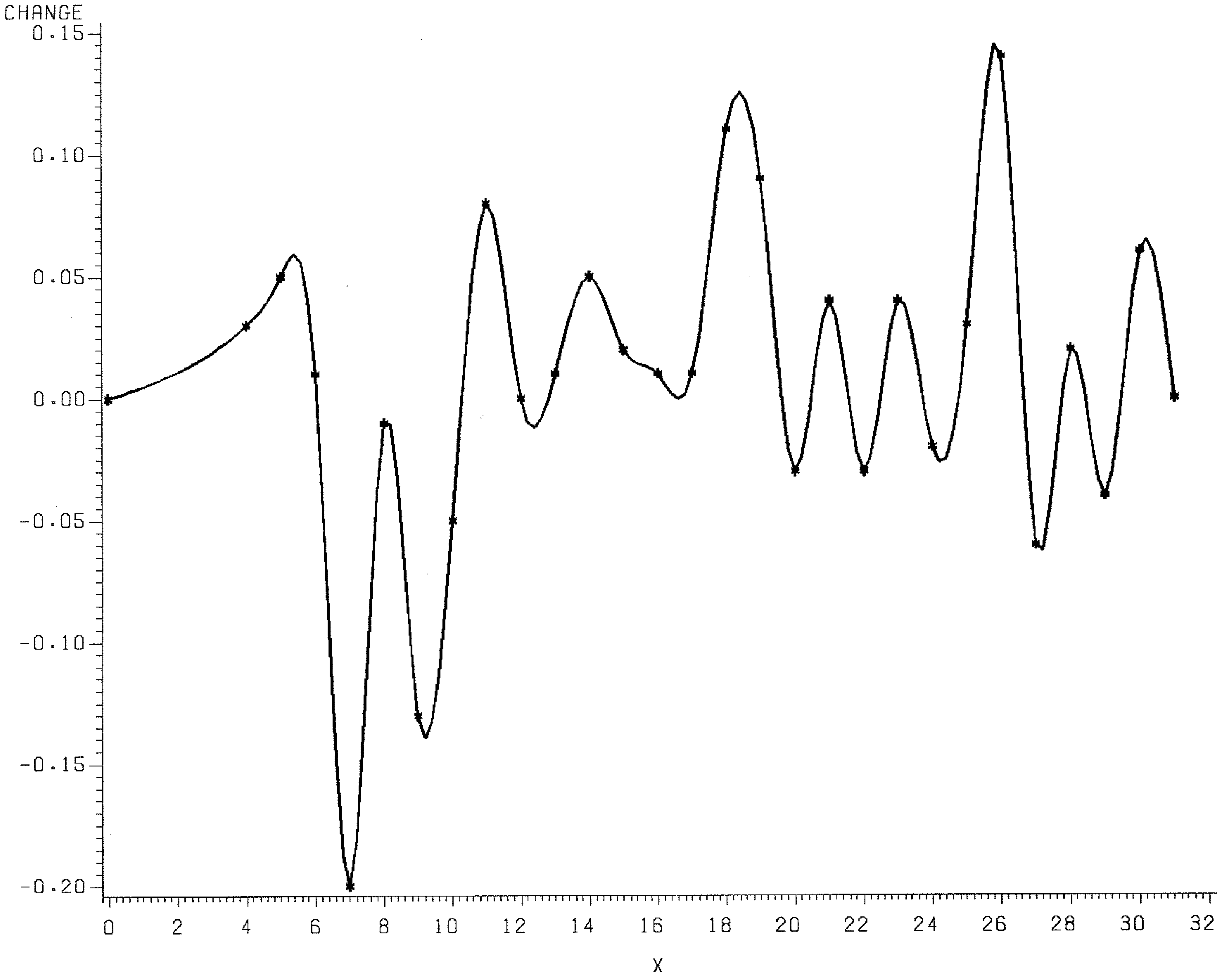
GRAVEL CREEK CHANNEL CHANGE B-1 (post breakup to postflood 1982)



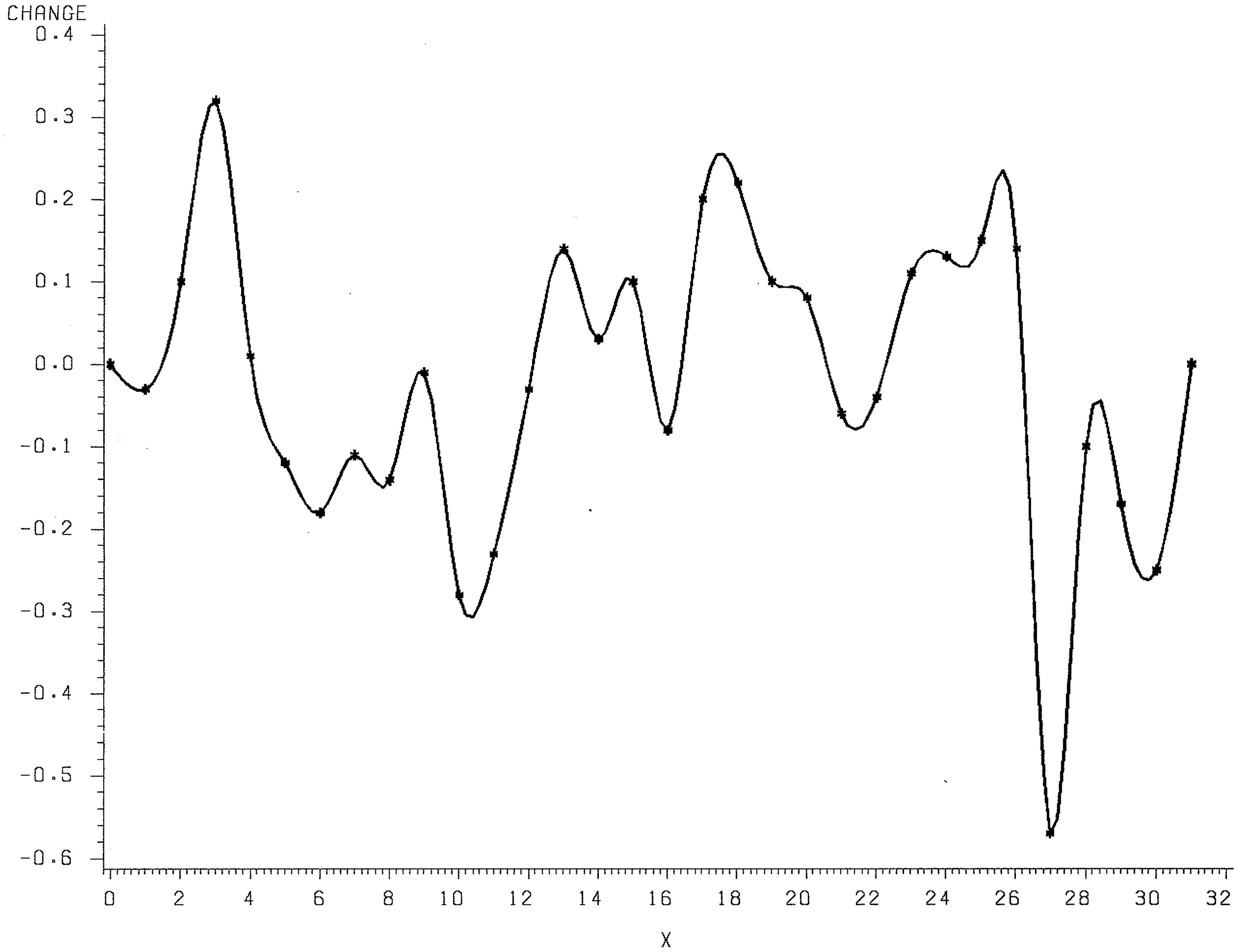
GRAVEL CREEK CHANNEL CHANGE B-2 (post breakup to postflood 1982)



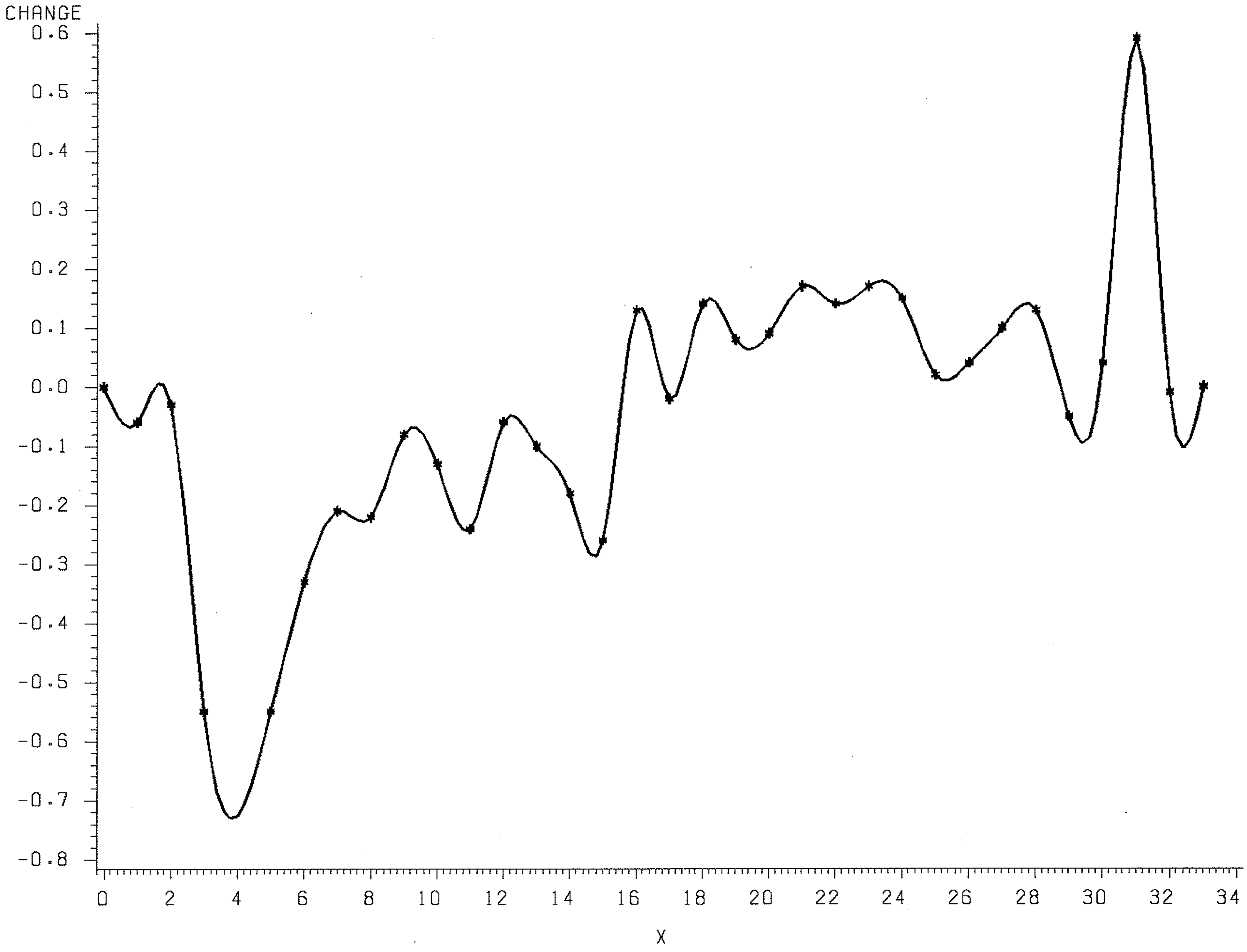
GRAVEL CREEK CHANNEL CHANGE B-3 (post breakup to postflood 1982)

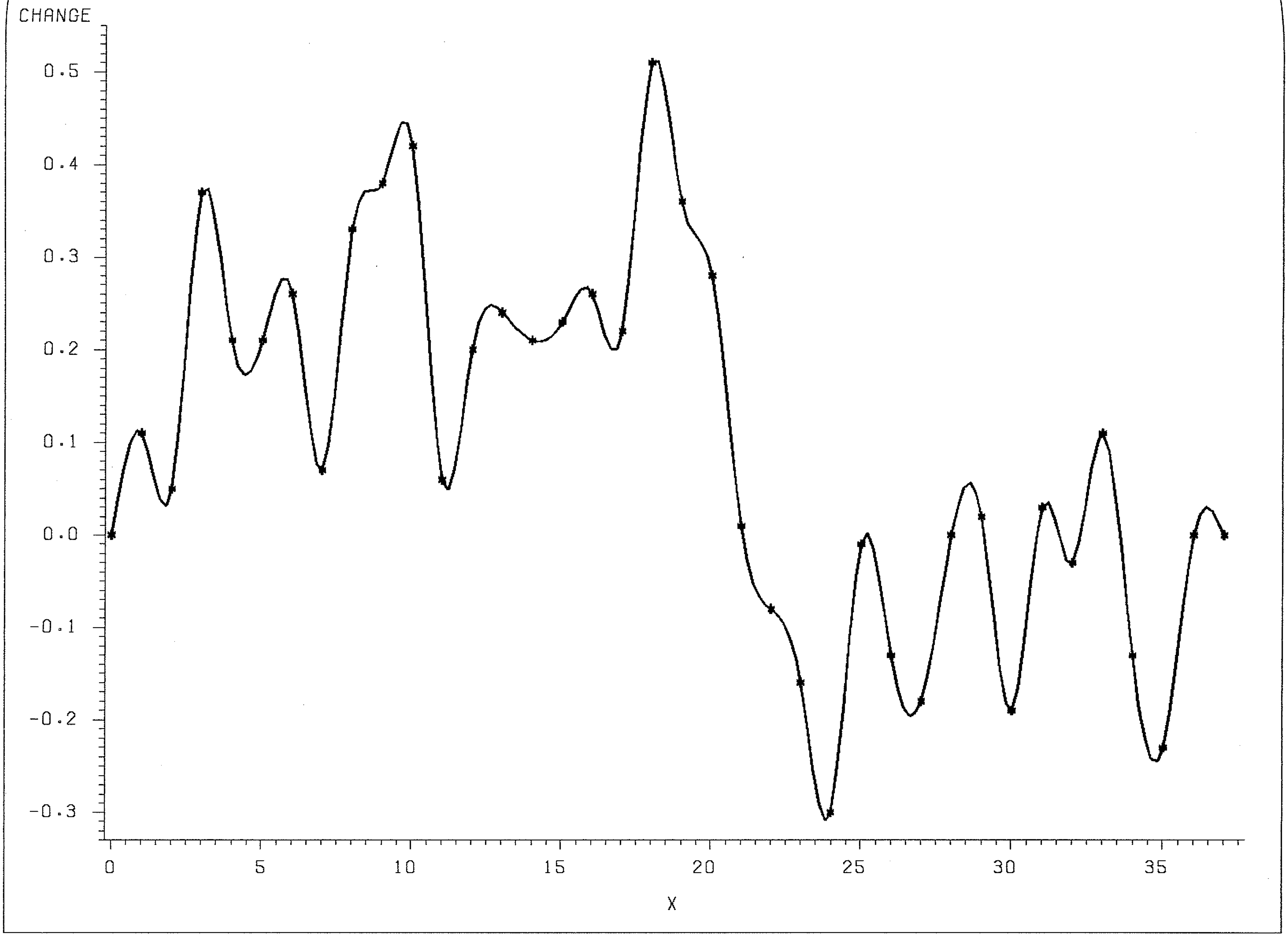


GRAVEL CREEK CHANNEL CHANGE B-4 (post breakup to postflood 1982)



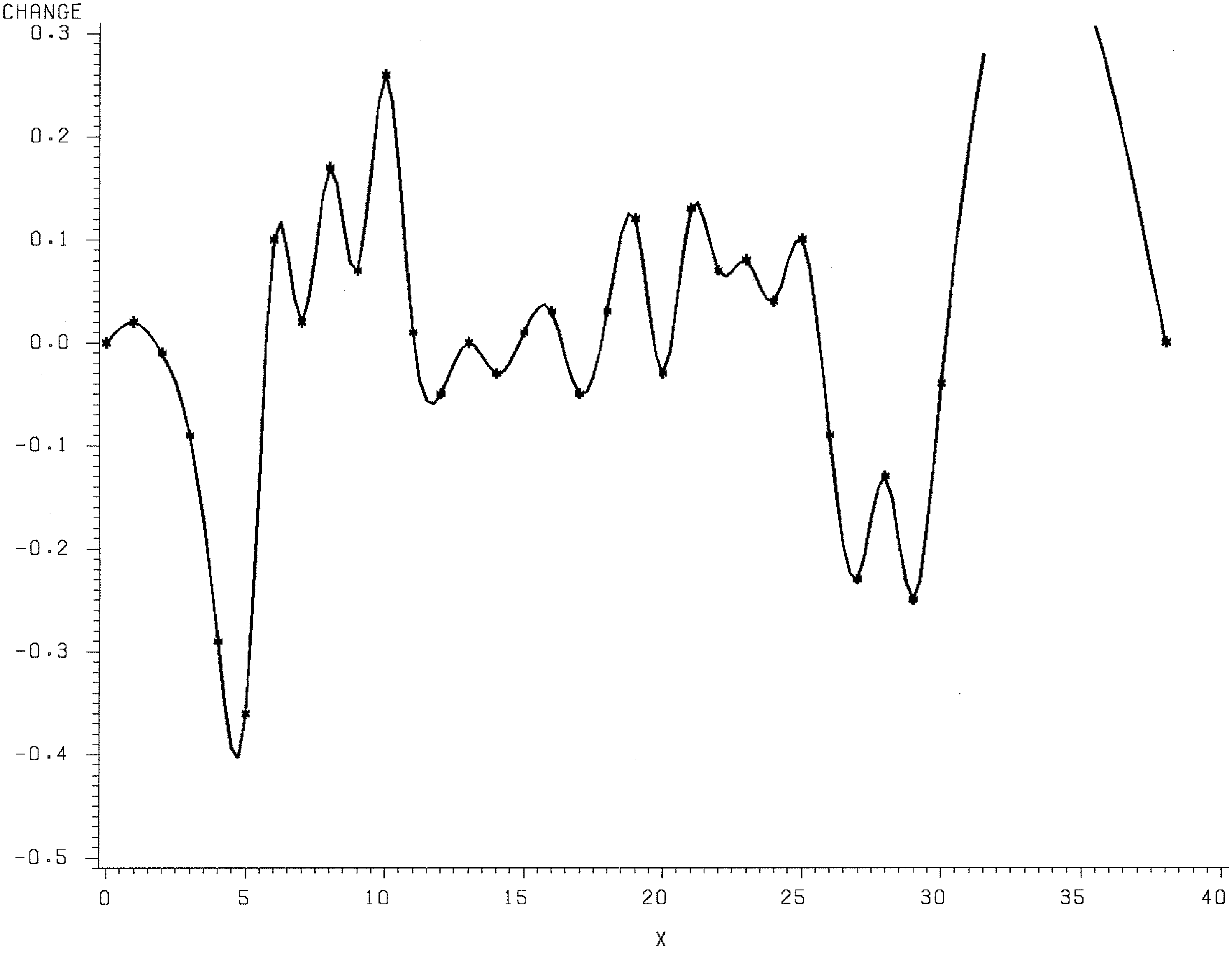
GRAVEL CREEK CHANNEL CHANGE B-5 (post breakup to postflood 1982)

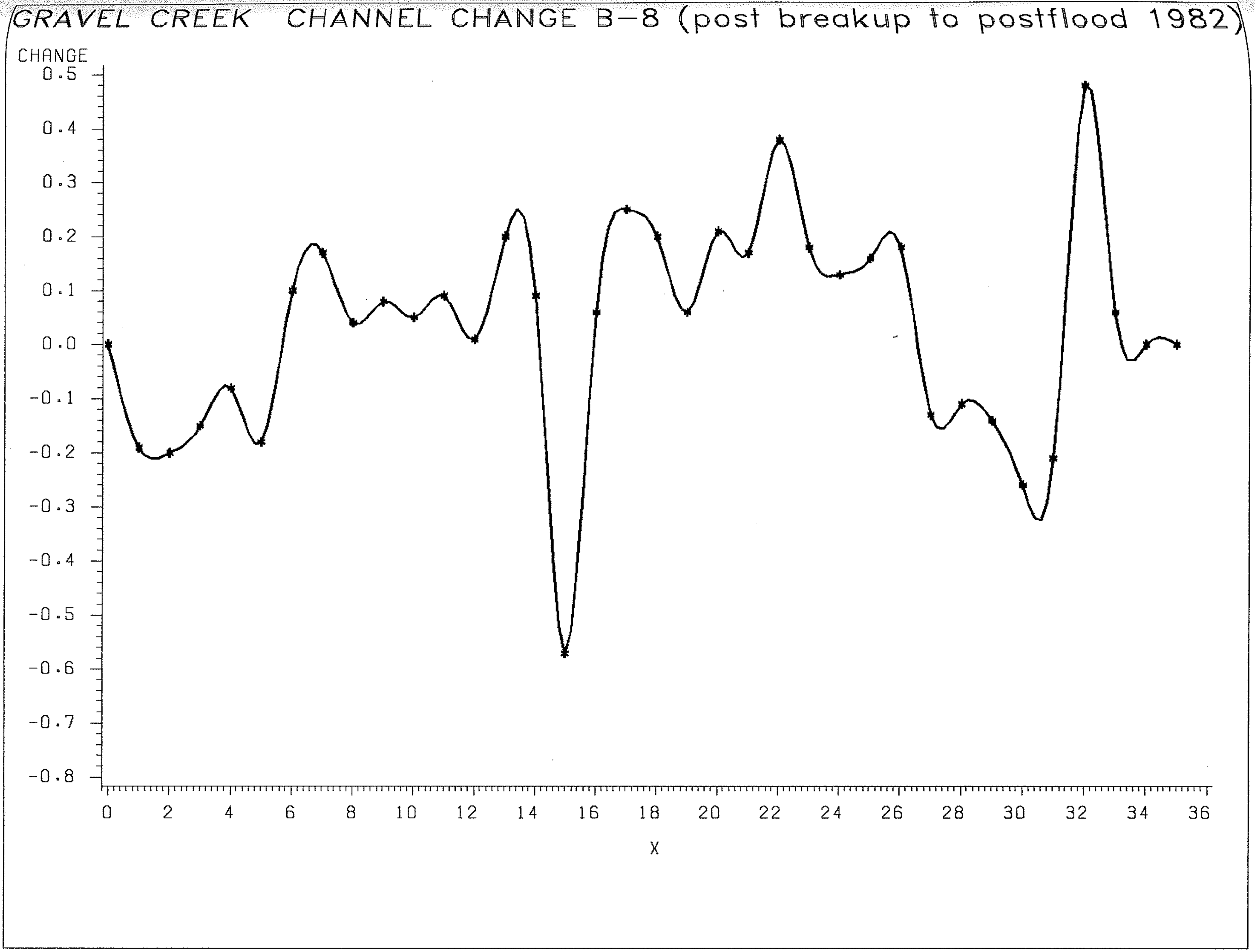




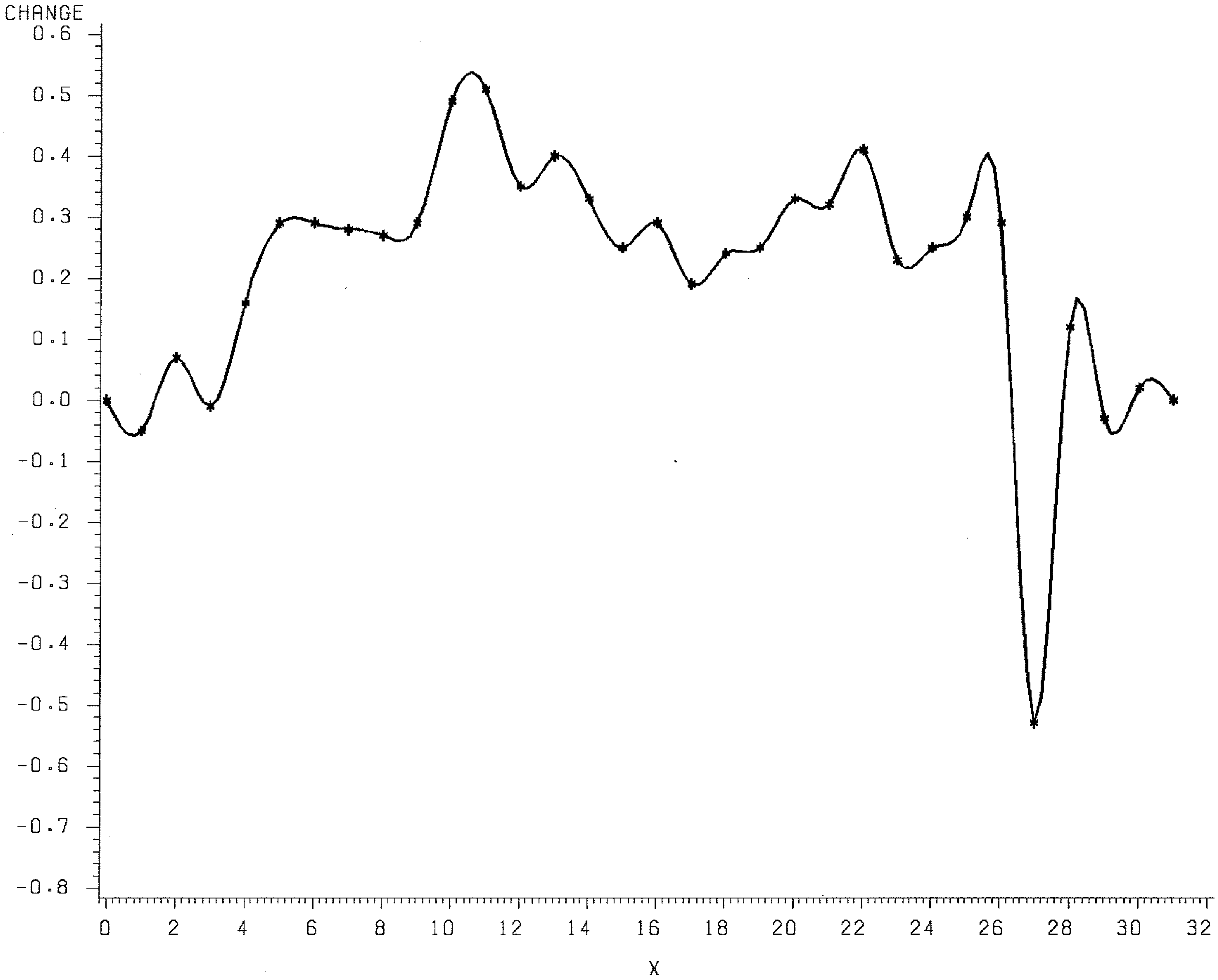
GRAVEL CREEK CHANNEL CHANGE B-6 (post breakup to postflood 1982)

GRAVEL CREEK CHANNEL CHANGE B-7 (post breakup to postflood 1982)

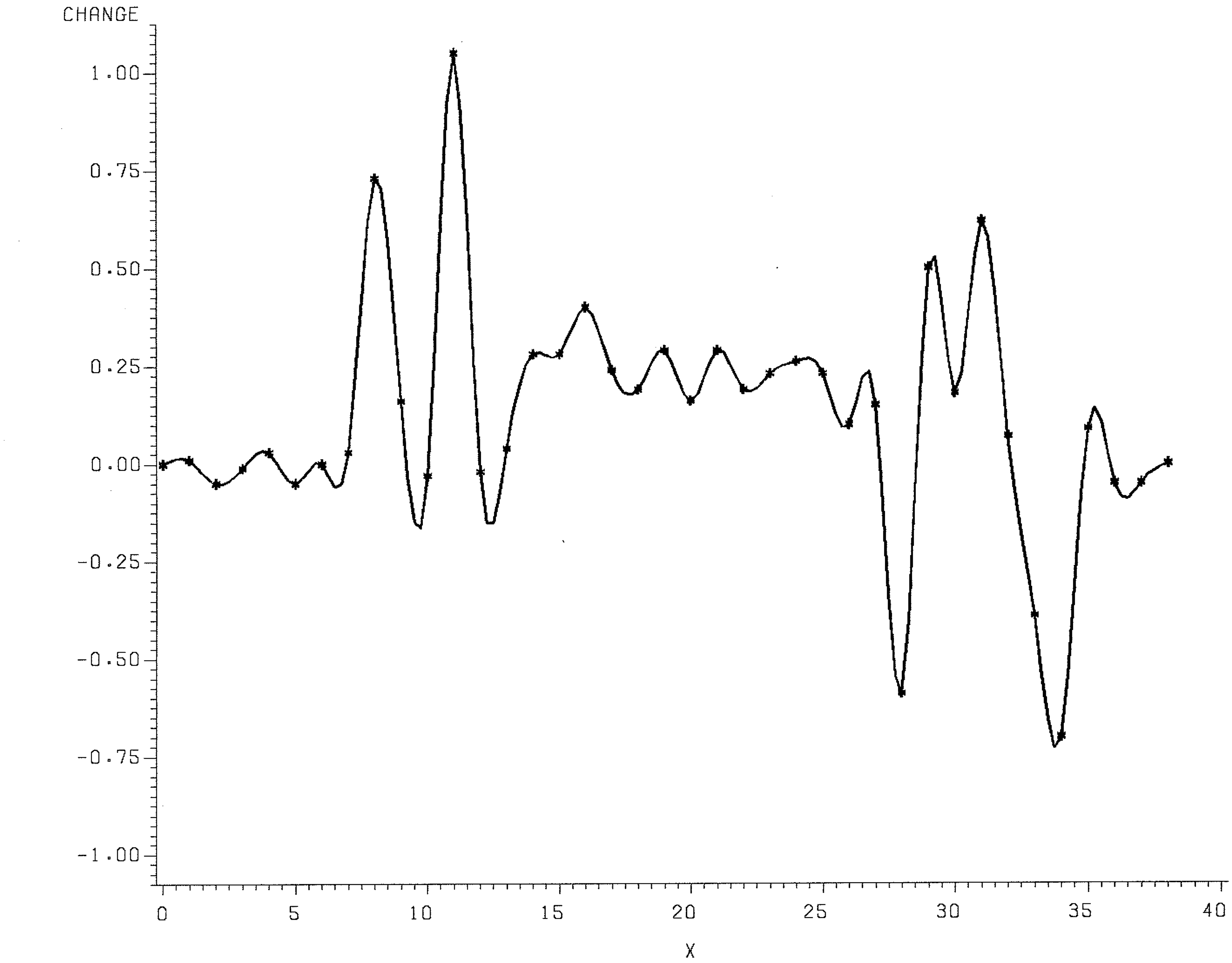



GRAVEL CREEK CHANNEL CHANGE B-8 (post breakup to postflood 1982)
CHANGE
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
X

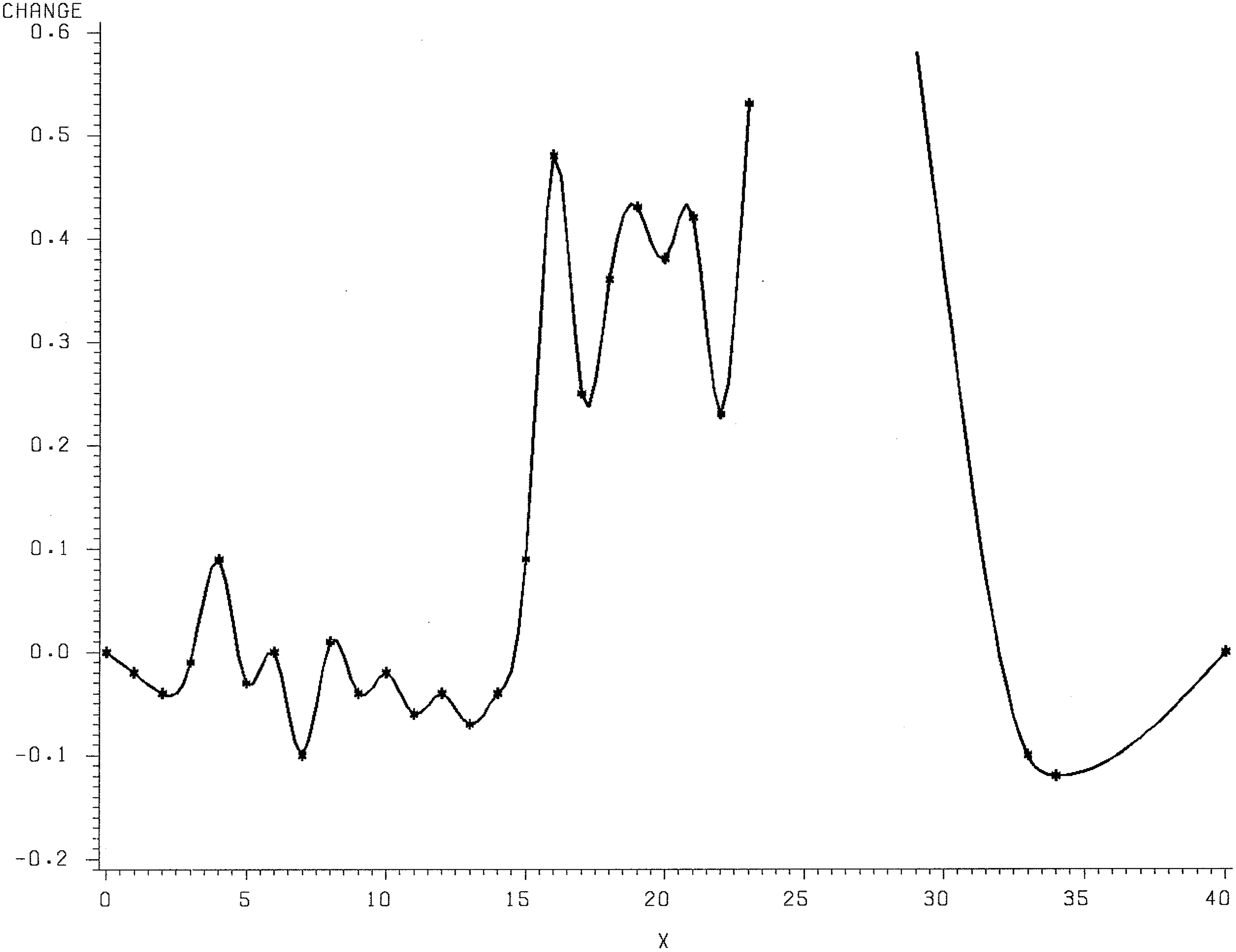
GRAVEL CREEK CHANNEL CHANGE B-9 (post breakup to postflood 1982)



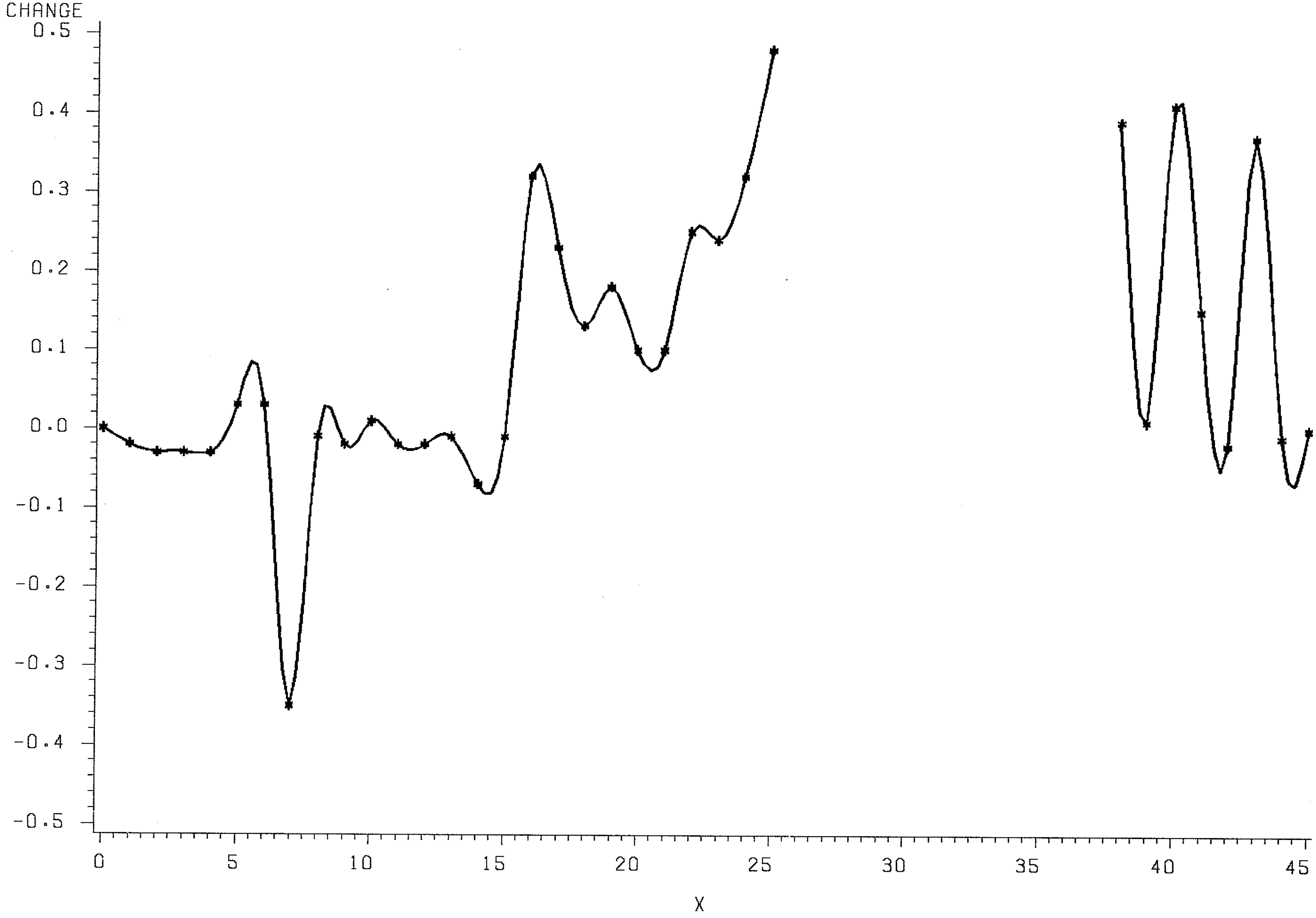
GRAVEL CREEK CHANNEL CHANGE B-10(post breakup to postflood 1982)



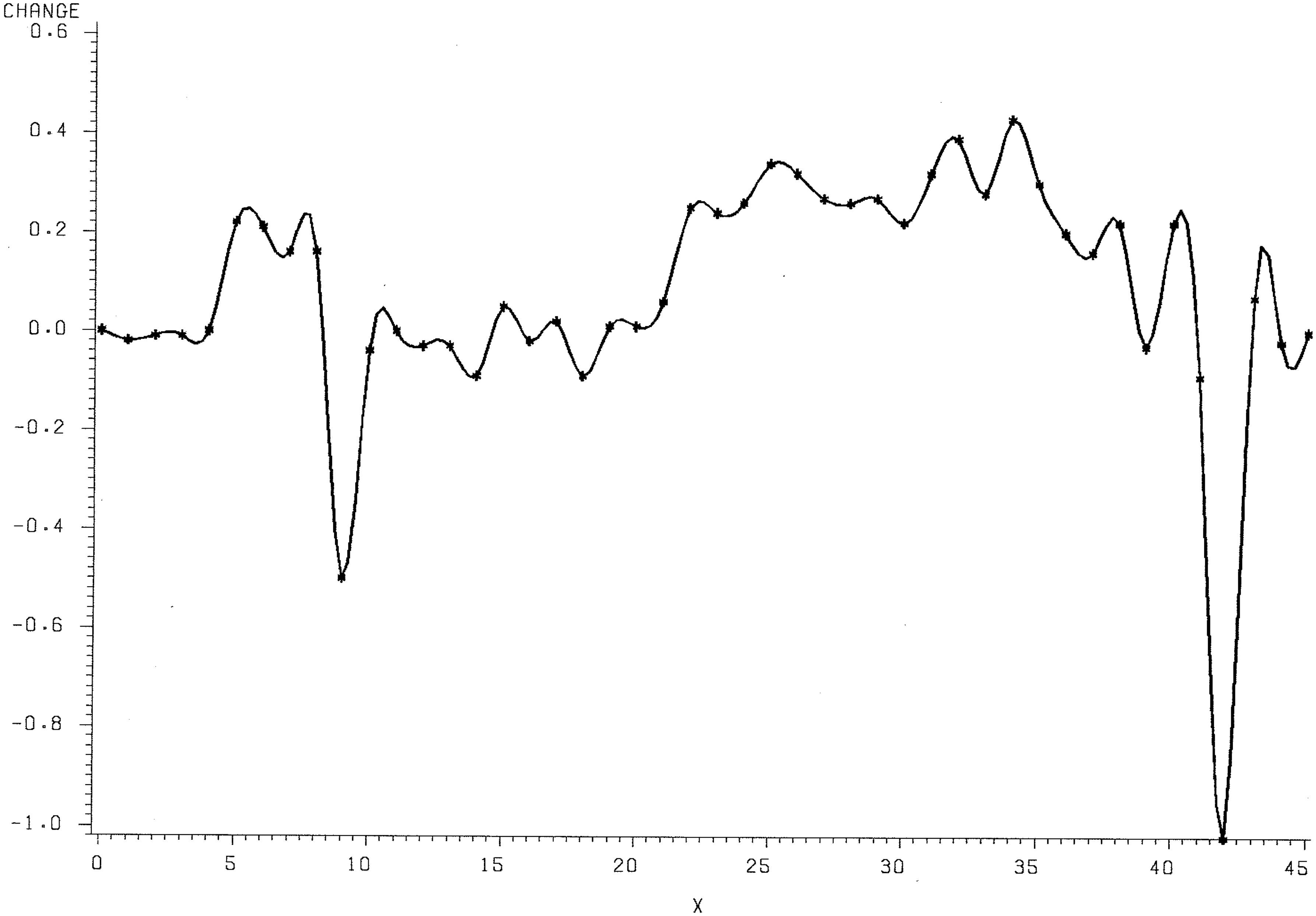
GRAVEL CREEK CHANNEL CHANGE B-12(post breakup to postflood 1982)



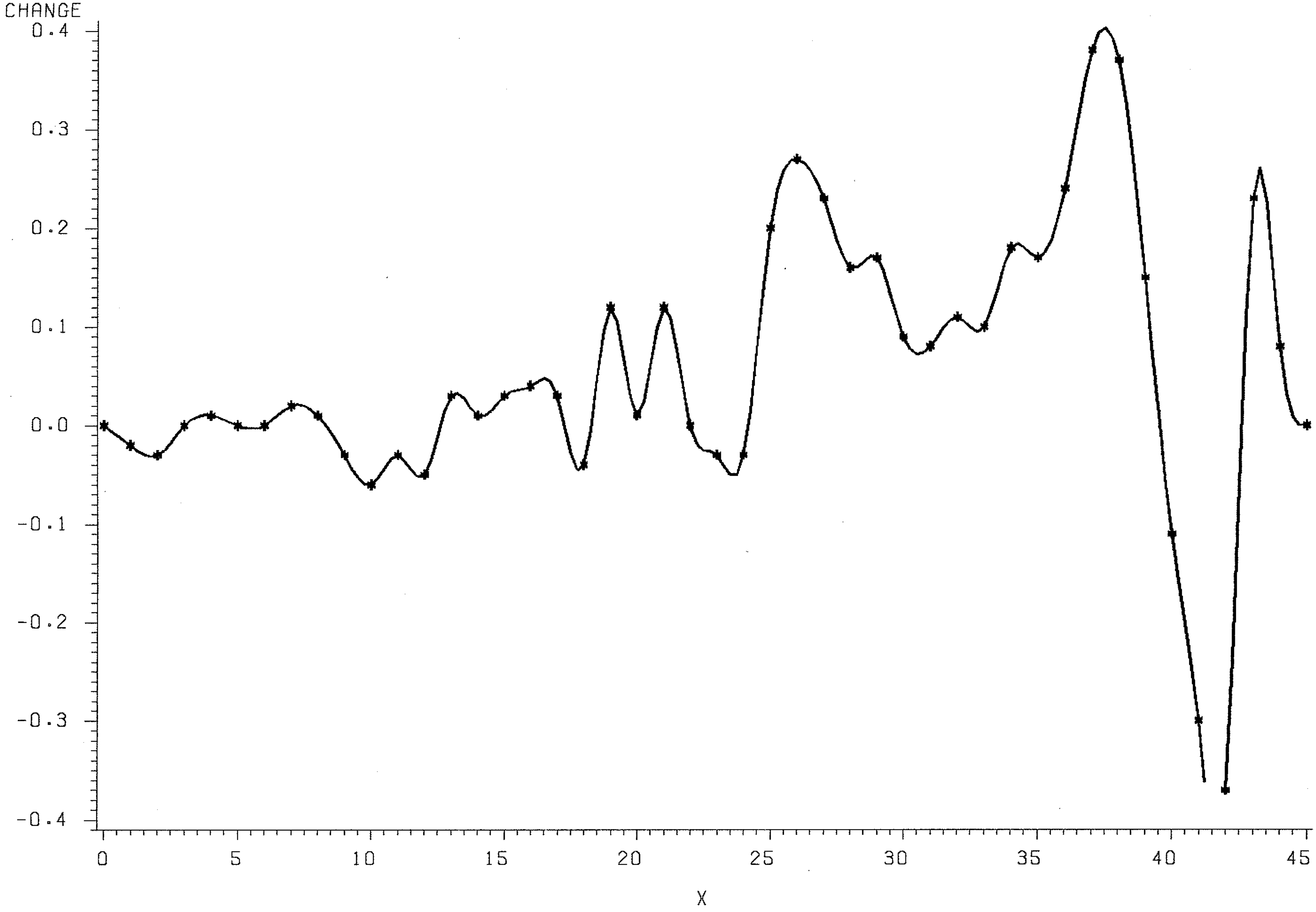
GRAVEL CREEK CHANNEL CHANGE B-13(post breakup to postflood 1982)



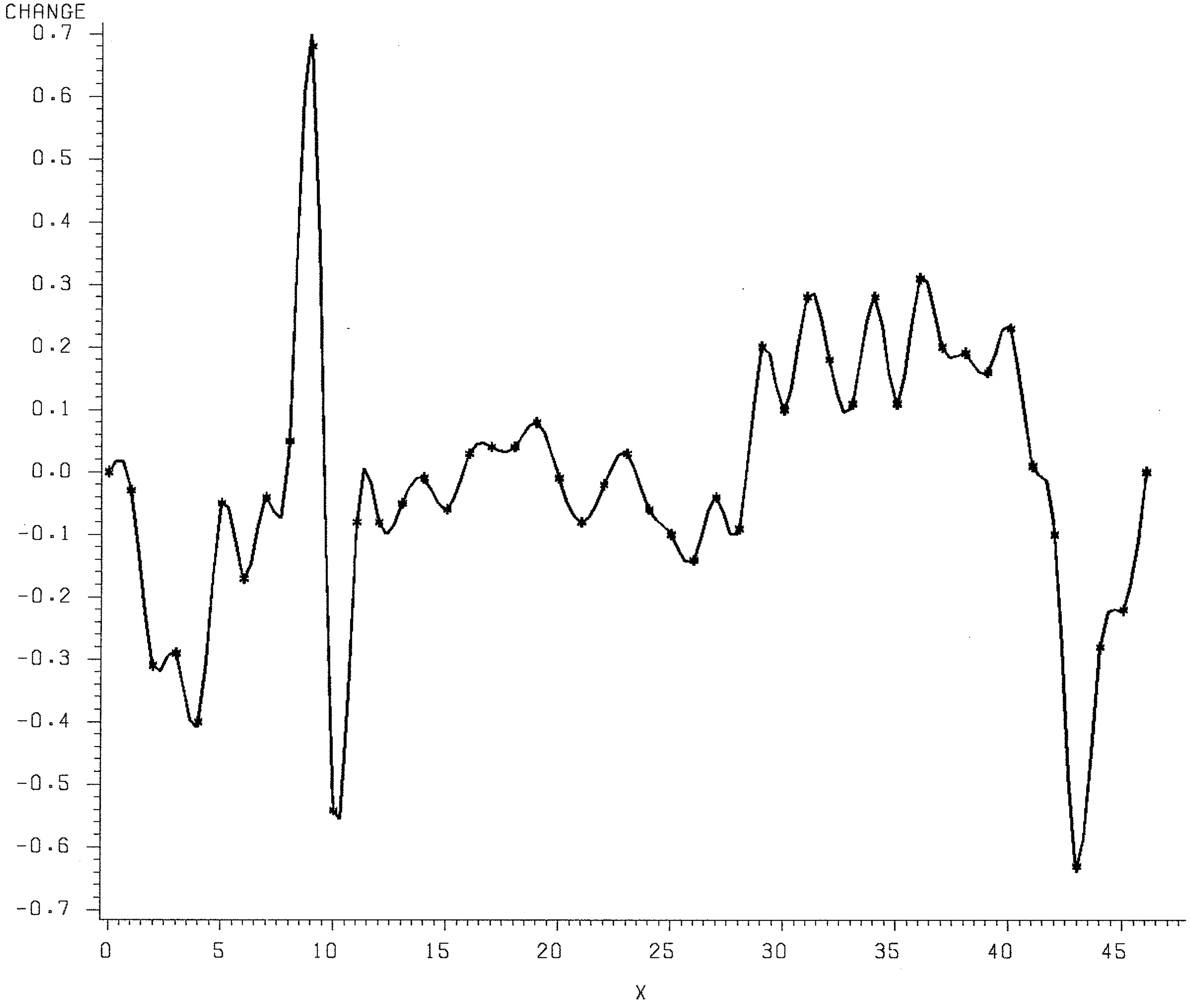
GRAVEL CREEK CHANNEL CHANGE B-14(post breakup to postflood 1982)



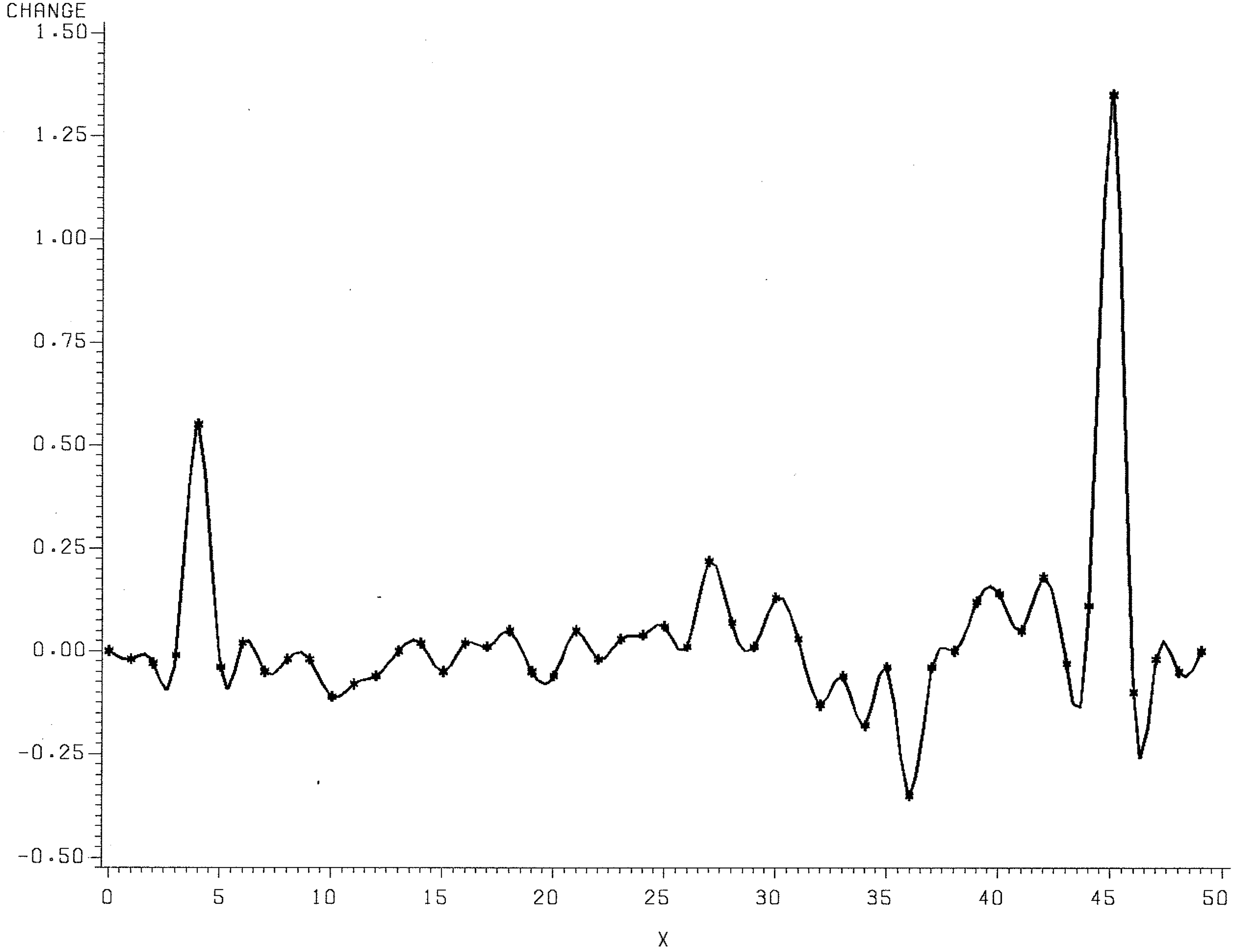
GRAVEL CREEK CHANNEL CHANGE B-15(post breakup to postflood 1982)



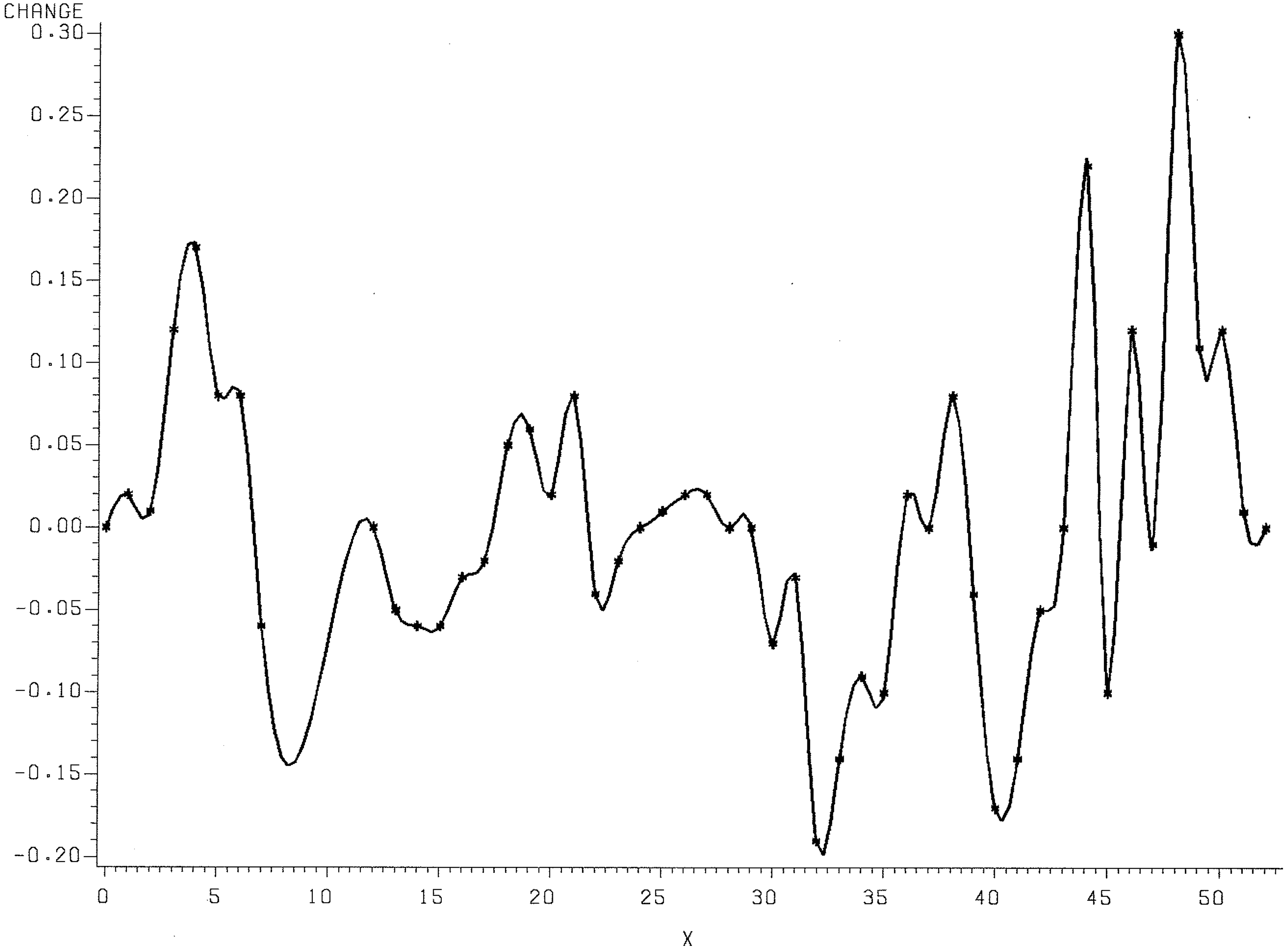
GRAVEL CREEK CHANNEL CHANGE B-16(post breakup to postflood 1982)



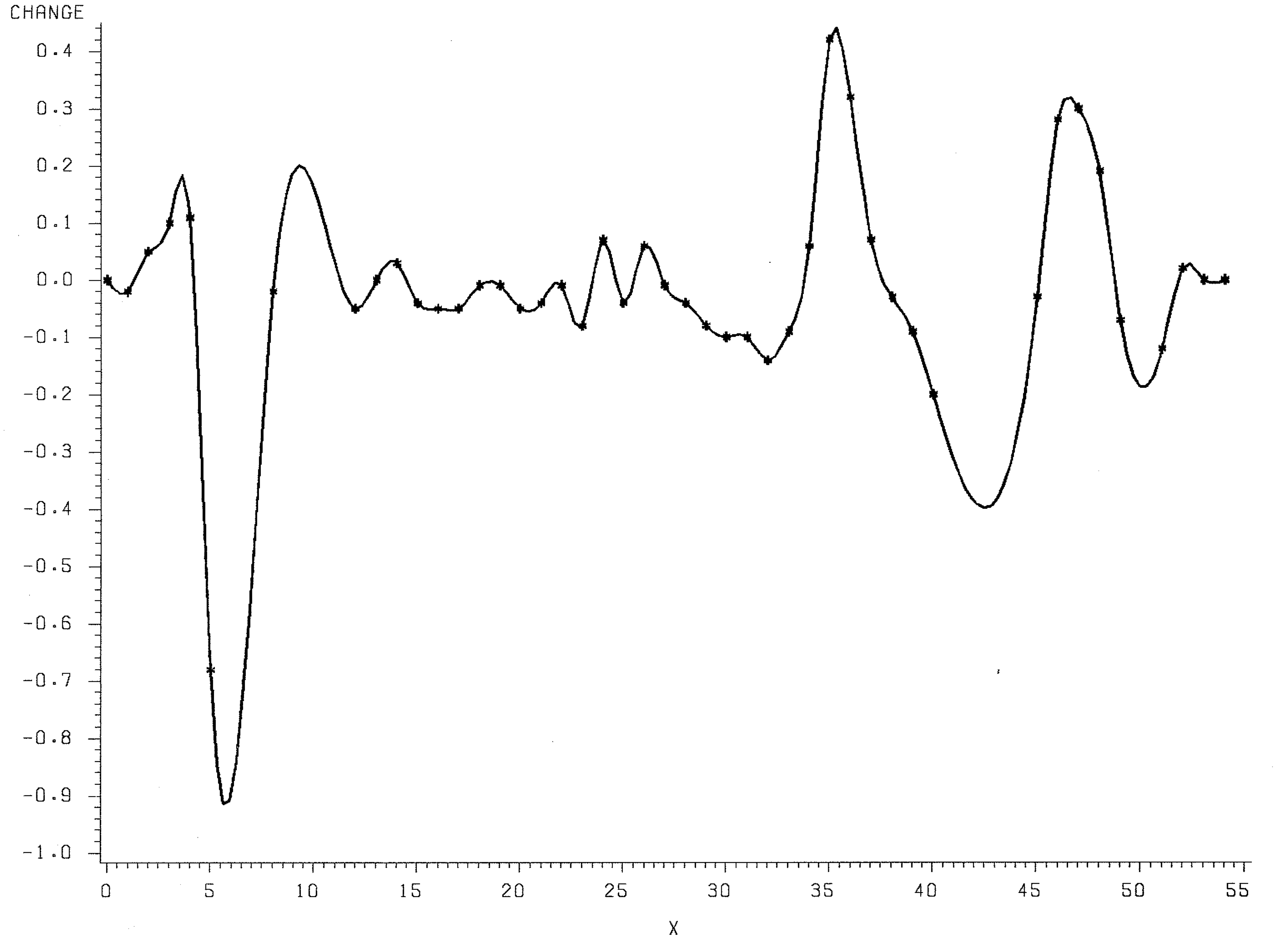
GRAVEL CREEK CHANNEL CHANGE B-17(post breakup to postflood 1982)



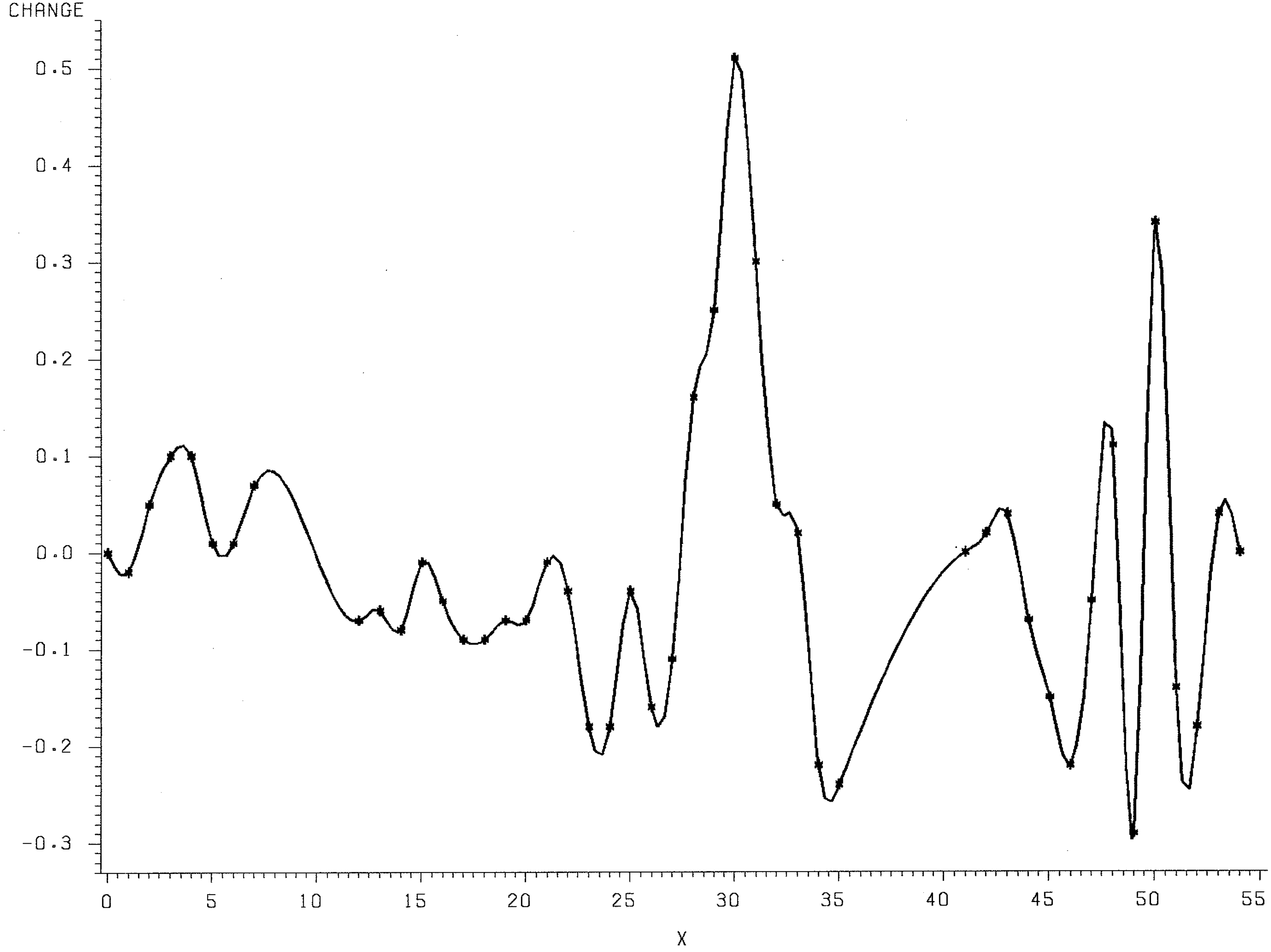
GRAVEL CREEK CHANNEL CHANGE B-18(post breakup to postflood 1982)



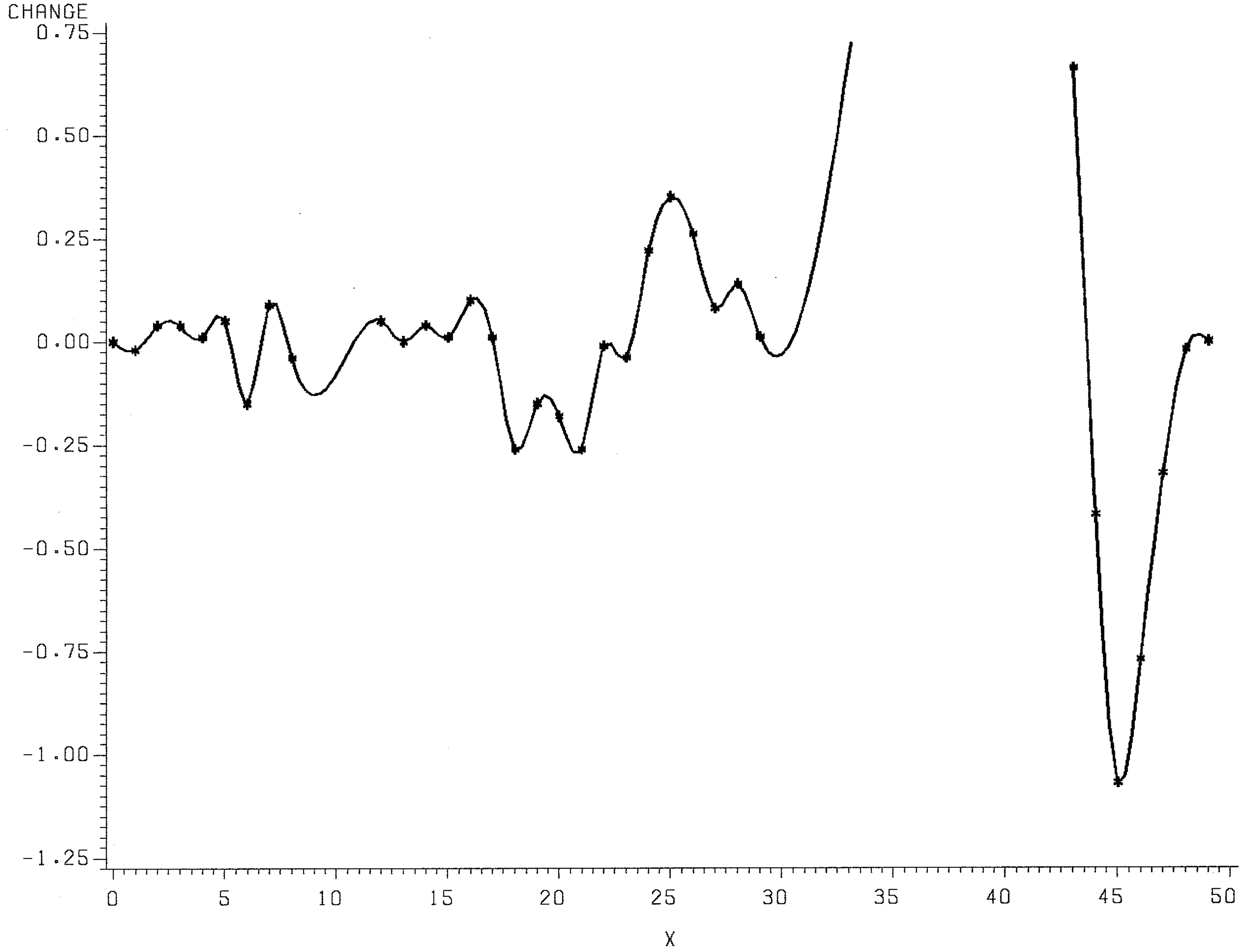
GRAVEL CREEK CHANNEL CHANGE B−18b(post breakup to postflood 1982)



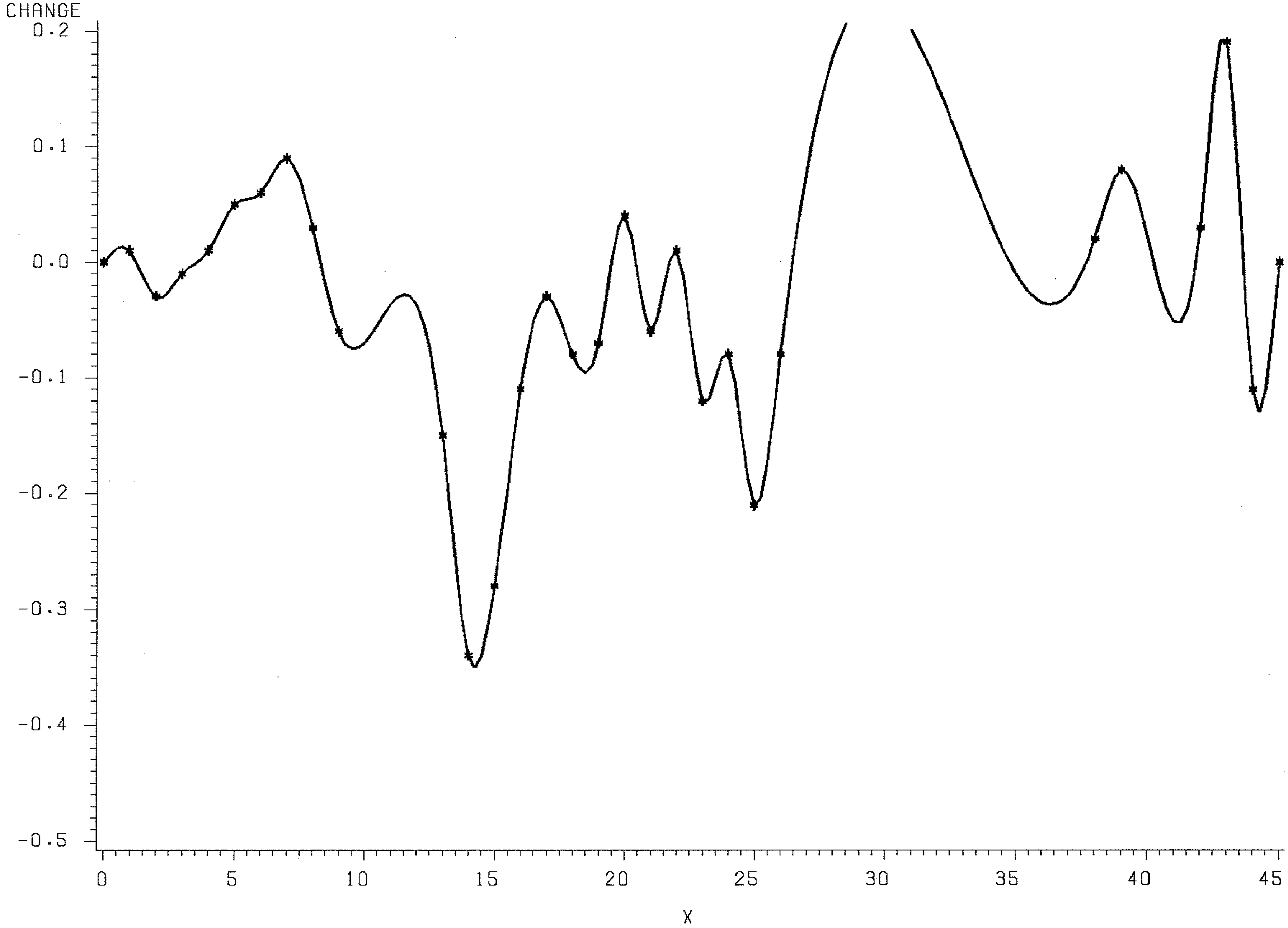
GRAVEL CREEK CHANNEL CHANGE B-1cb(post breakup to postflood 1982)



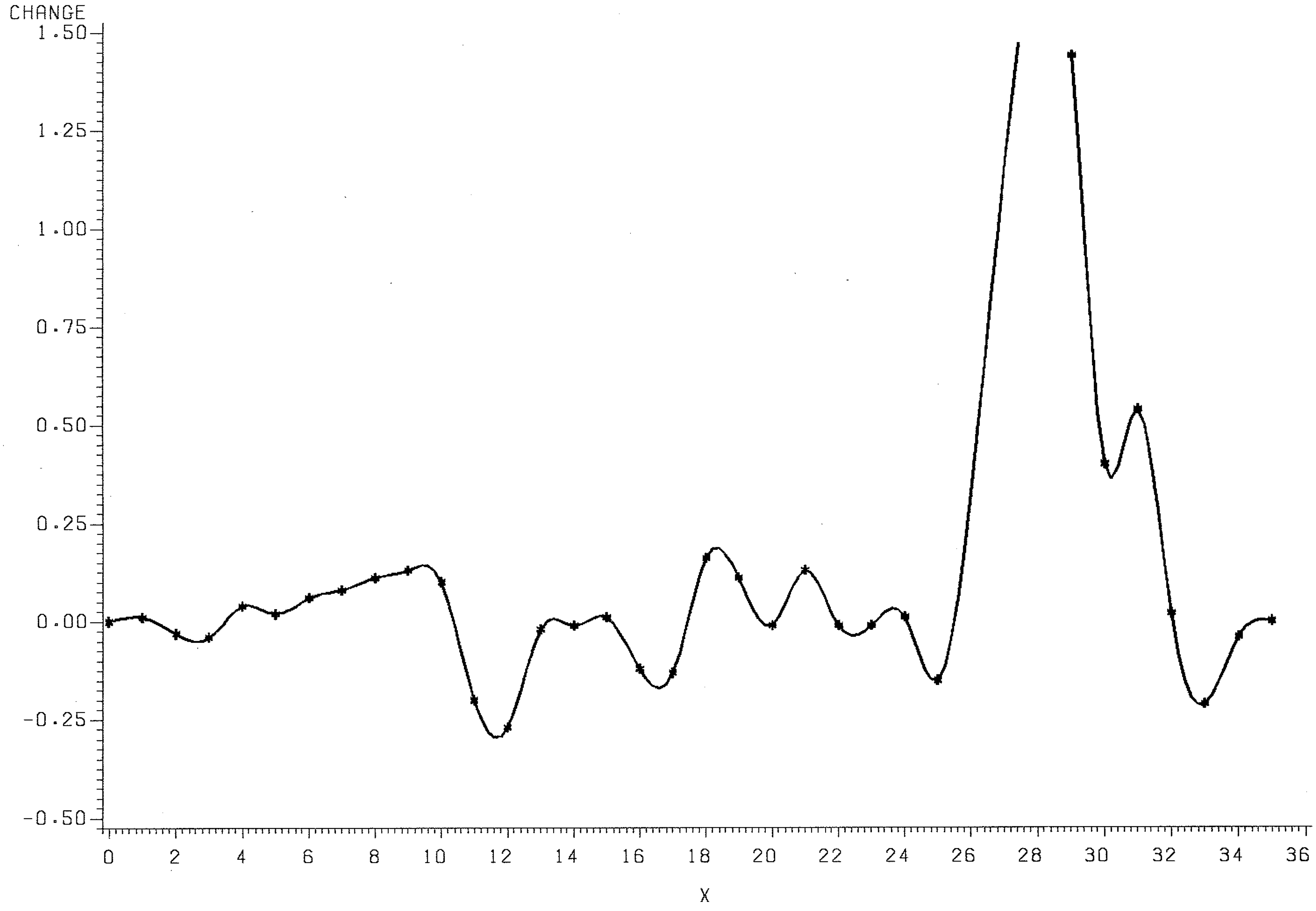
GRAVEL CREEK CHANNEL CHANGE B-1d(post breakup to postflood 1982)



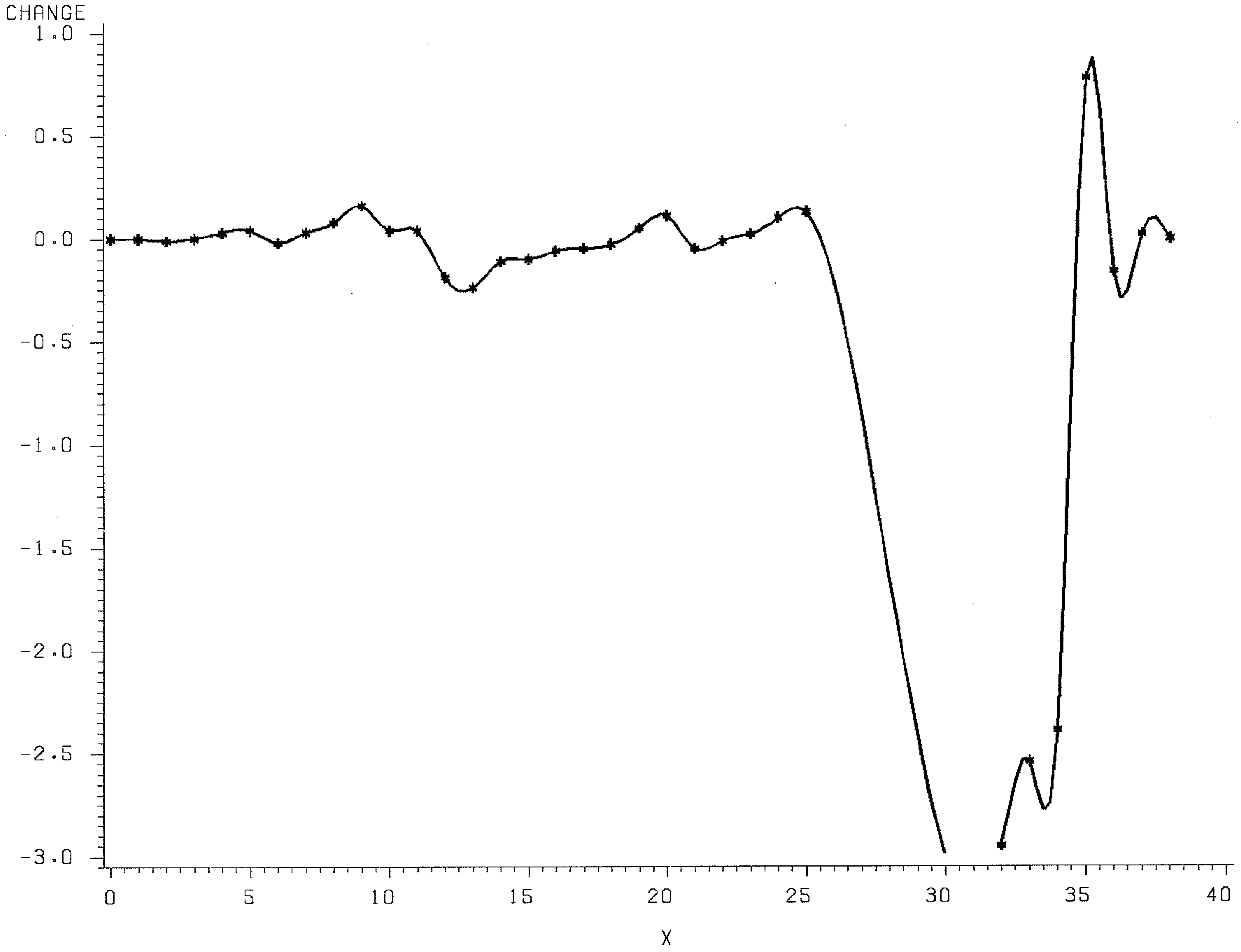
GRAVEL CREEK CHANNEL CHANGE B-18e(post breakup to postflood 1982)

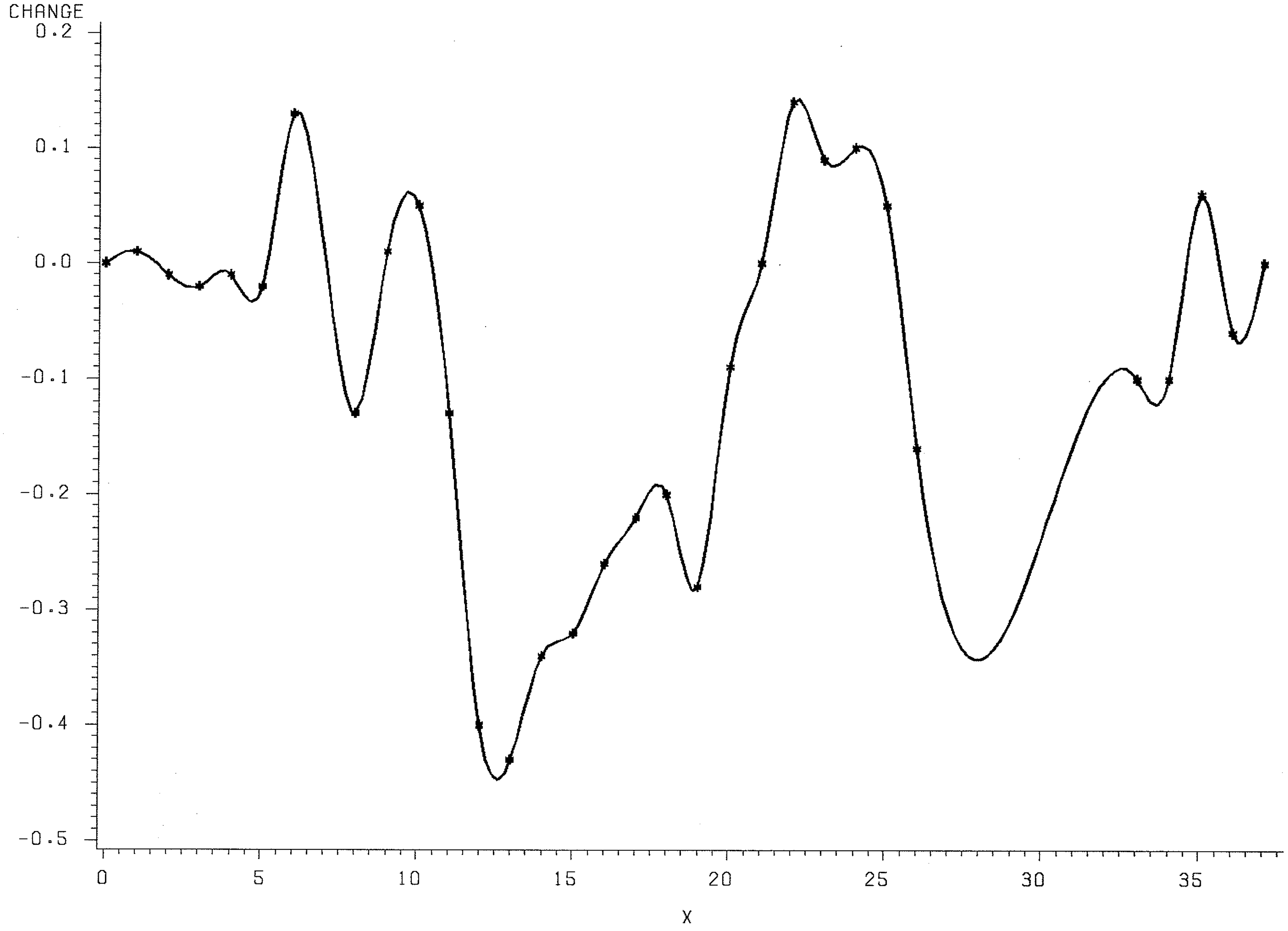


GRAVEL CREEK CHANNEL CHANGE B-18f(post breakup to postflood 1982)



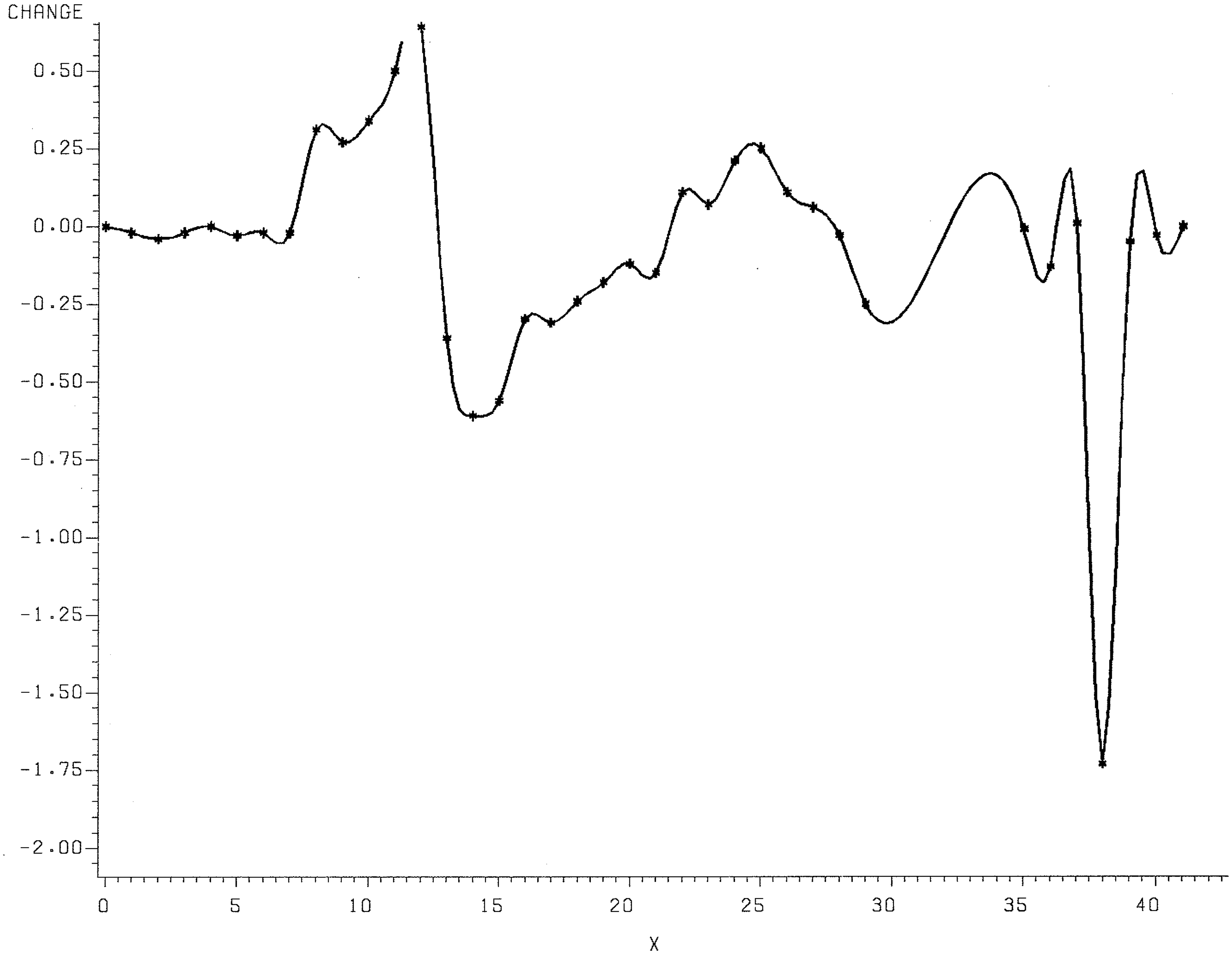
GRAVEL CREEK CHANNEL CHANGE B–18g(post breakup to postflood 1982)



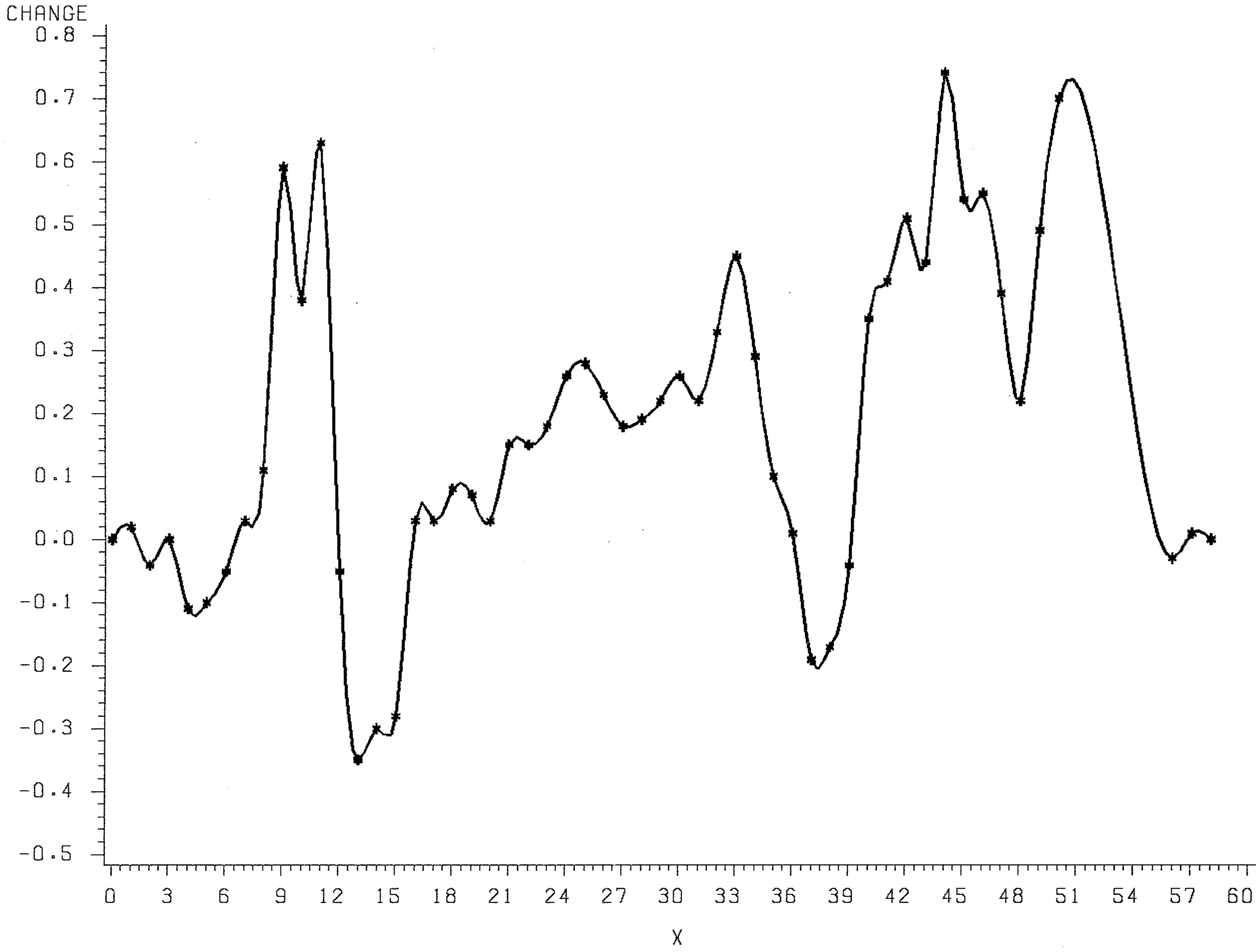


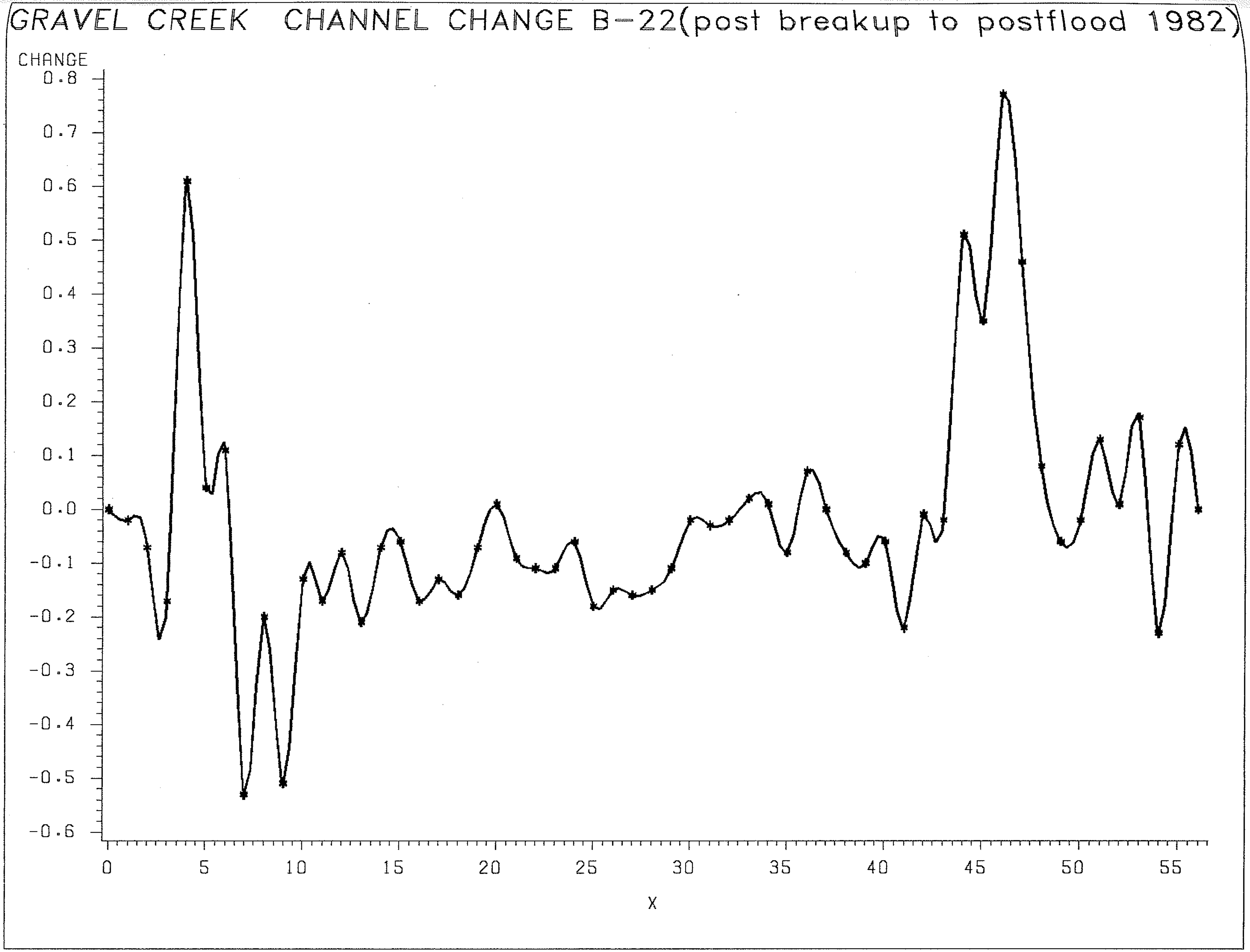
GRAVEL CREEK CHANNEL CHANGE B-19(post breakup to postflood 1982)

GRAVEL CREEK CHANNEL CHANGE B-20(post breakup to postflood 1982)



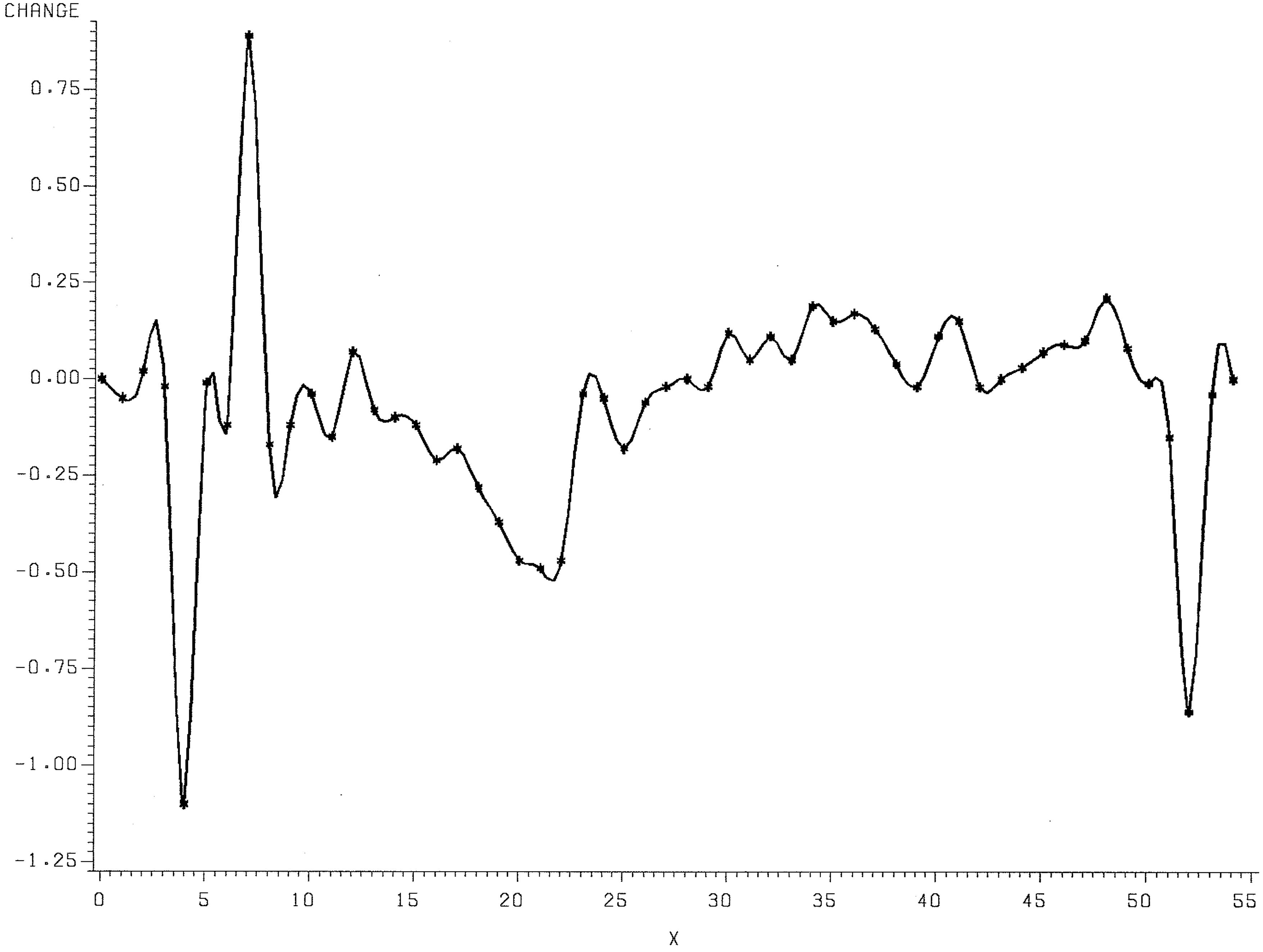
GRAVEL CREEK CHANNEL CHANGE B-21(post breakup to postflood 1982)



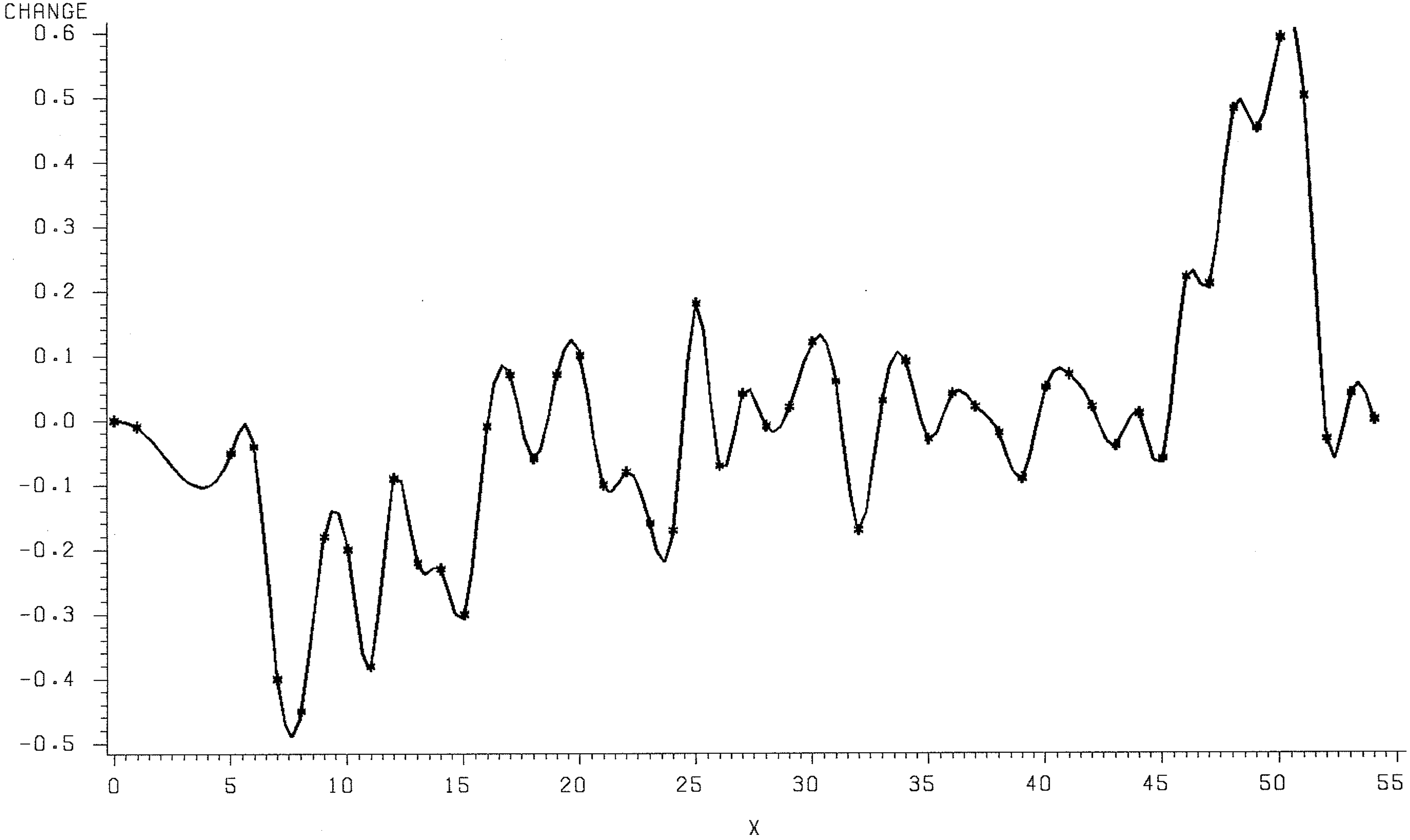


GRAVEL CREEK CHANNEL CHANGE B-22(post breakup to postflood 1982)

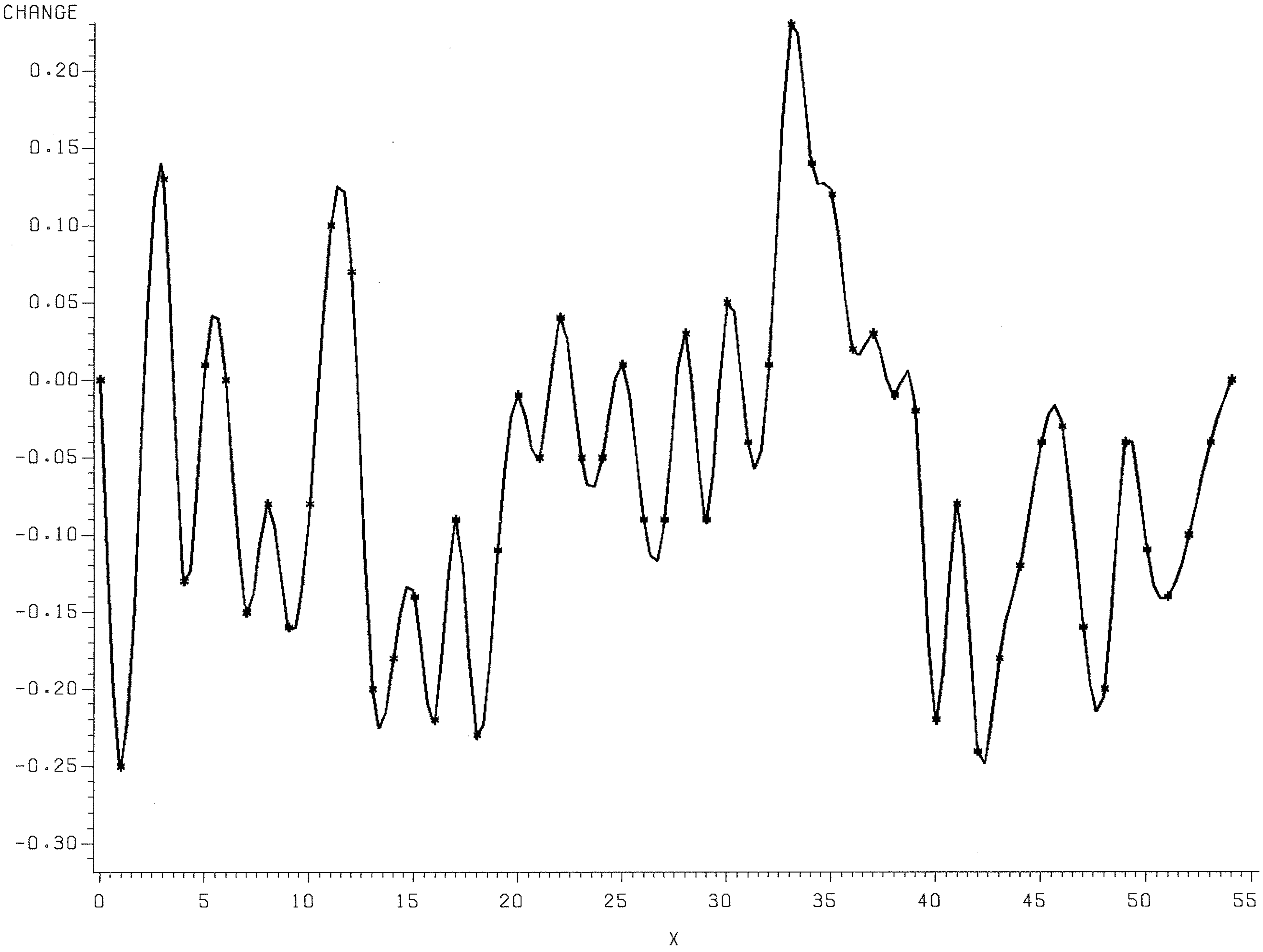
GRAVEL CREEK CHANNEL CHANGE B-23(post breakup to postflood 1982)

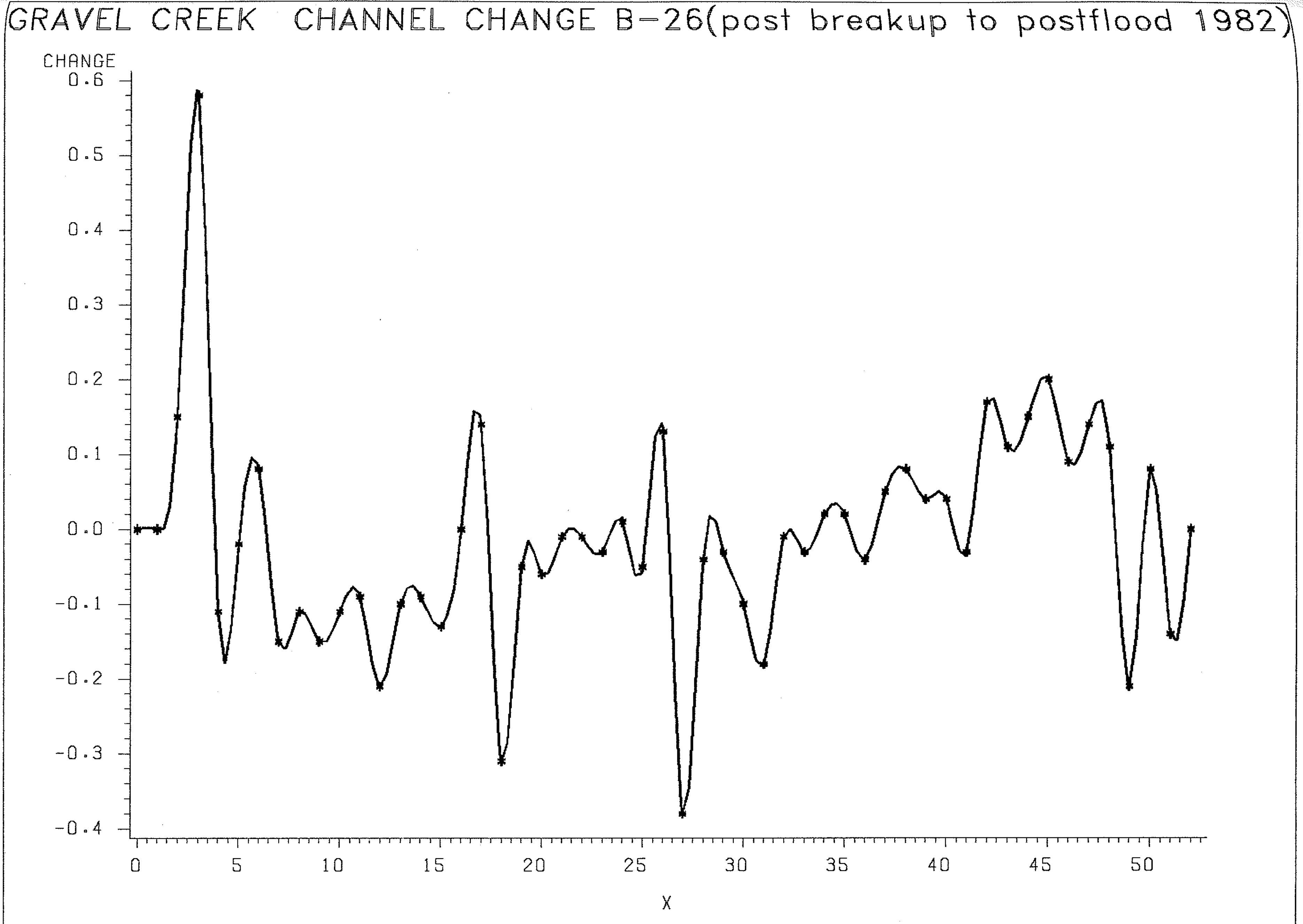


GRAVEL CREEK CHANNEL CHANGE B-24(post breakup to postflood 1982)

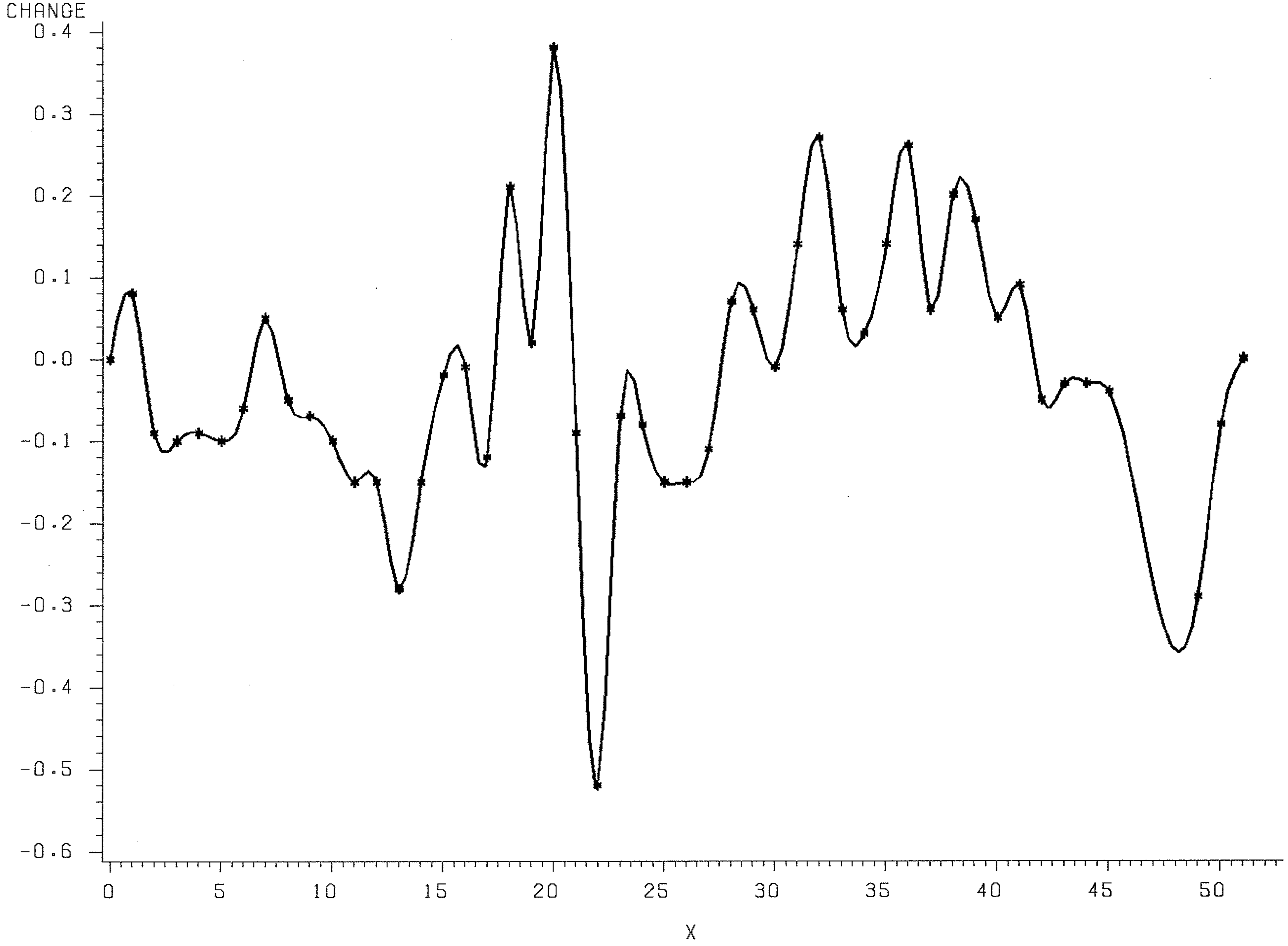


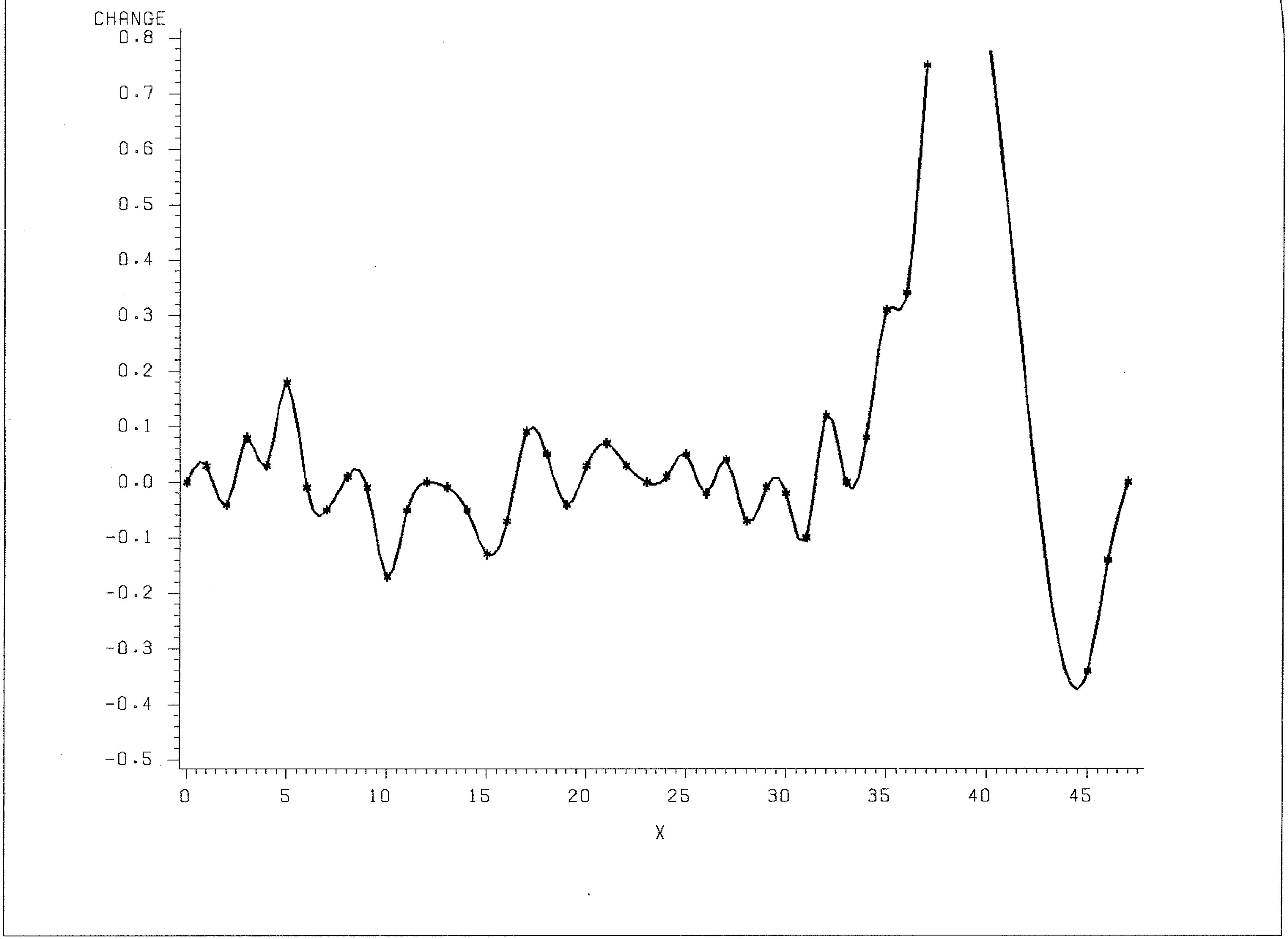
GRAVEL CREEK CHANNEL CHANGE B-25(post breakup to postflood 1982)



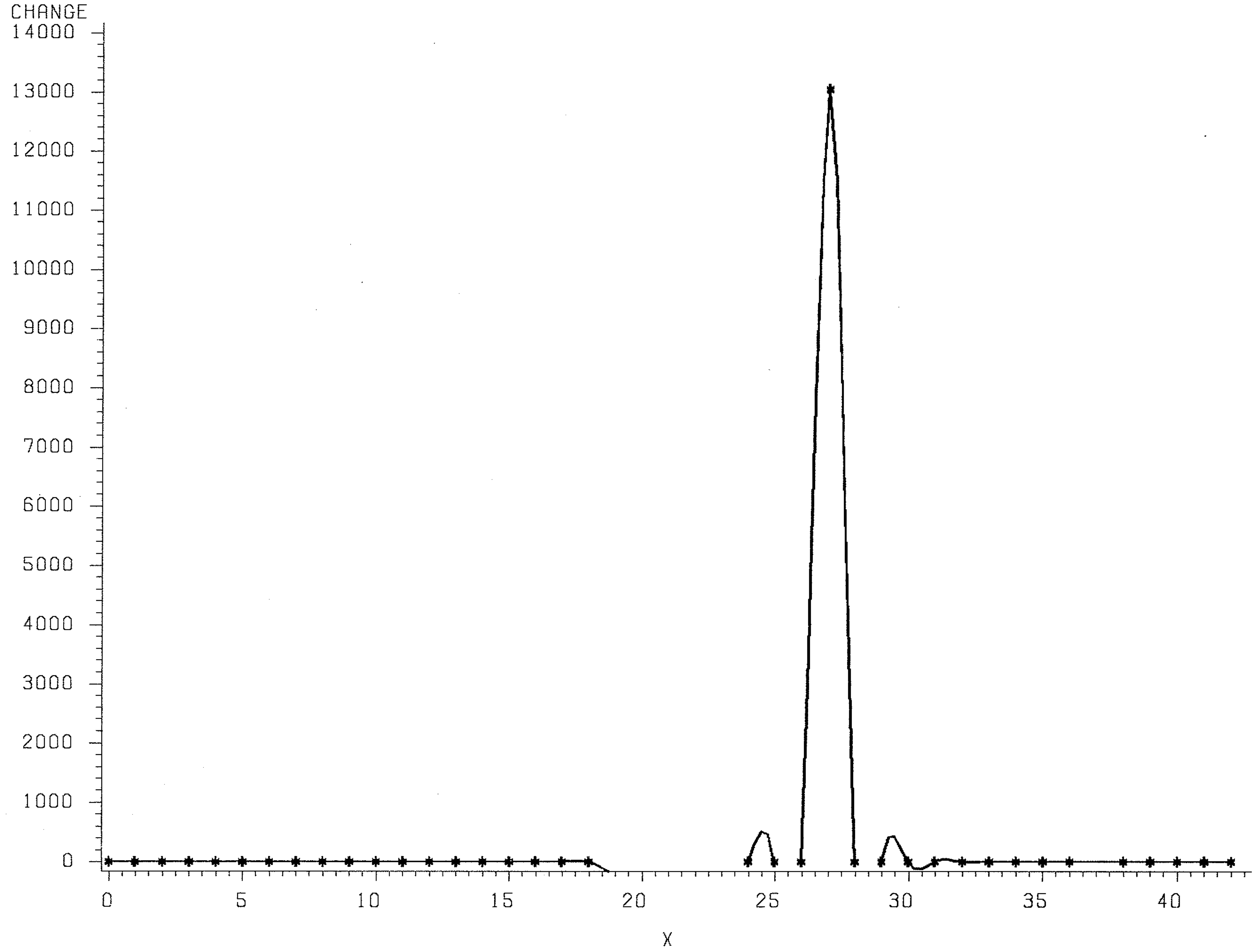

GRAVEL CREEK CHANNEL CHANGE B-26(post breakup to postflood 1982)
CHANGE
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0
5
10
15
20
25
30
35
40
45
50
X

GRAVEL CREEK CHANNEL CHANGE B-27(post breakup to postflood 1982)

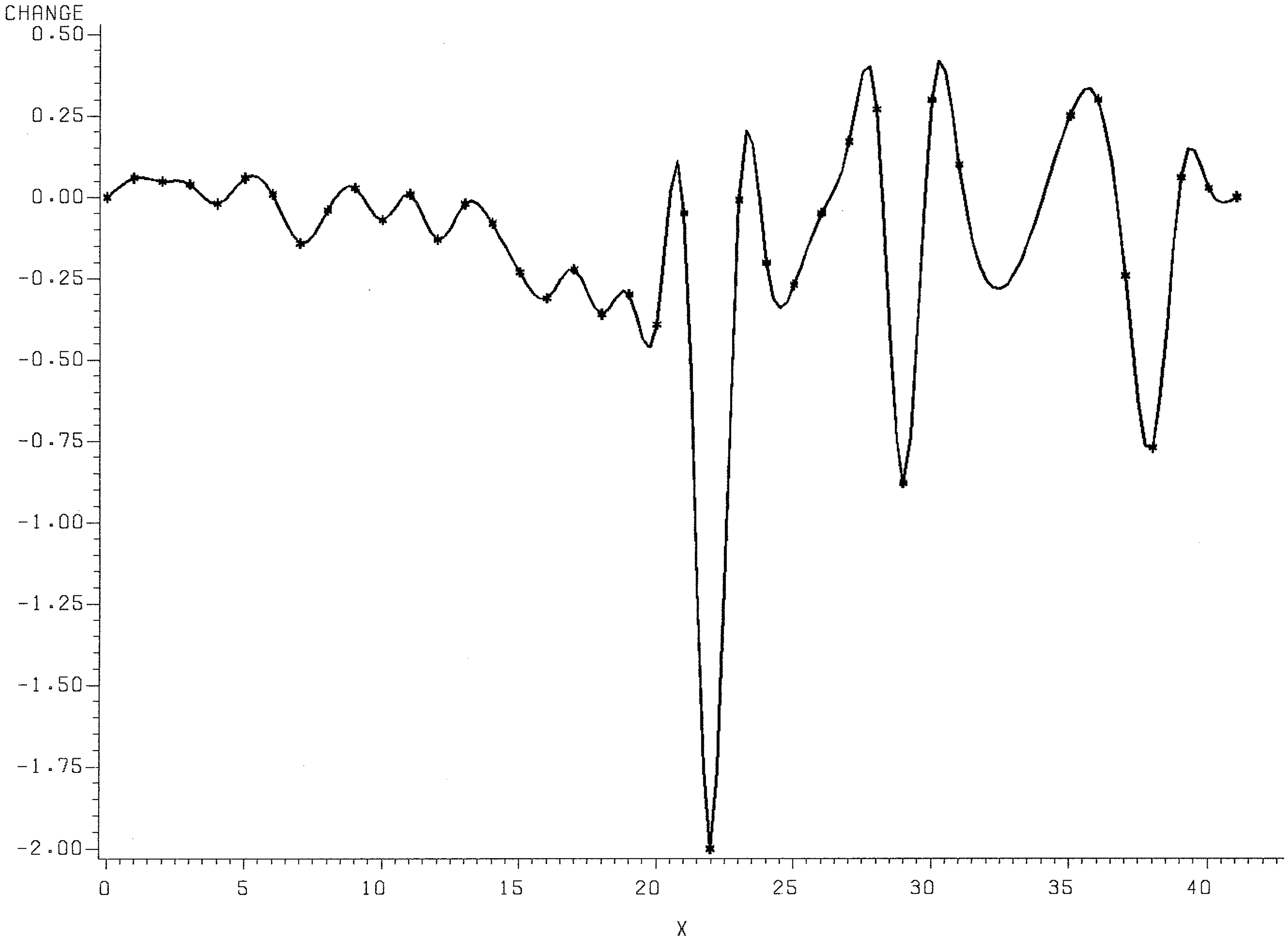



GRAVEL CREEK CHANNEL CHANGE B-28(post breakup to postflood 1982)

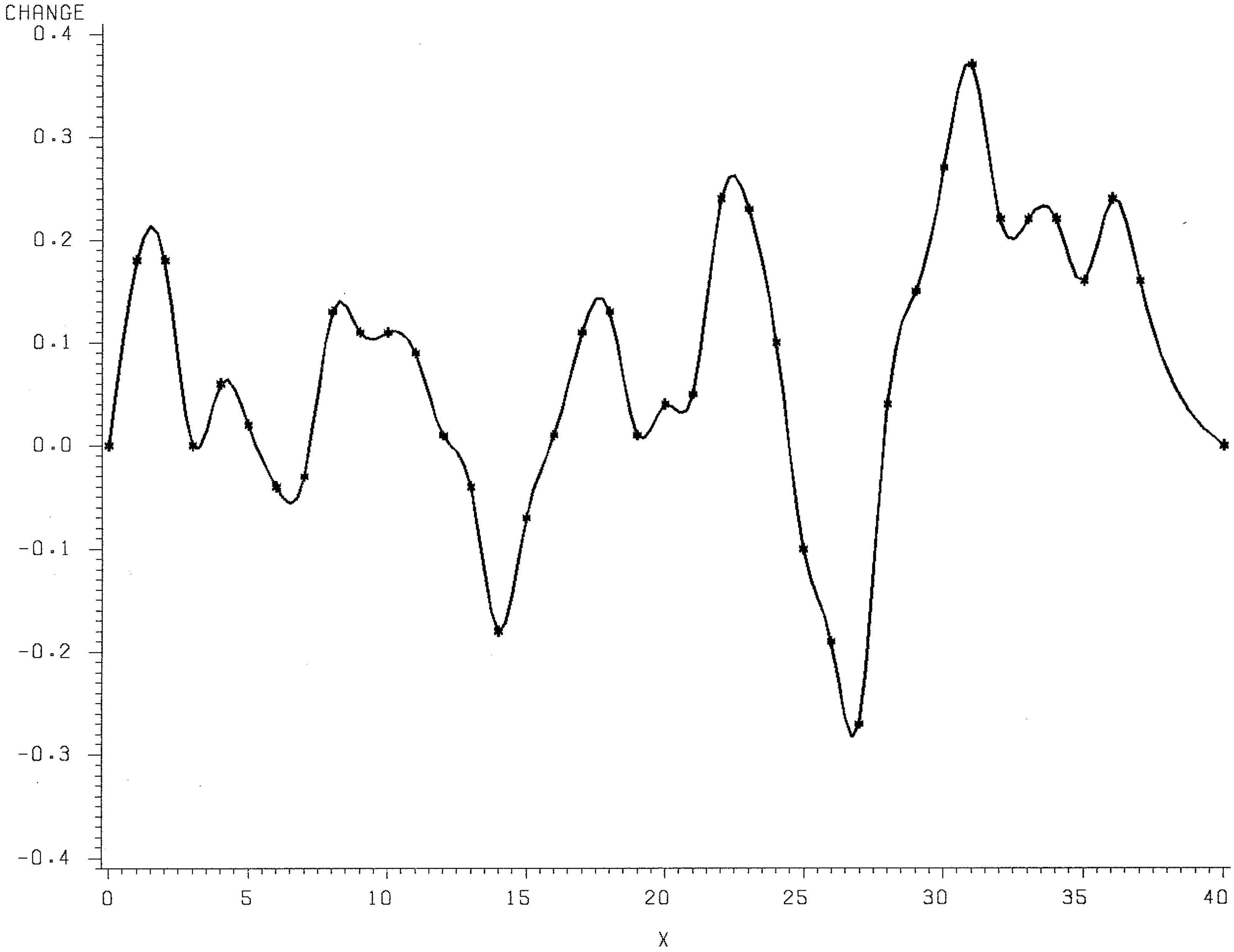
GRAVEL CREEK CHANNEL CHANGE B-29(post breakup to postflood 1982)



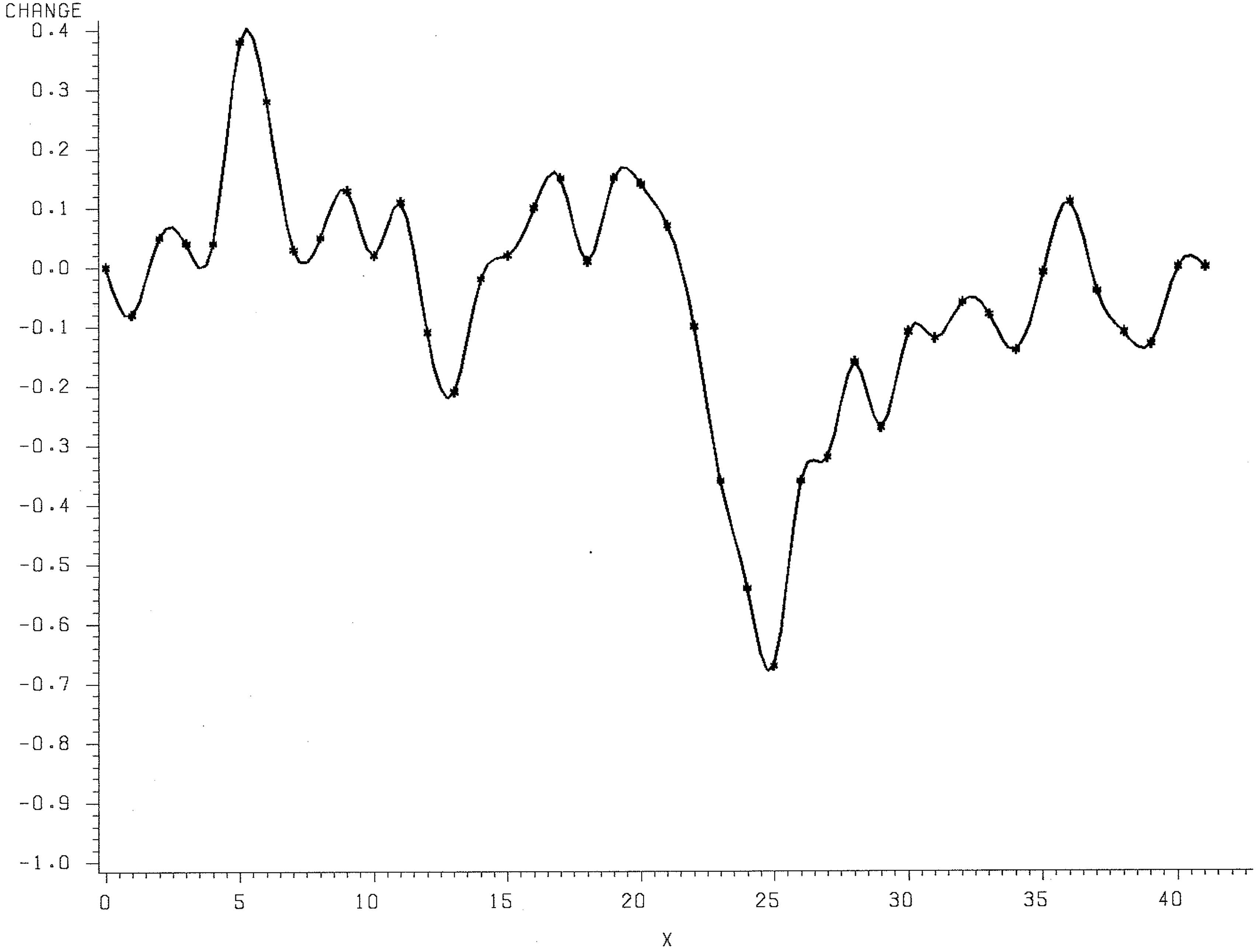
GRAVEL CREEK CHANNEL CHANGE B-30(post breakup to postflood 1982)



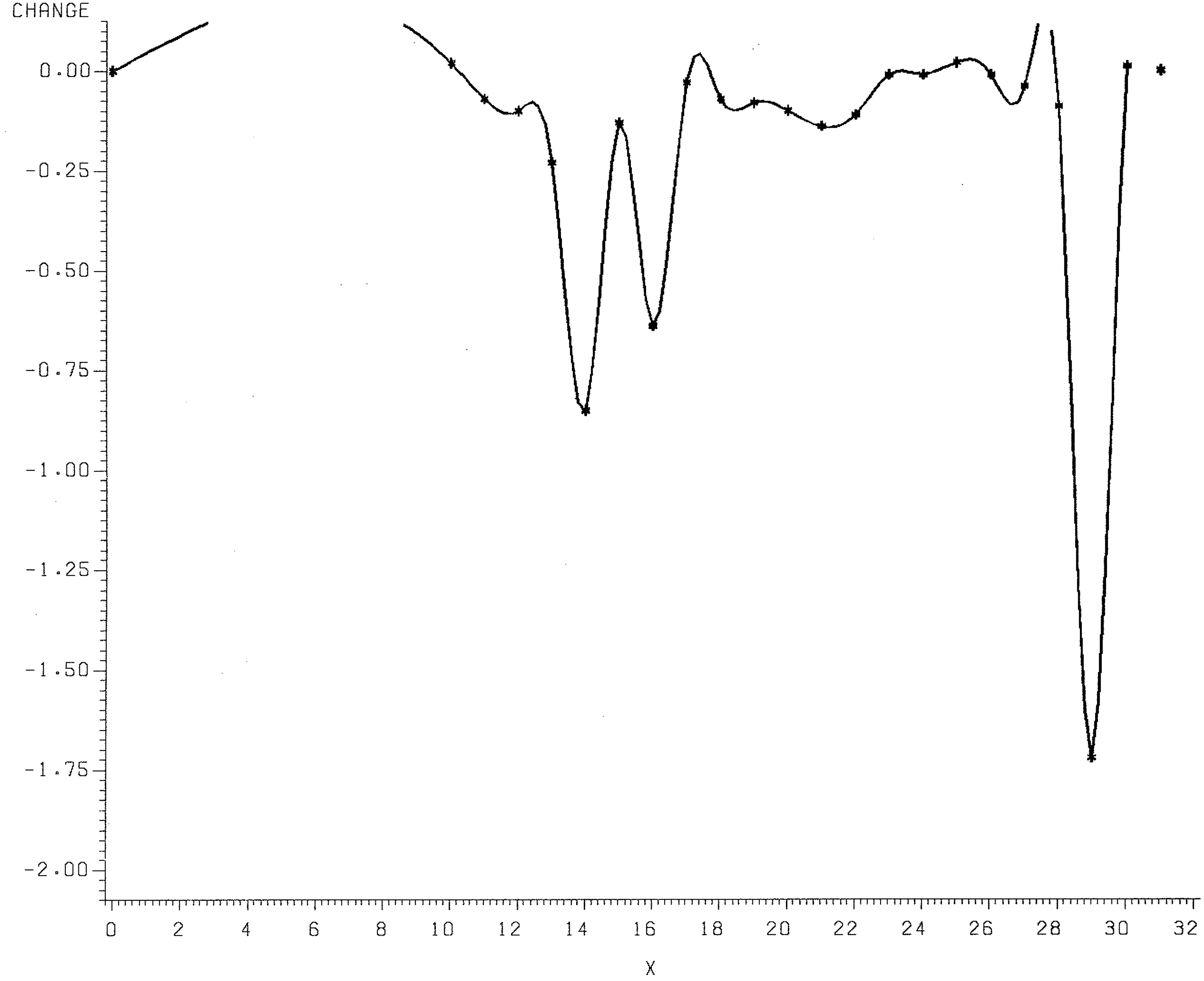
GRAVEL CREEK CHANNEL CHANGE B-31(post breakup to postflood 1982)



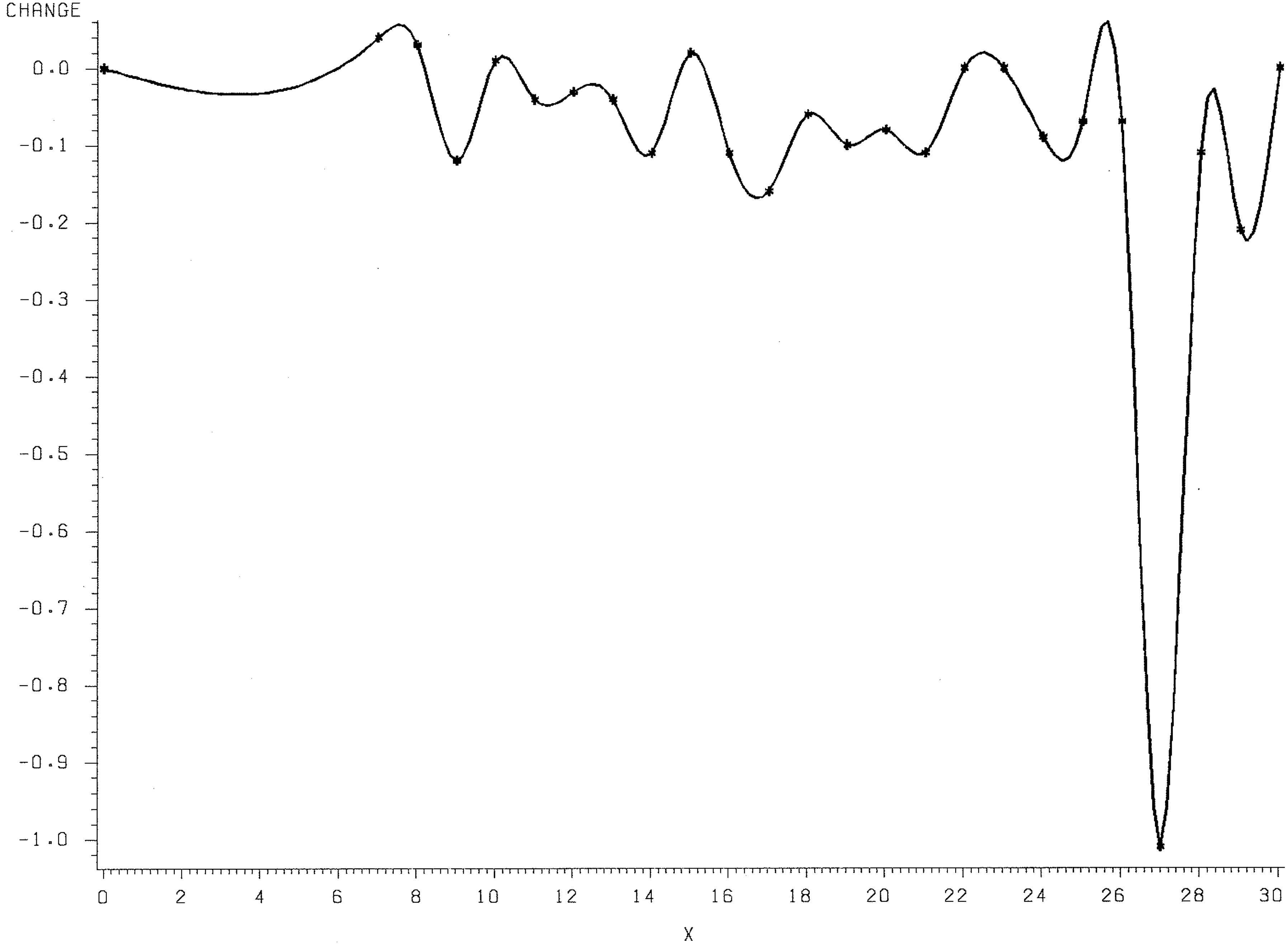
GRAVEL CREEK CHANNEL CHANGE B-32(post breakup to postflood 1982)



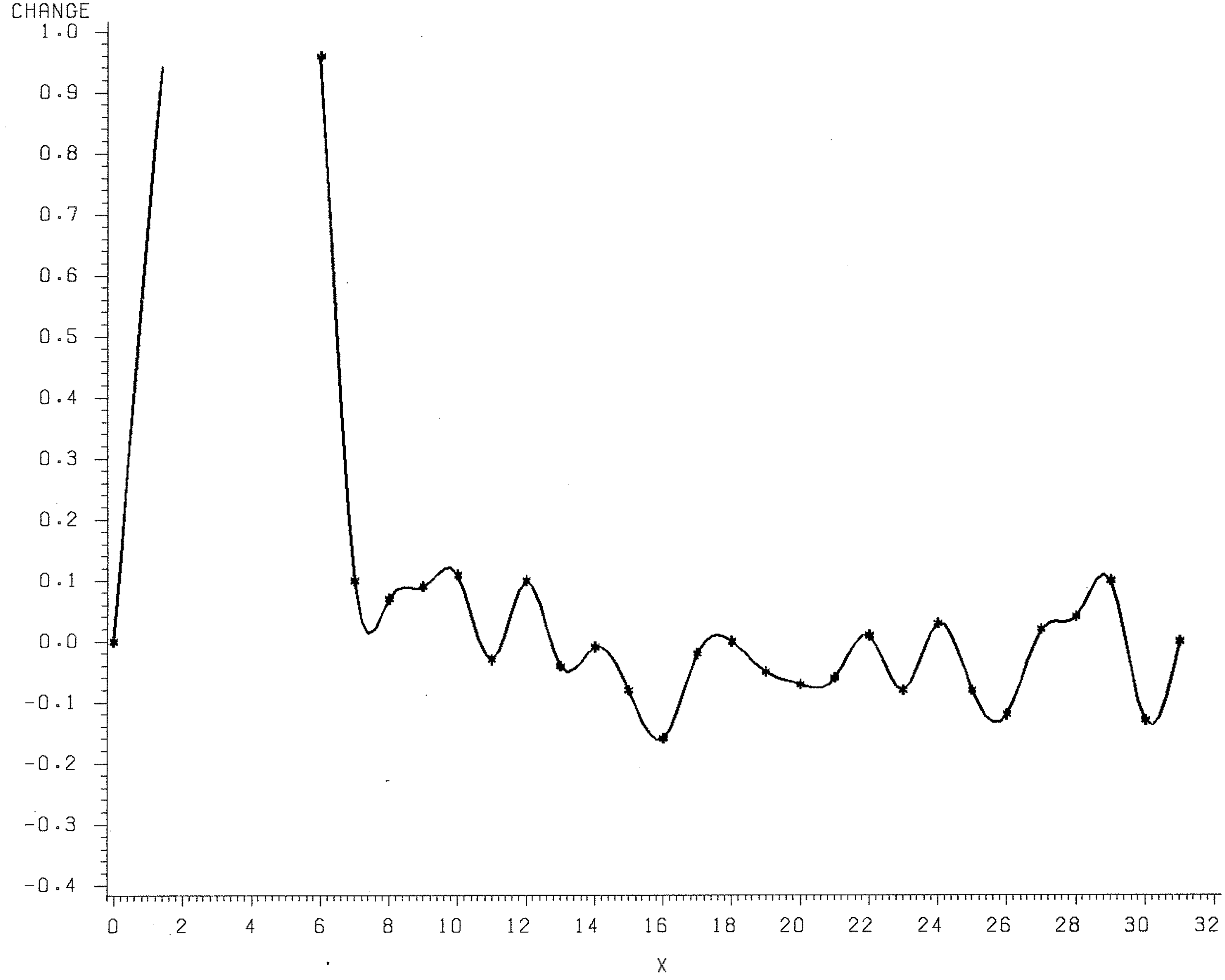
GRAVEL CREEK CHANNEL CHANGE B-1(June 1982 to May 1983)



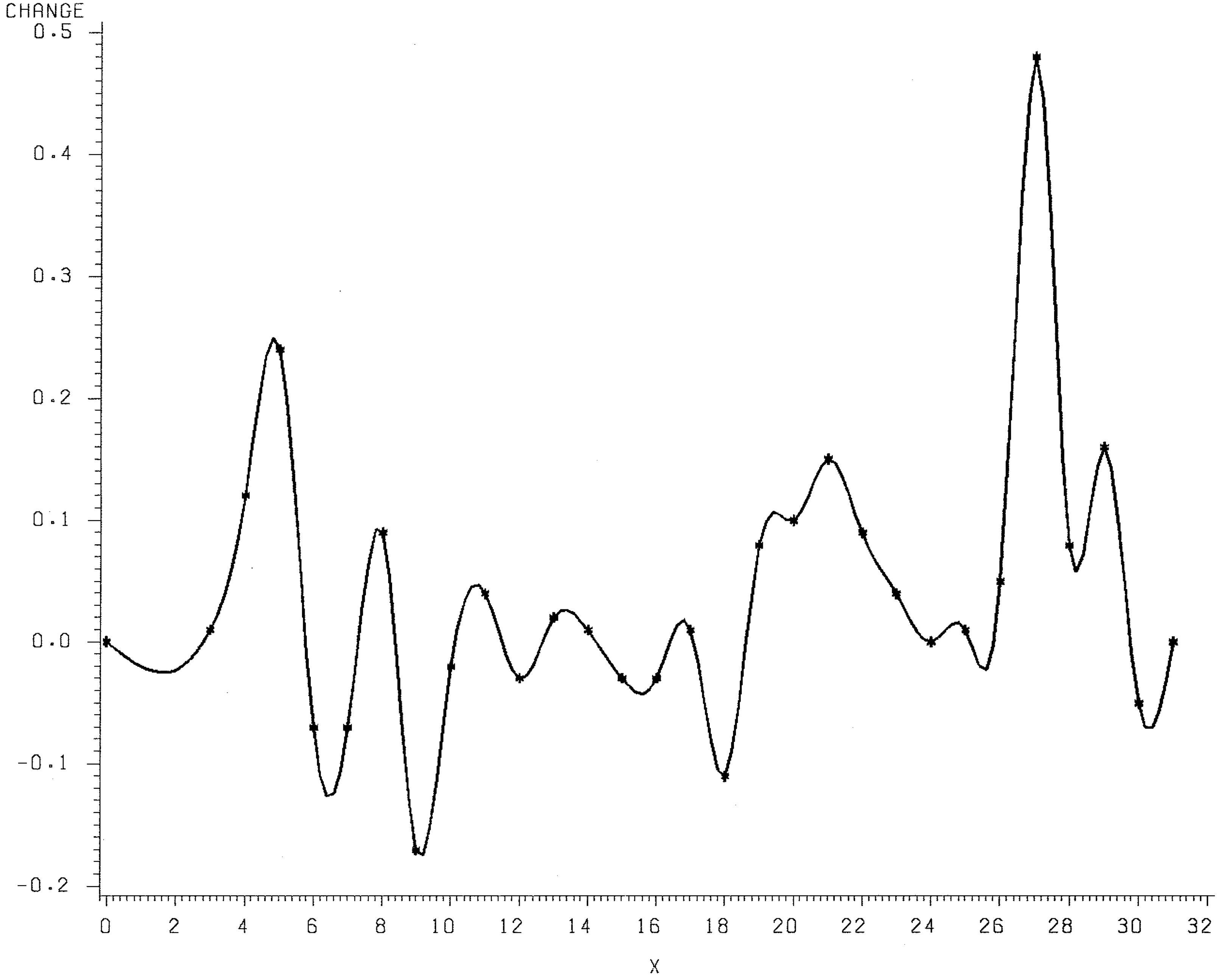
GRAVEL CREEK CHANNEL CHANGE B-2(June 1982 to May 1983)



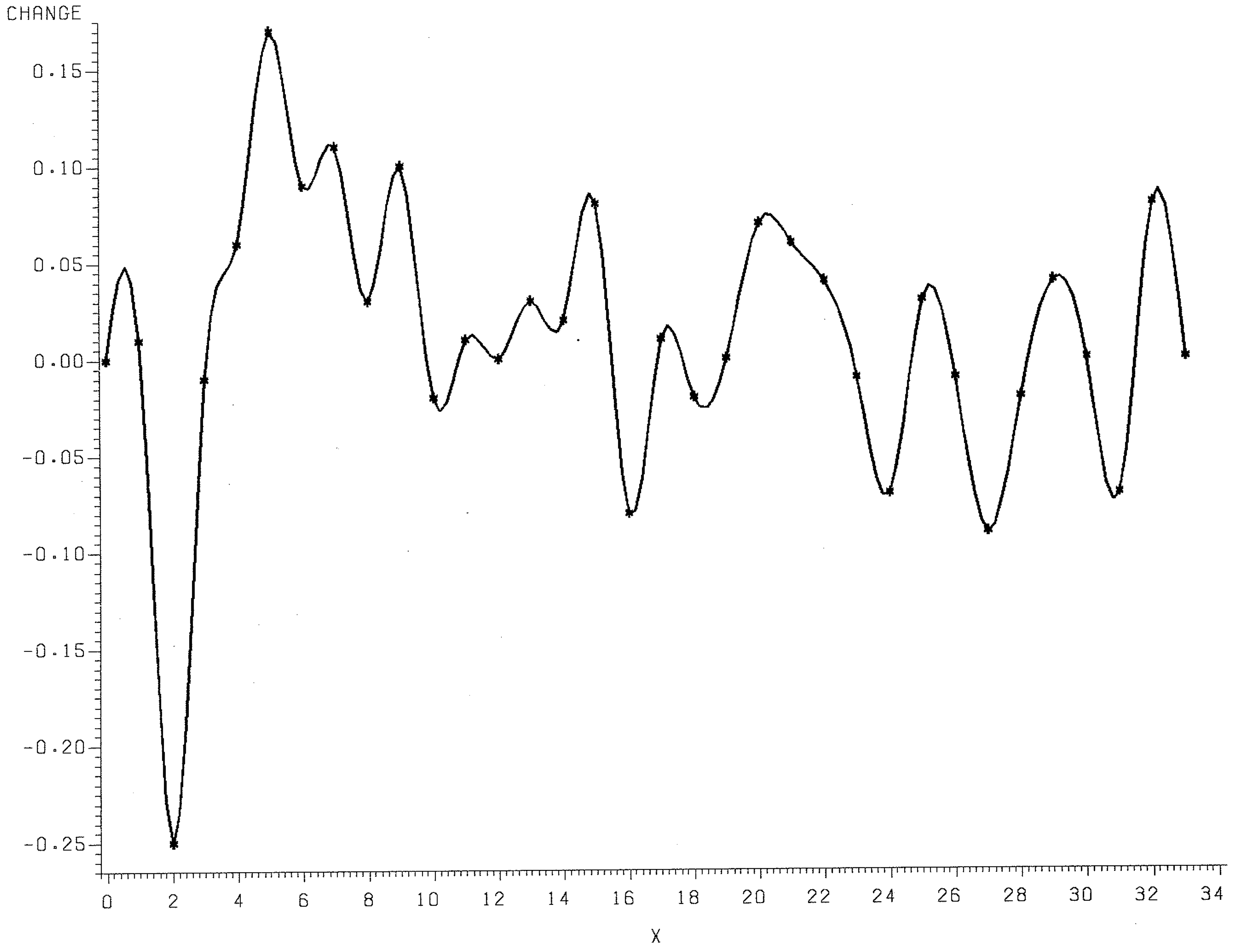
GRAVEL CREEK CHANNEL CHANGE B-3(June 1982 to May 1983)



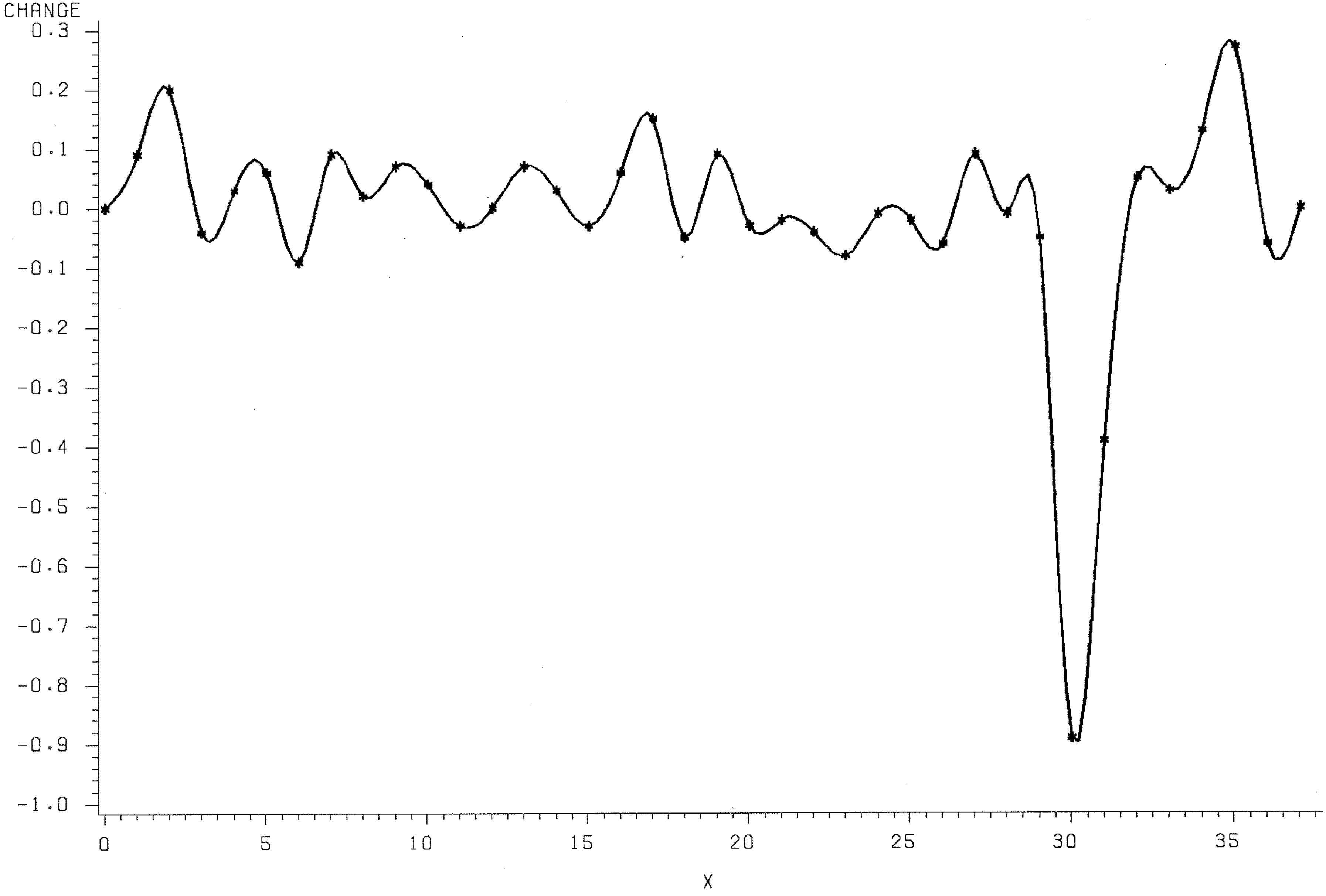
GRAVEL CREEK CHANNEL CHANGE B-4(June 1982 to May 1983)



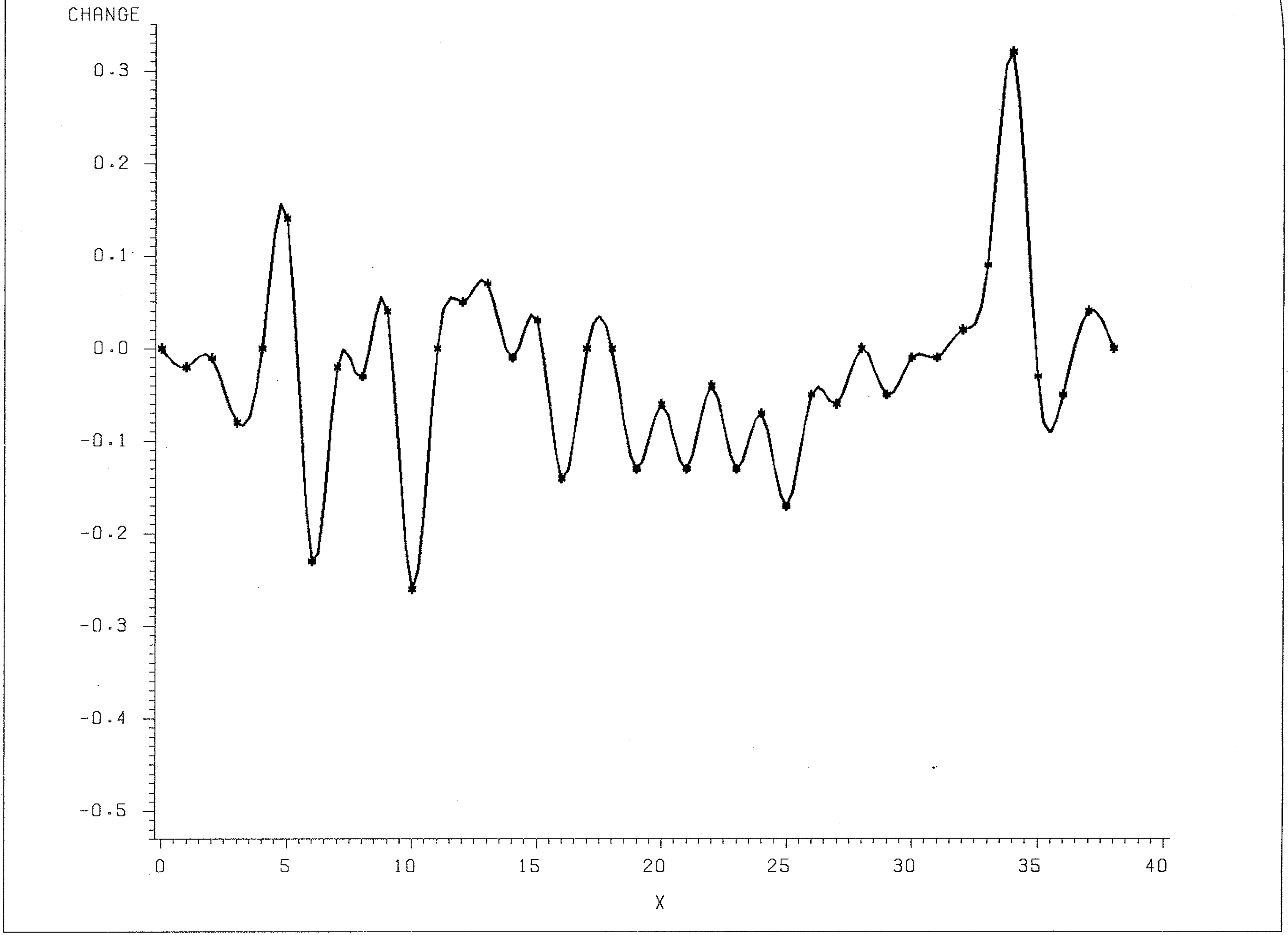
GRAVEL CREEK CHANNEL CHANGE B-5(June 1982 to May 1983)



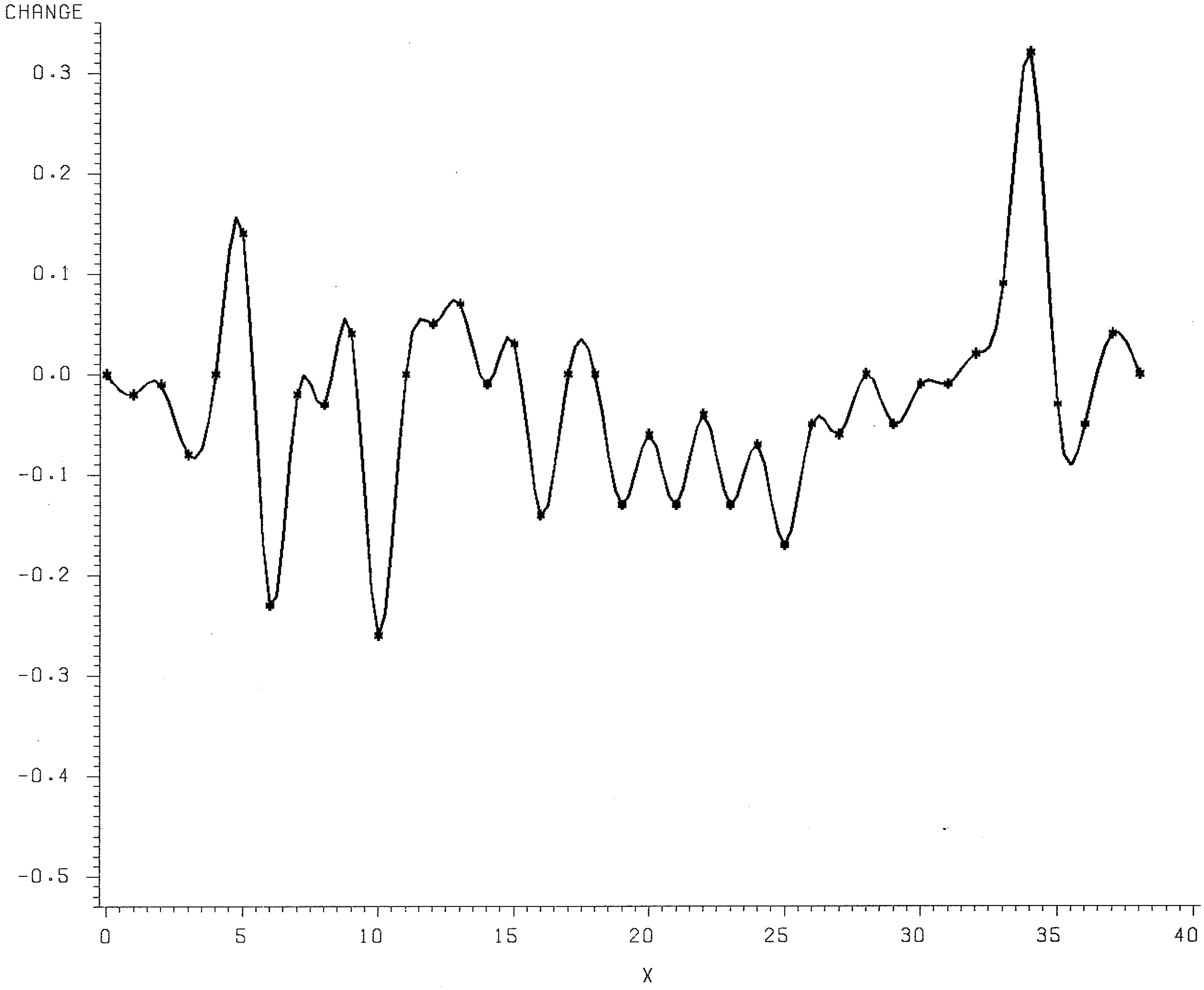
GRAVEL CREEK CHANNEL CHANGE B-6(June 1982 to May 1983)

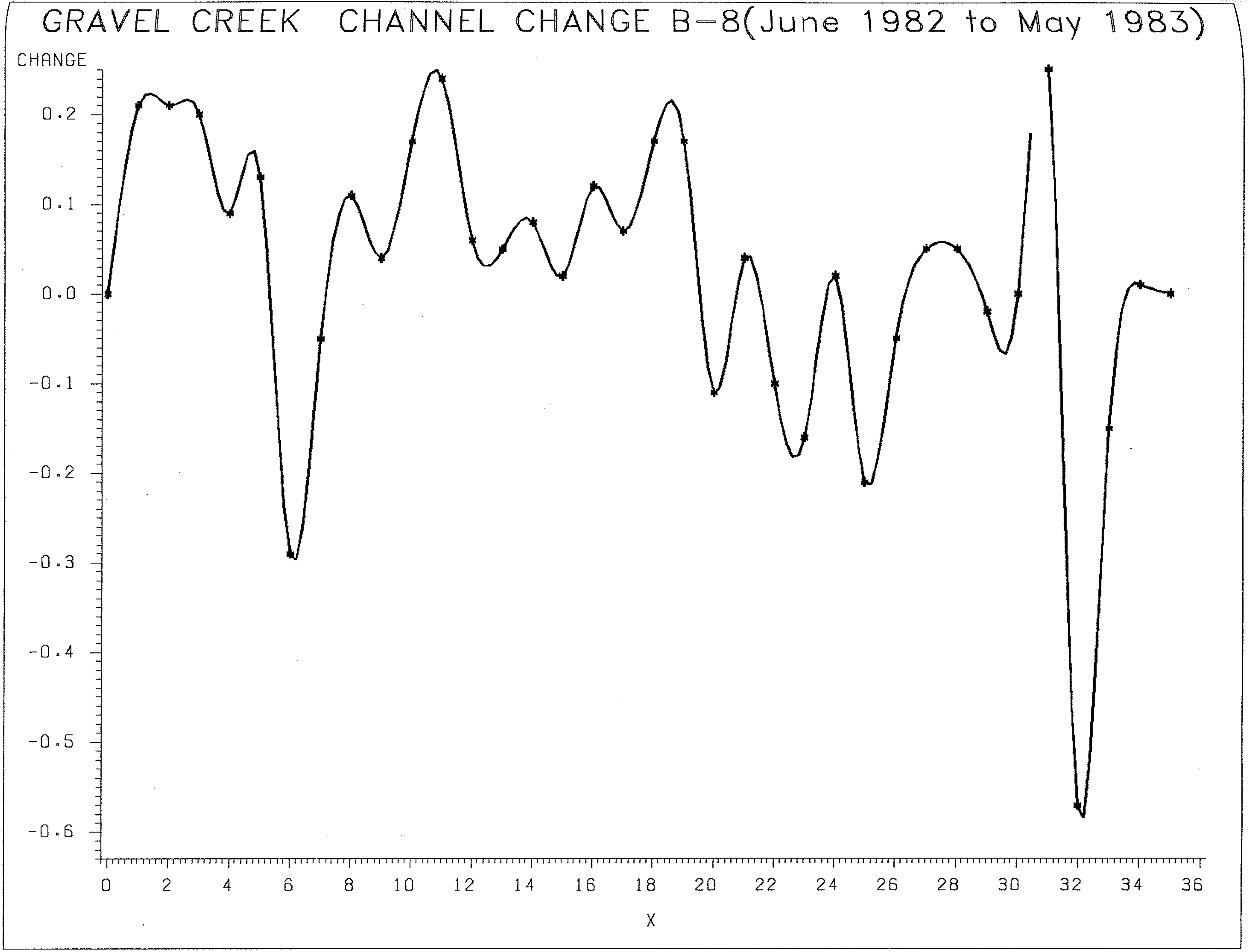


GRAVEL CREEK CHANNEL CHANGE B-7(June 1982 to May 1983)

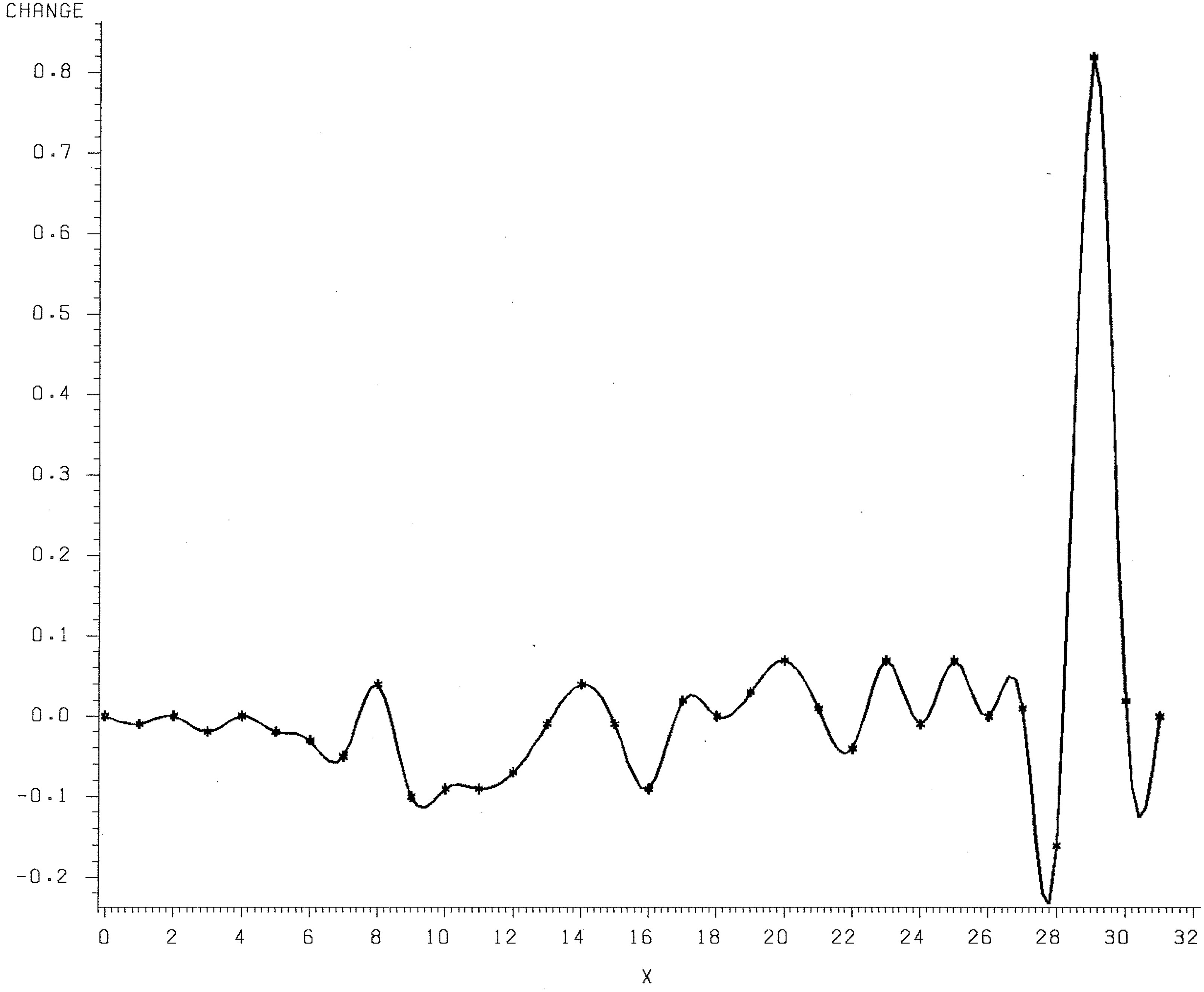


GRAVEL CREEK CHANNEL CHANGE B-7(June 1982 to May 1983)

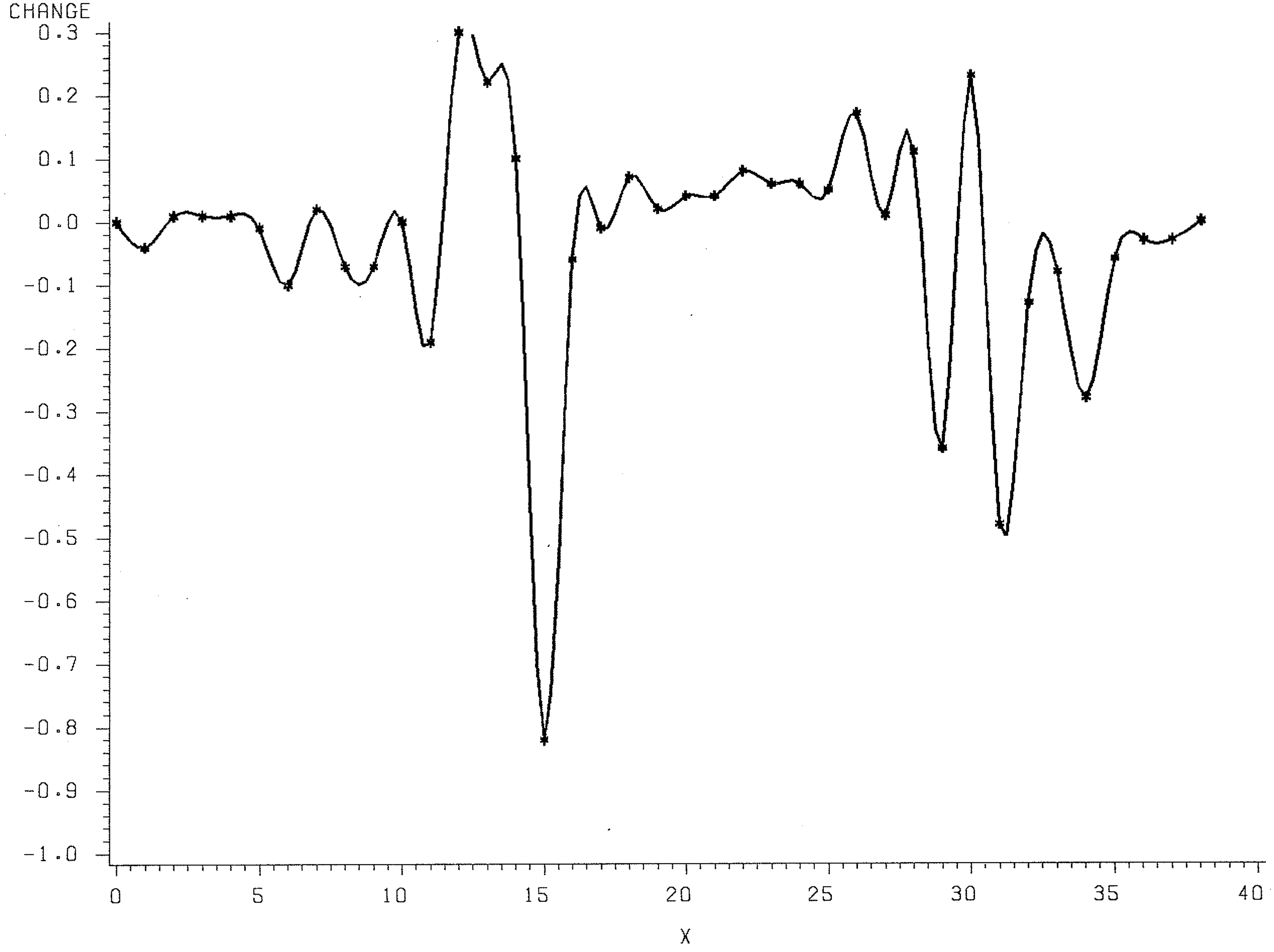


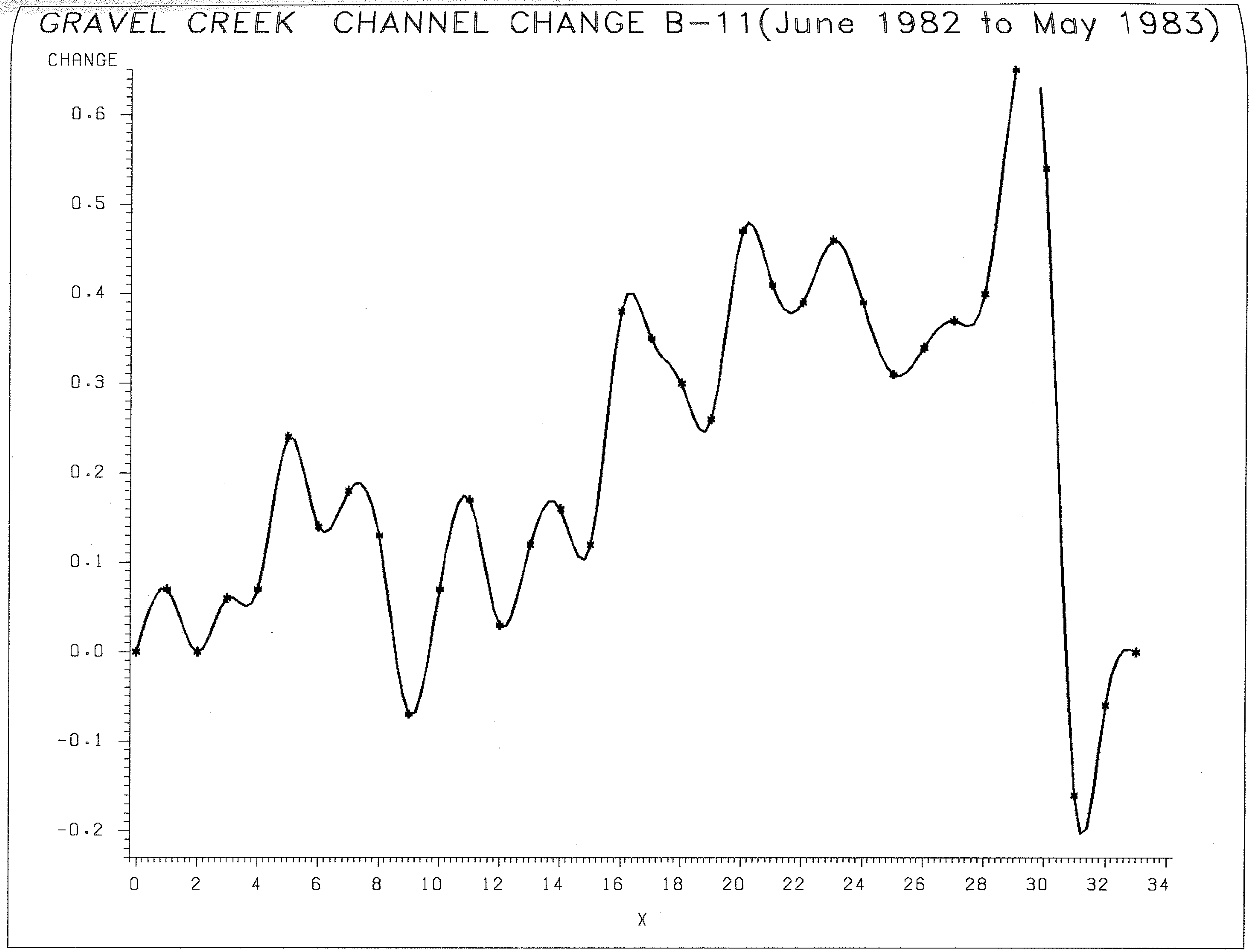

GRAVEL CREEK CHANNEL CHANGE B-8(June 1982 to May 1983)
CHANGE
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
X

GRAVEL CREEK CHANNEL CHANGE B-9(June 1982 to May 1983)

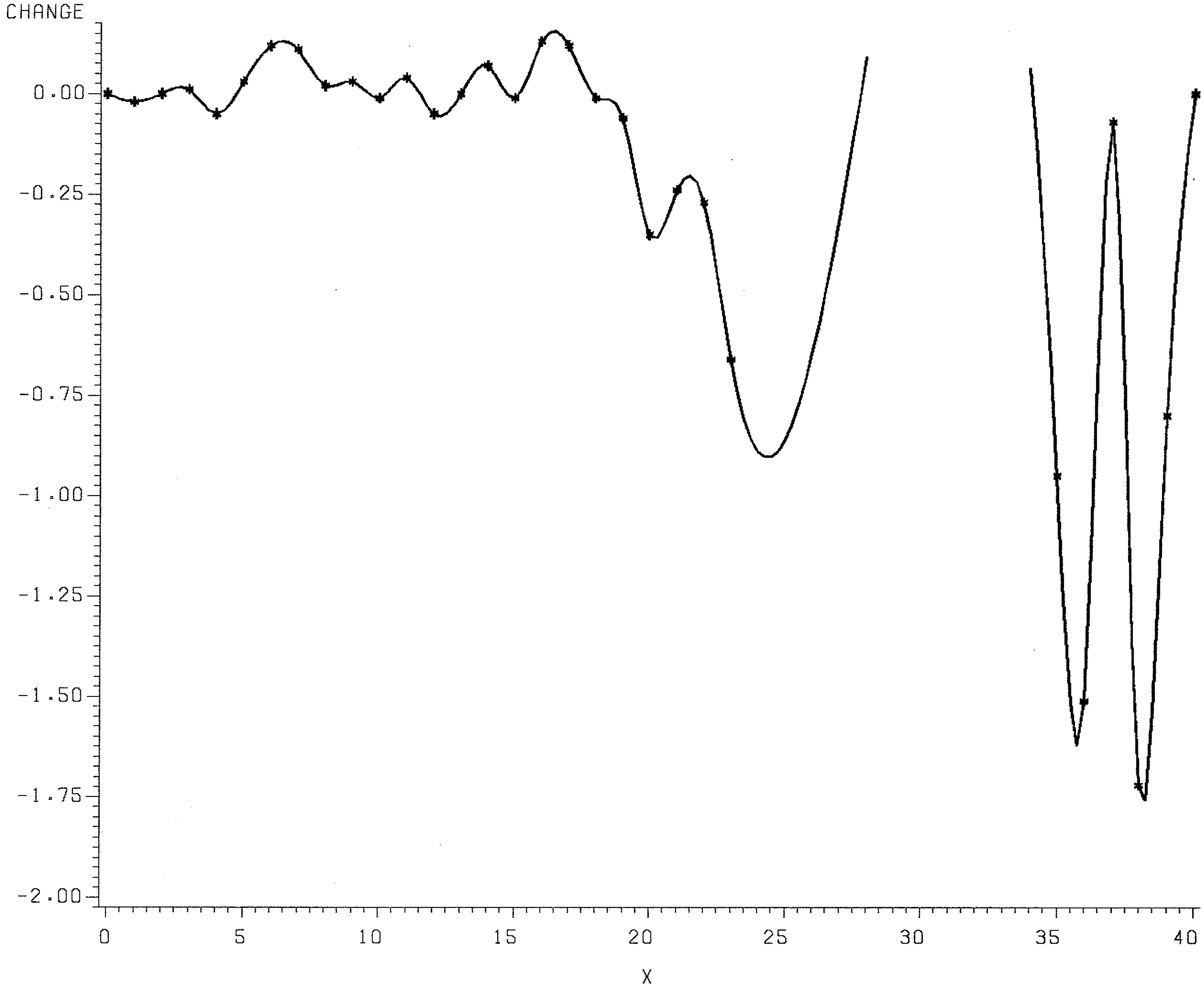


GRAVEL CREEK CHANNEL CHANGE B-10(June 1982 to May 1983)



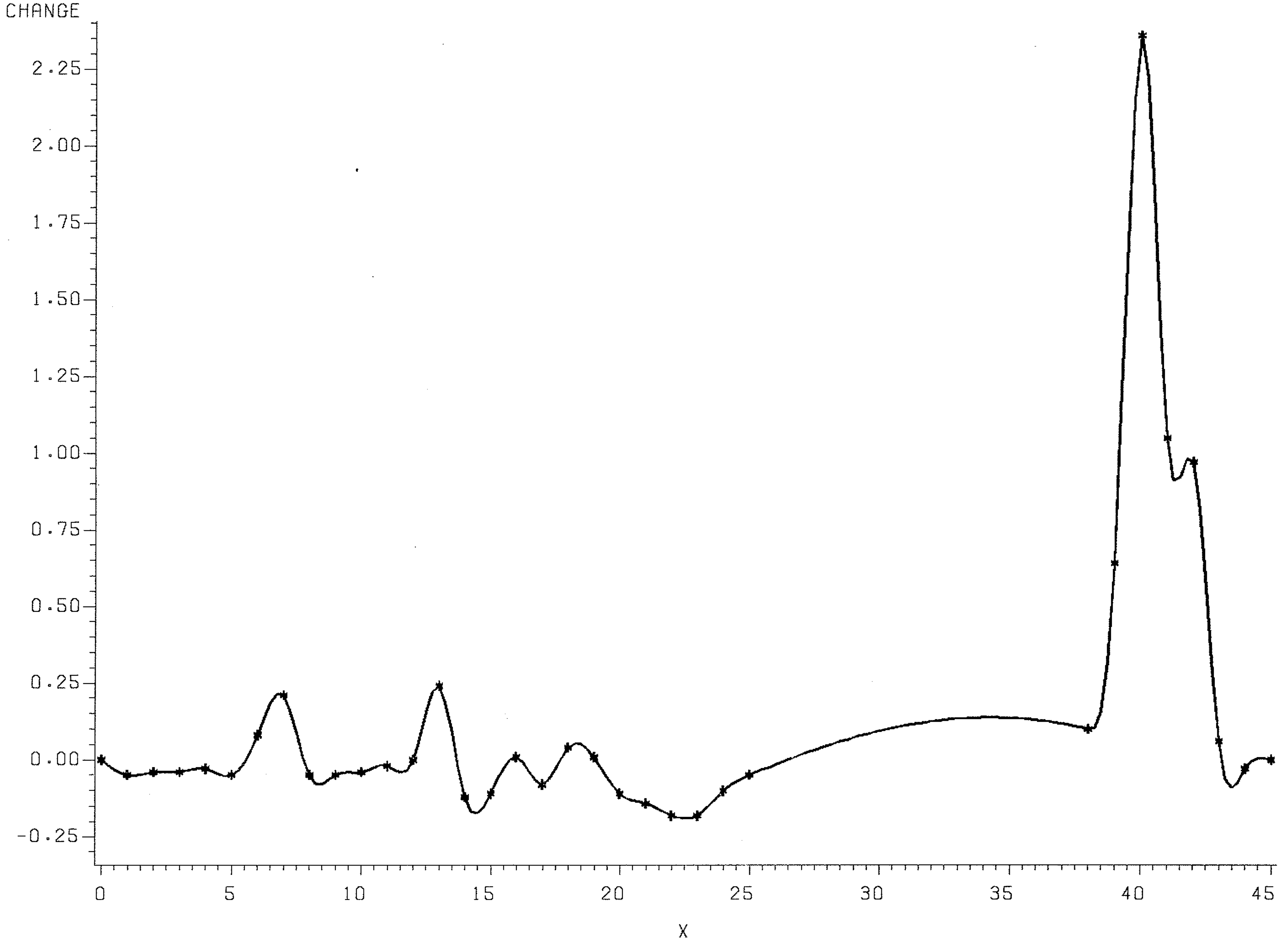


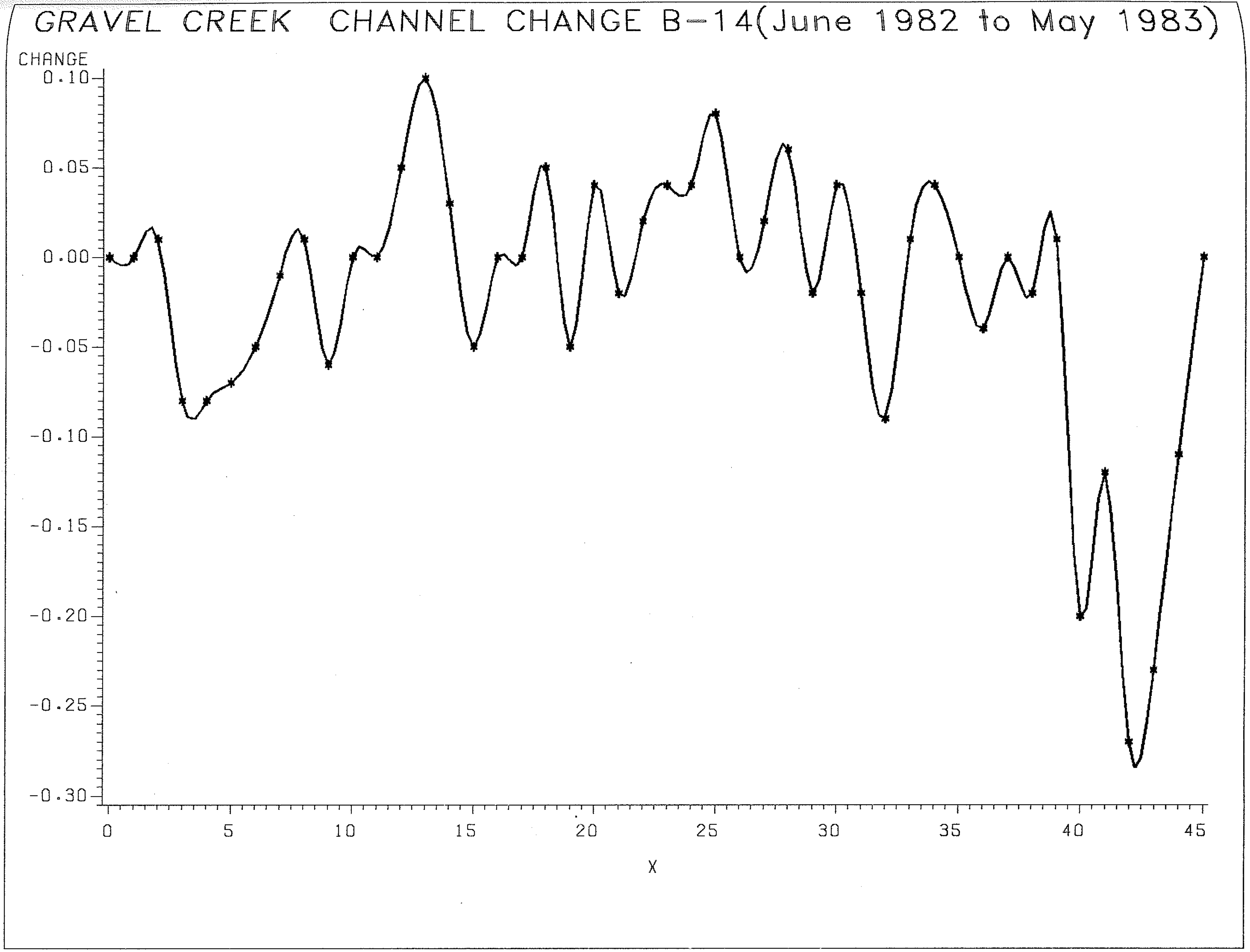
GRAVEL CREEK CHANNEL CHANGE B-11(June 1982 to May 1983)



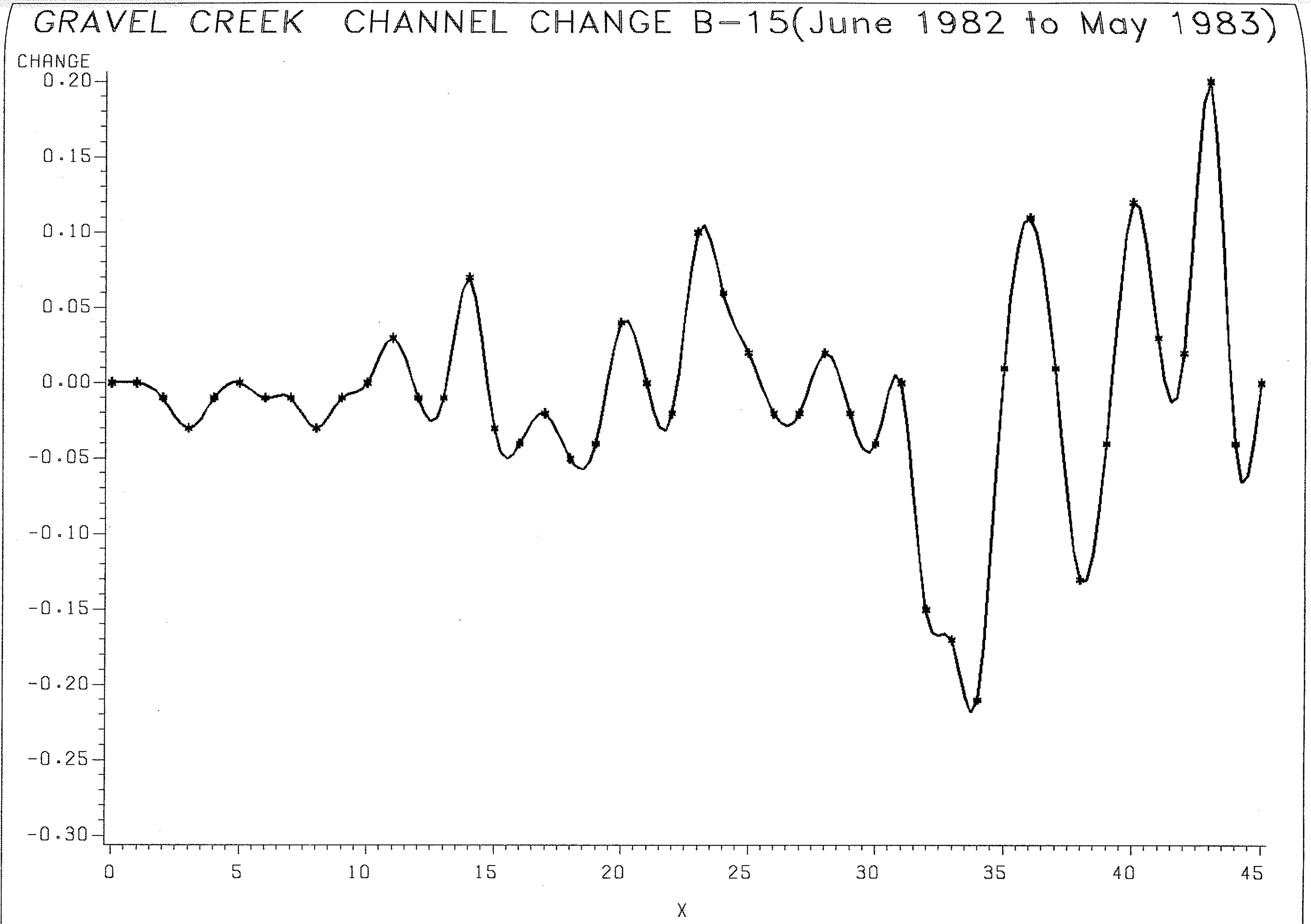
GRAVEL CREEK CHANNEL CHANGE B-12(June 1982 to May 1983)

GRAVEL CREEK CHANNEL CHANGE B-13(June 1982 to May 1983)

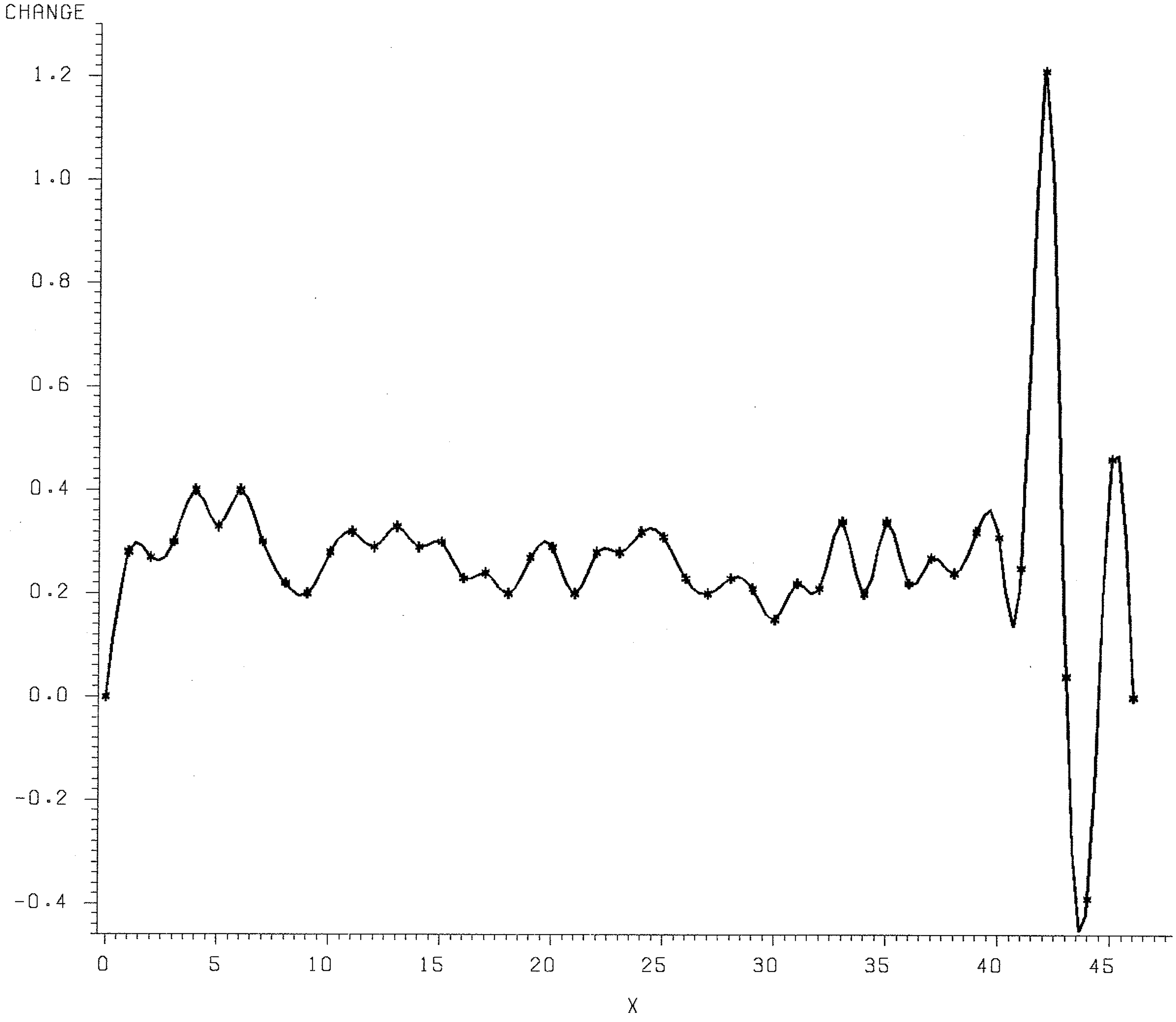




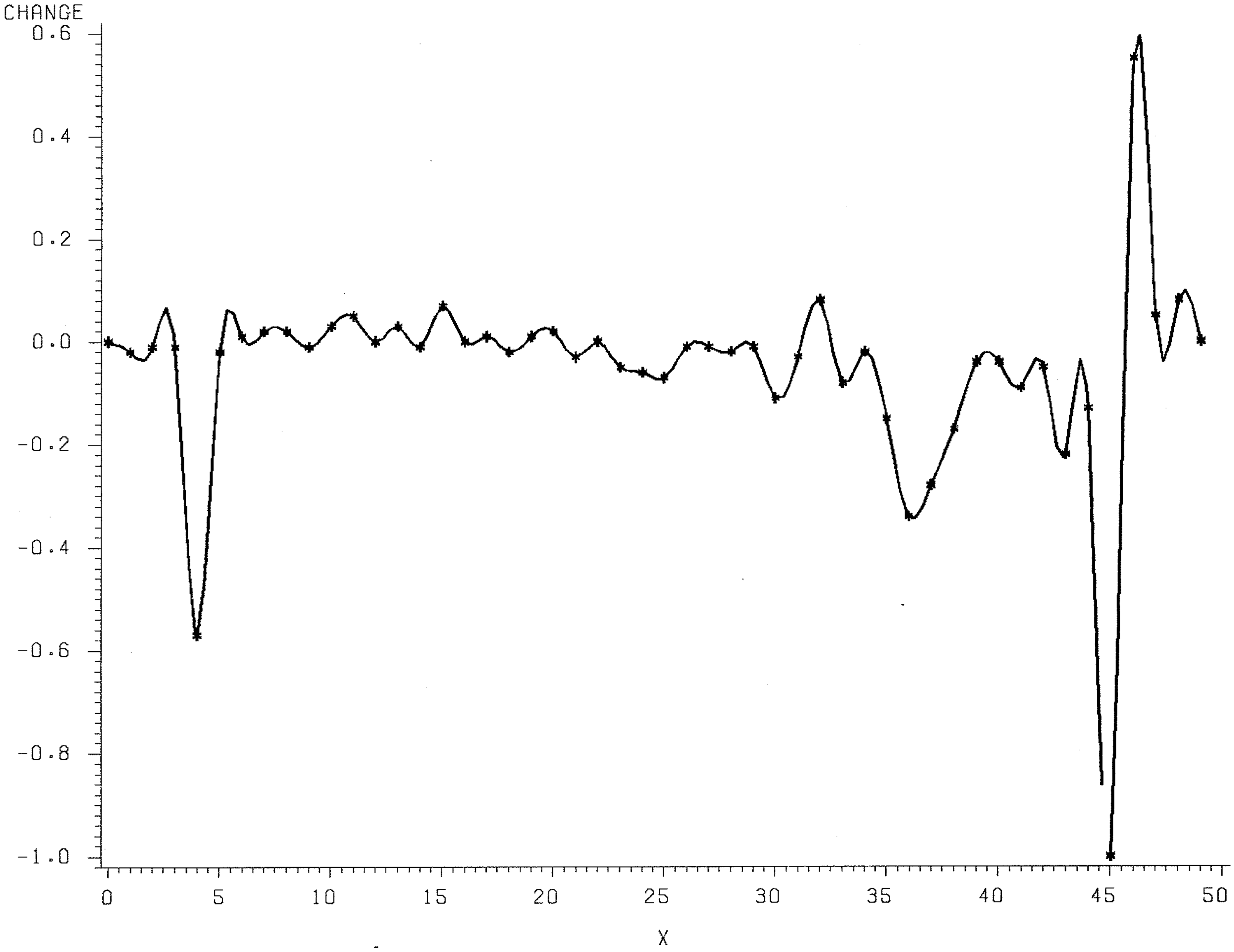
GRAVEL CREEK CHANNEL CHANGE B-14(June 1982 to May 1983)


GRAVEL CREEK CHANNEL CHANGE B-15(June 1982 to May 1983)
CHANGE
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
0
5
10
15
20
25
30
35
40
45
X

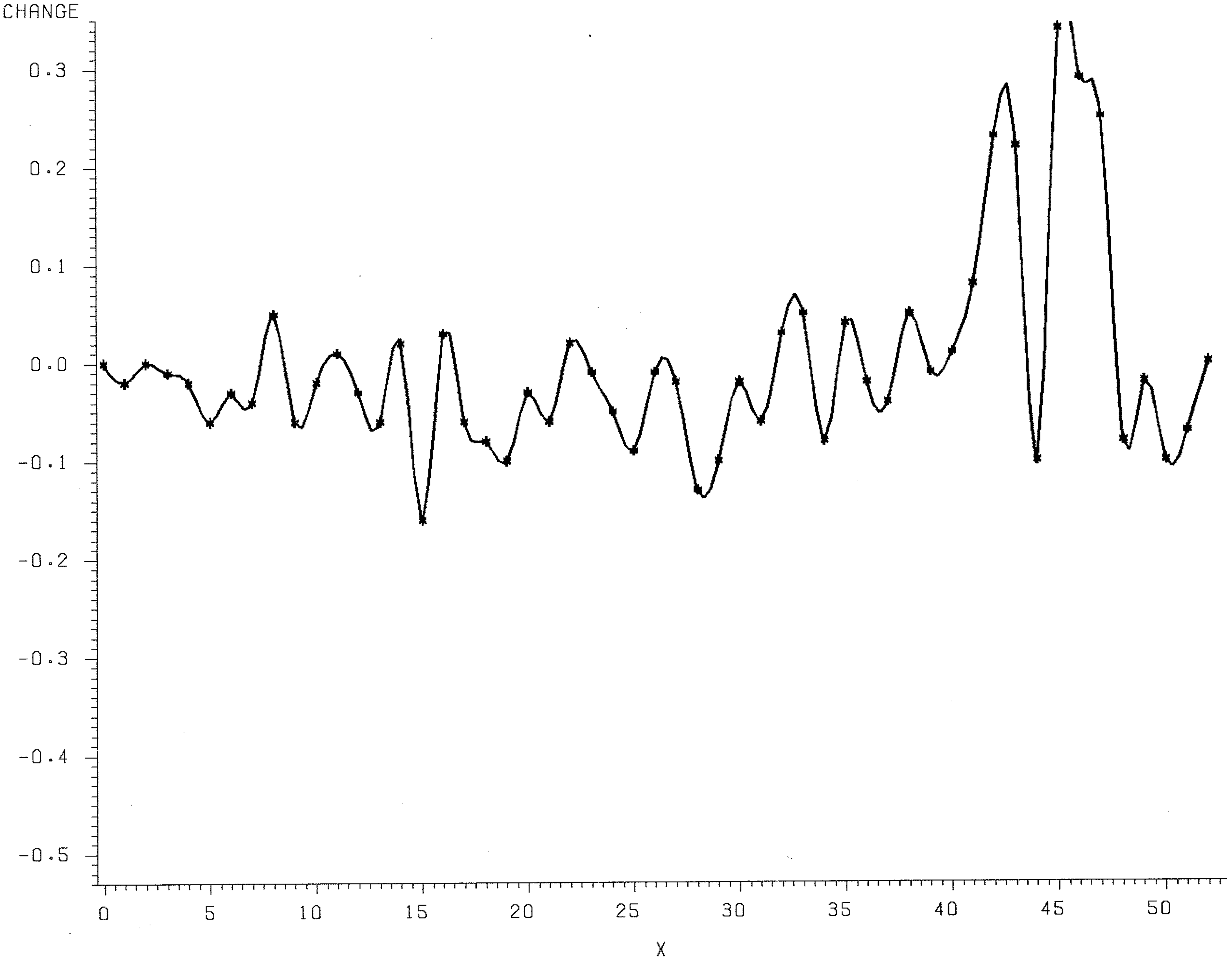
GRAVEL CREEK CHANNEL CHANGE B-16(June 1982 to May 1983)



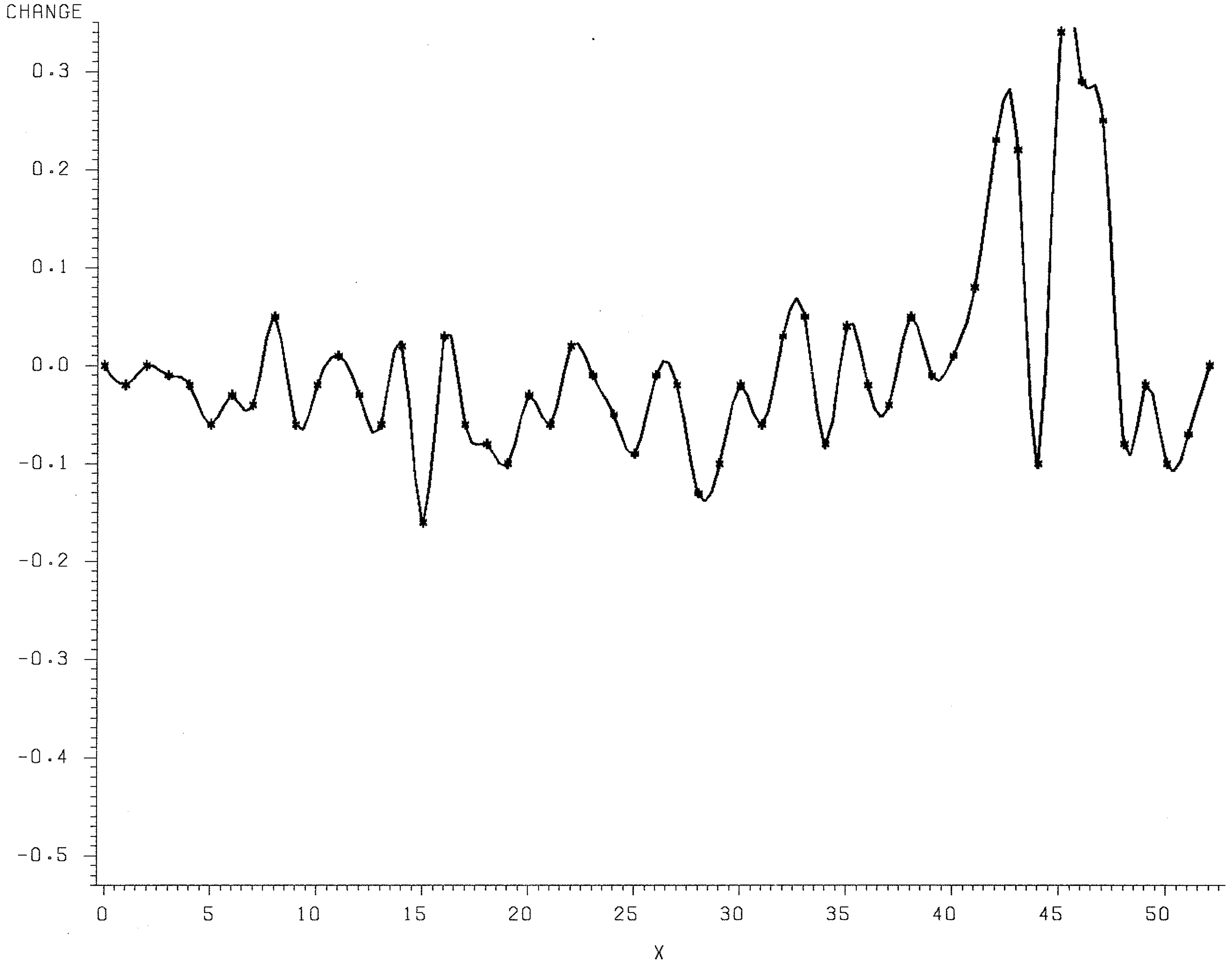
GRAVEL CREEK CHANNEL CHANGE B-17(June 1982 to May 1983)



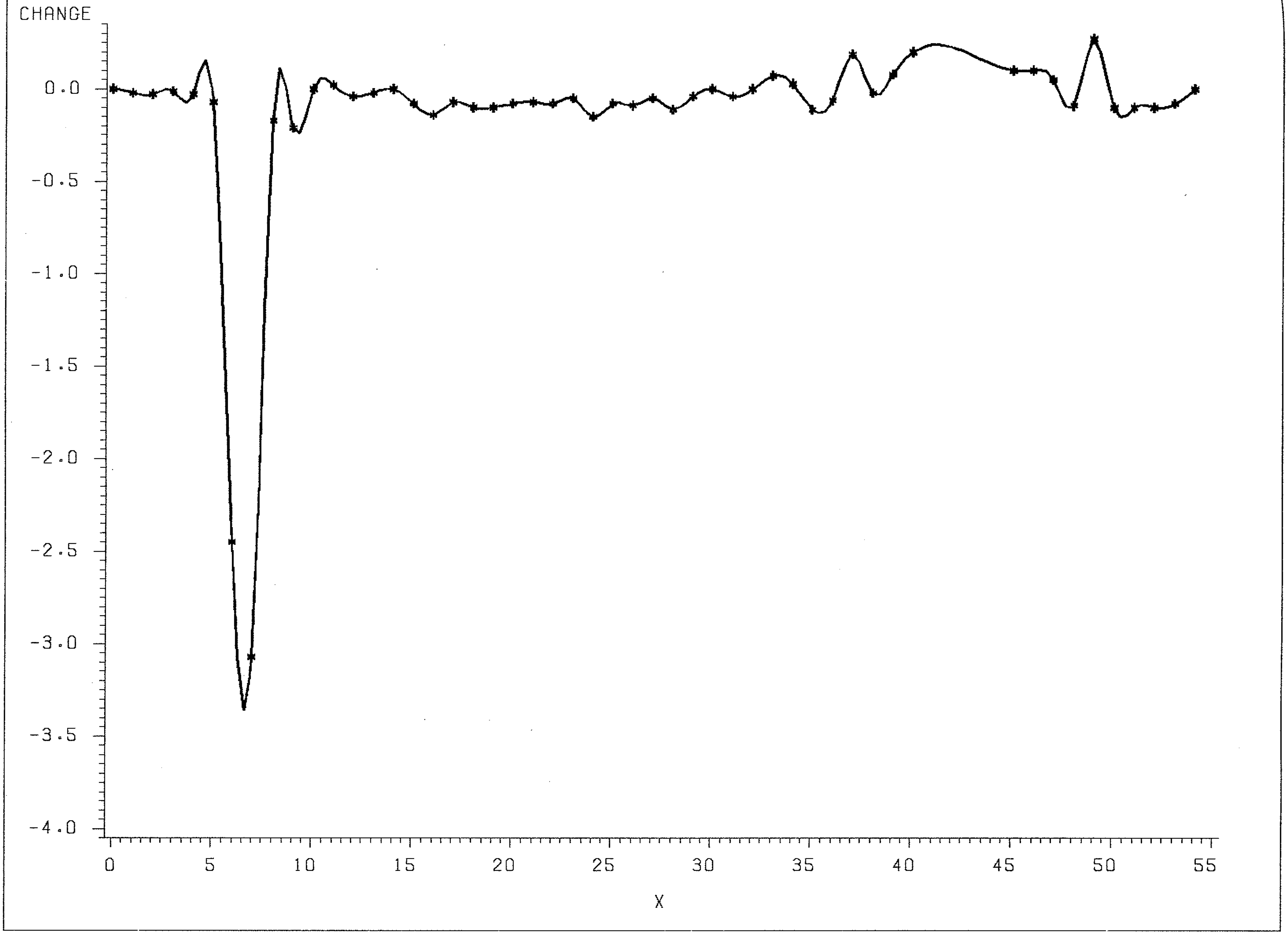
GRAVEL CREEK CHANNEL CHANGE B-18(June 1982 to May 1983)



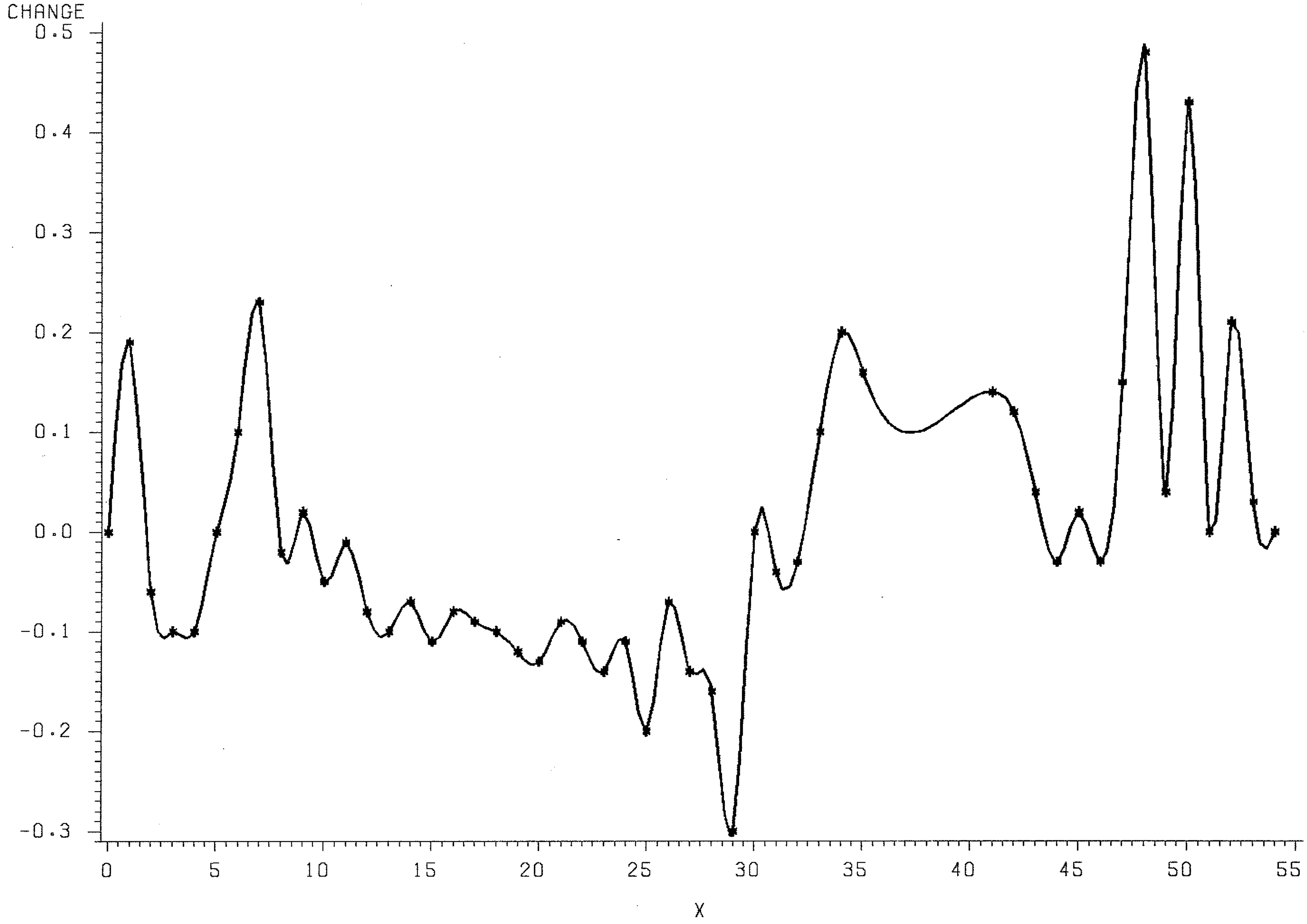
GRAVEL CREEK CHANNEL CHANGE B-18(June 1982 to May 1983)



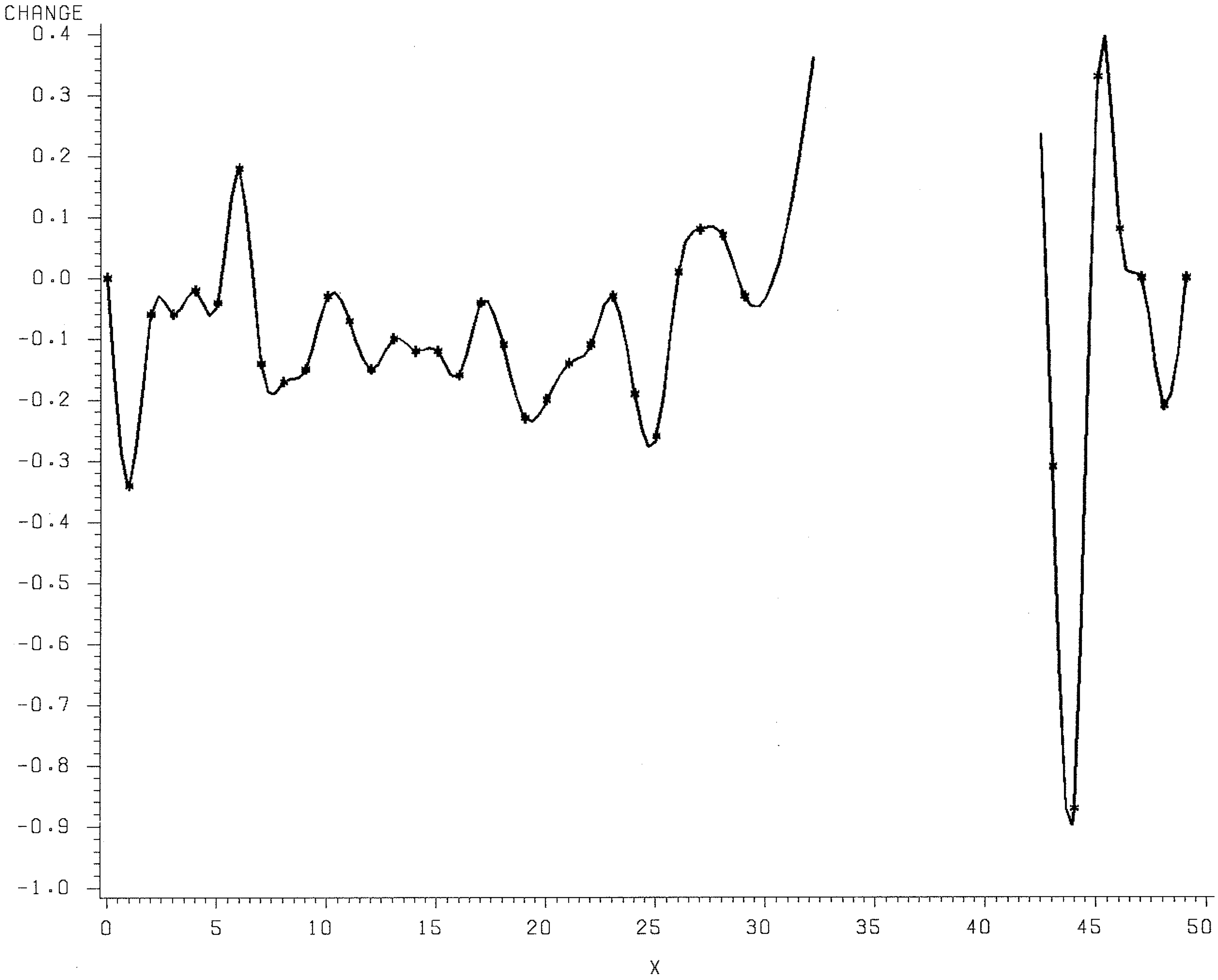
GRAVEL CREEK CHANNEL CHANGE B-18b(June 1982 to May 1983)



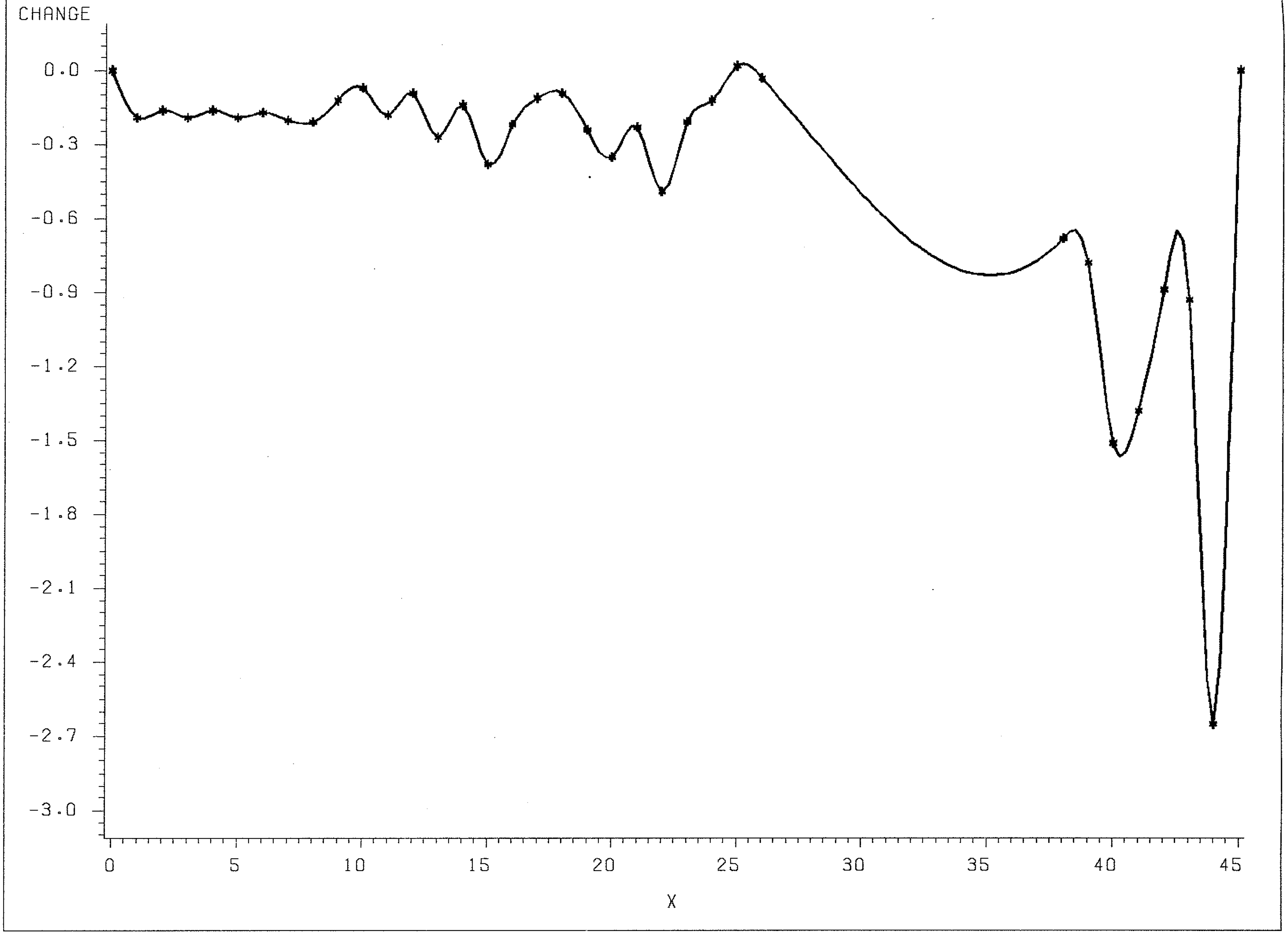
GRAVEL CREEK CHANNEL CHANGE B-18c(June 1982 to May 1983)



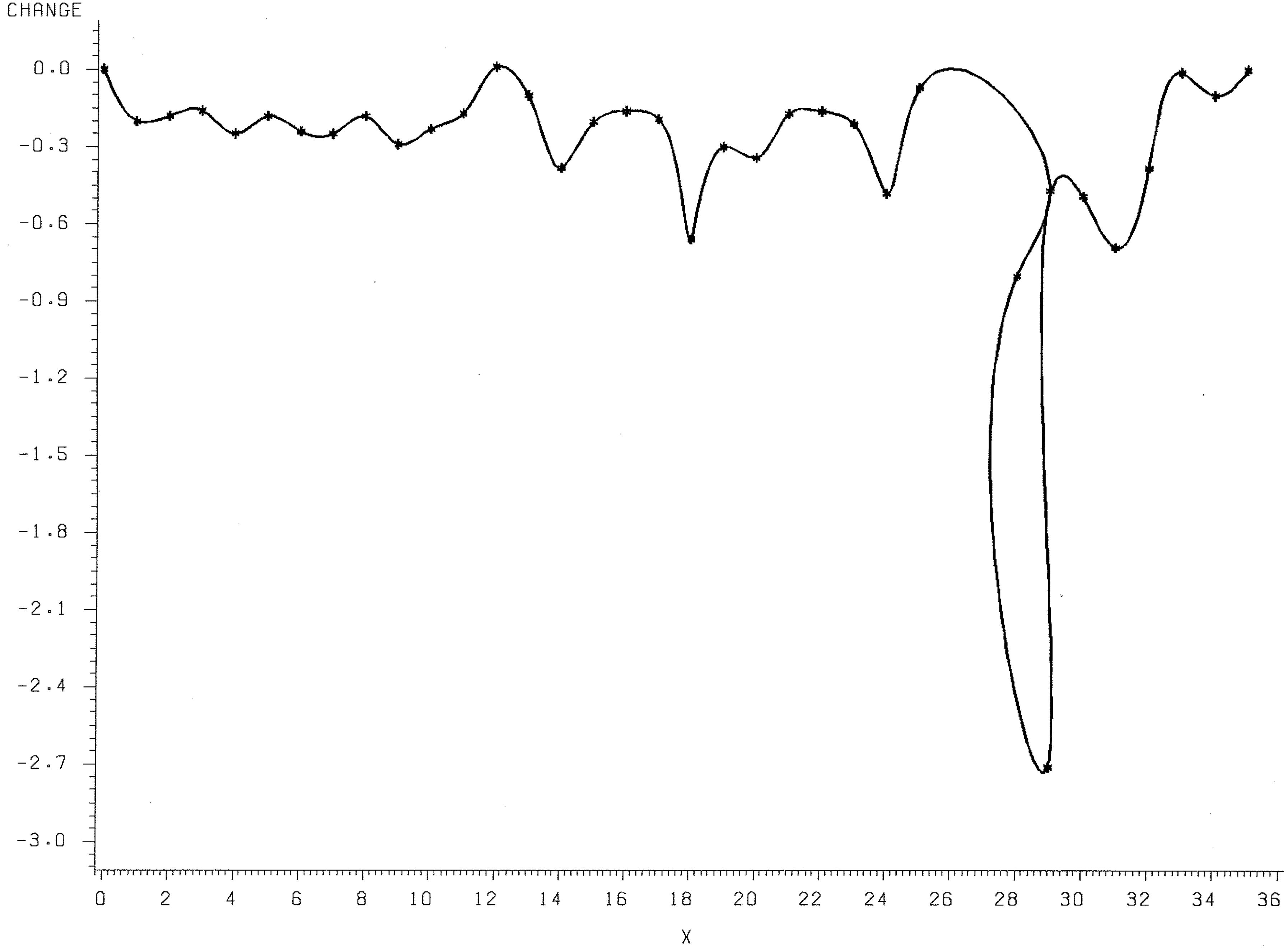
GRAVEL CREEK CHANNEL CHANGE B-18d(June 1982 to May 1983)



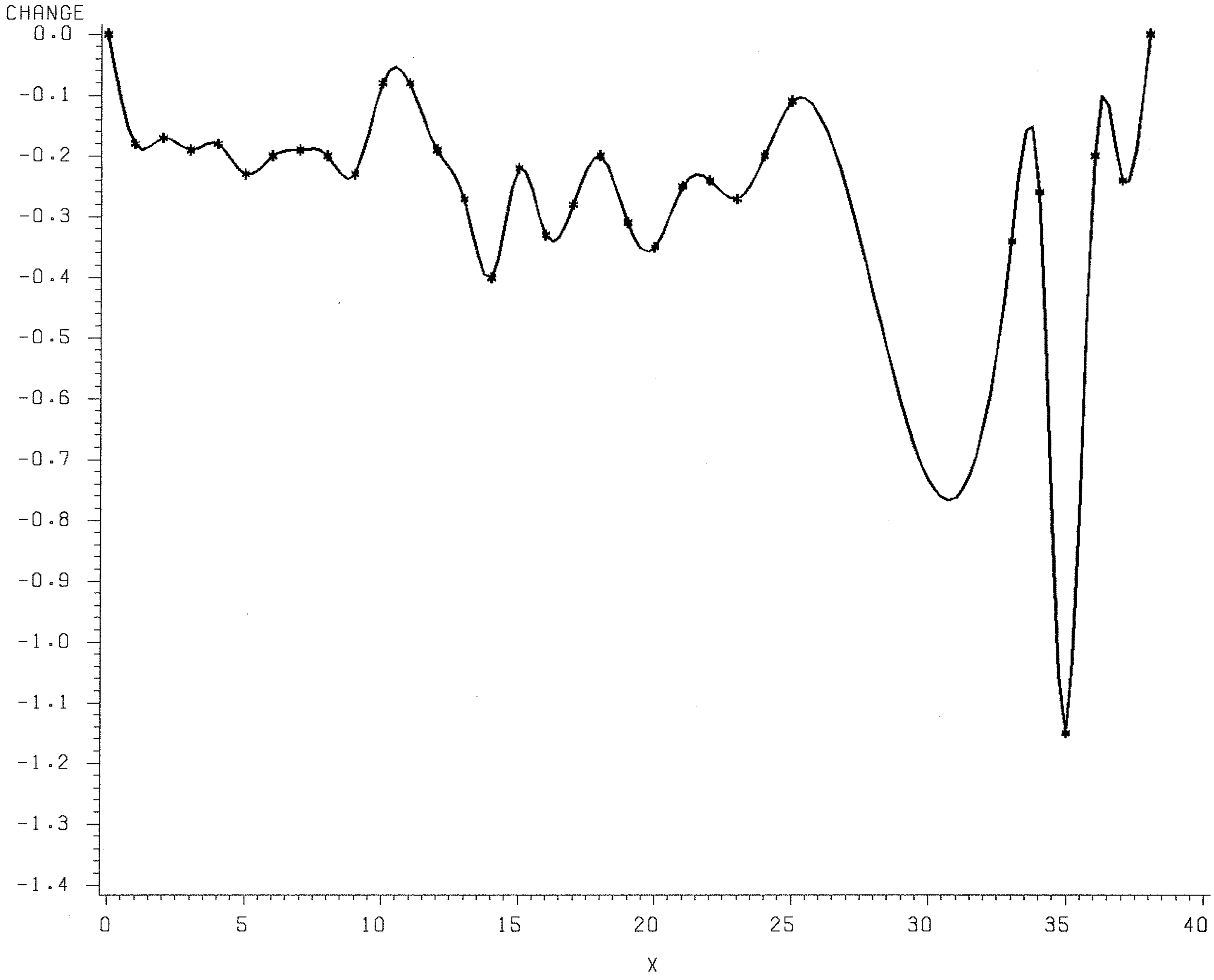
GRAVEL CREEK CHANNEL CHANGE B-18e(June 1982 to May 1983)

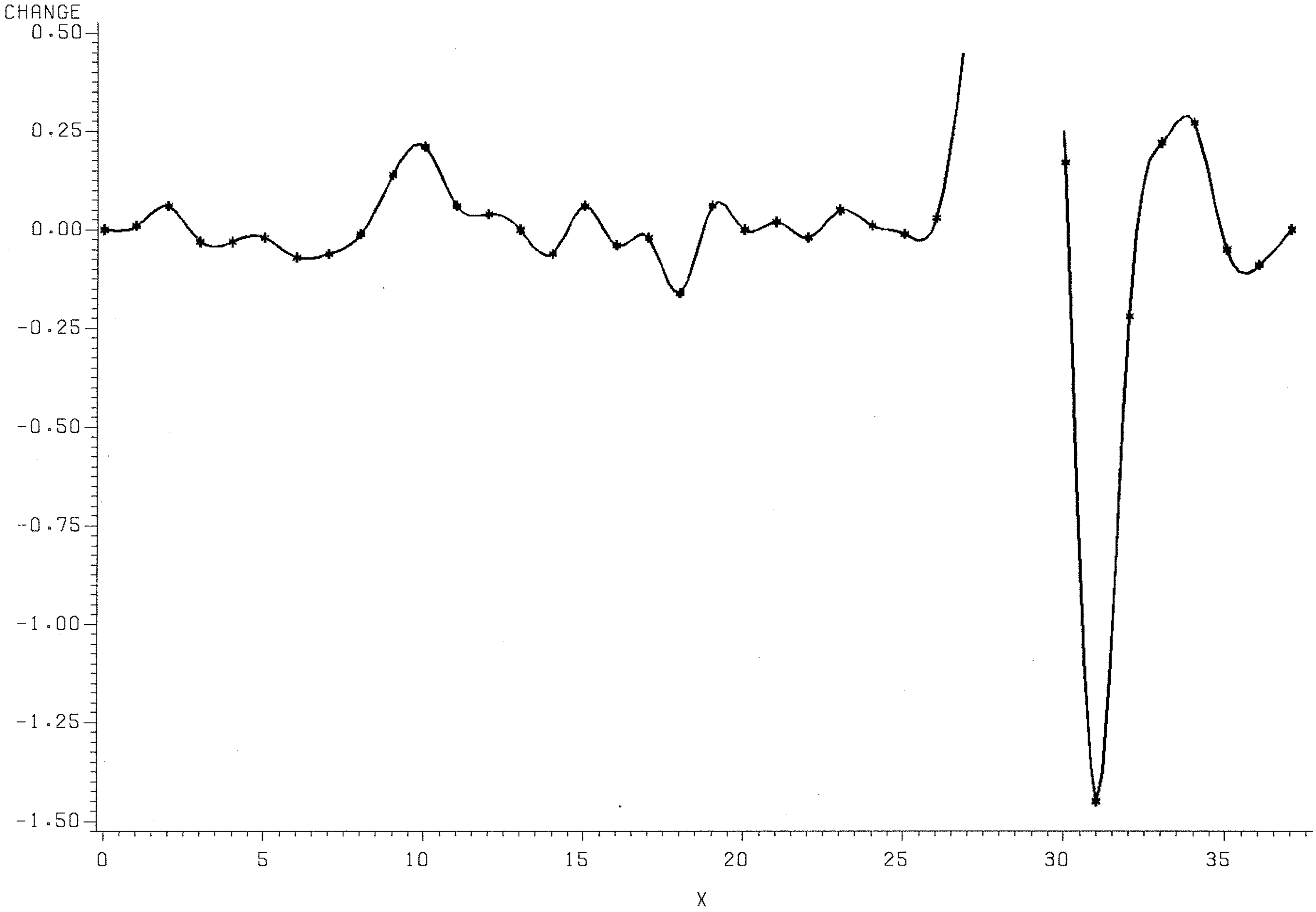


GRAVEL CREEK CHANNEL CHANGE B-18f(June 1982 to May 1983)



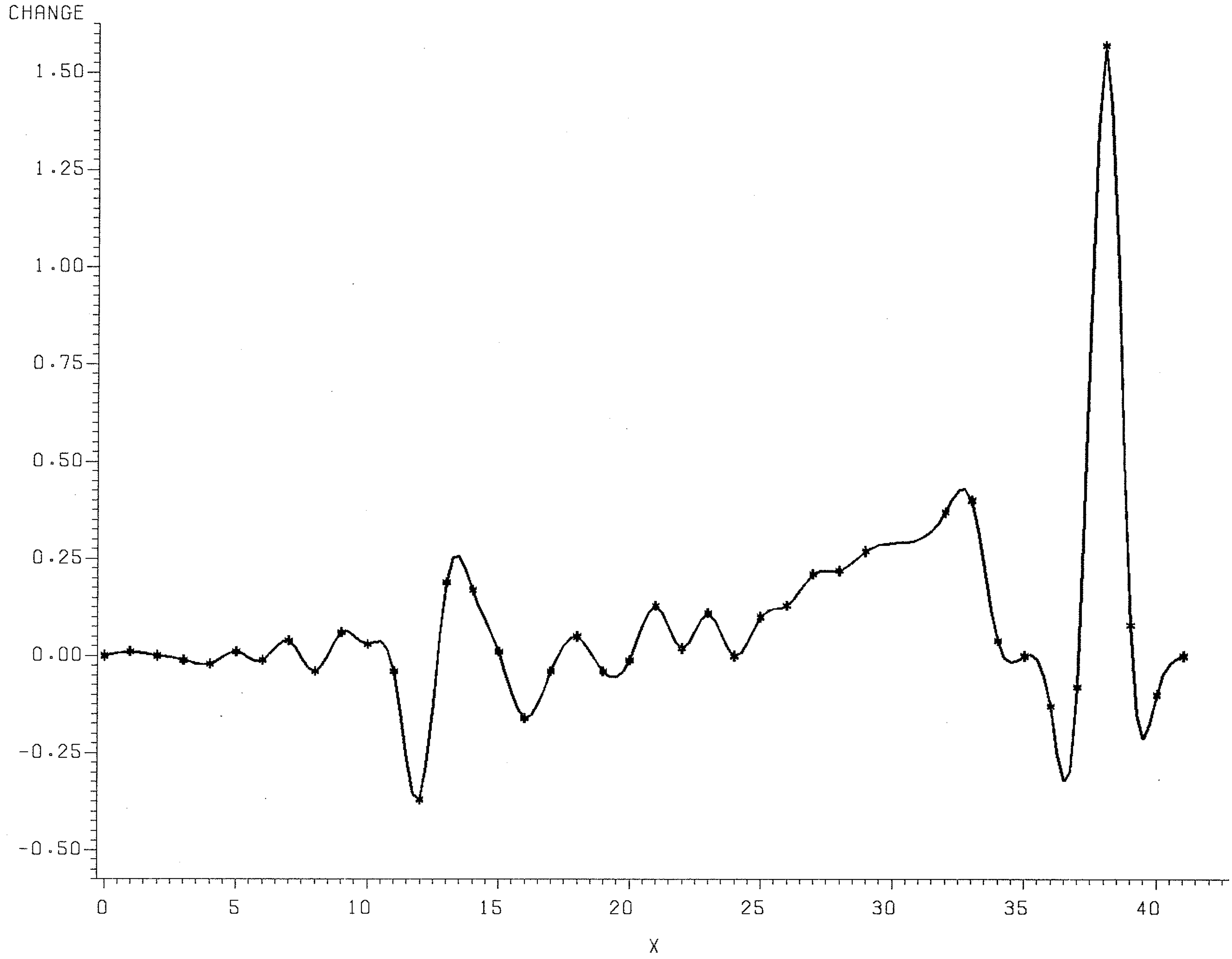
GRAVEL CREEK CHANNEL CHANGE B-18g(June 1982 to May 1983)



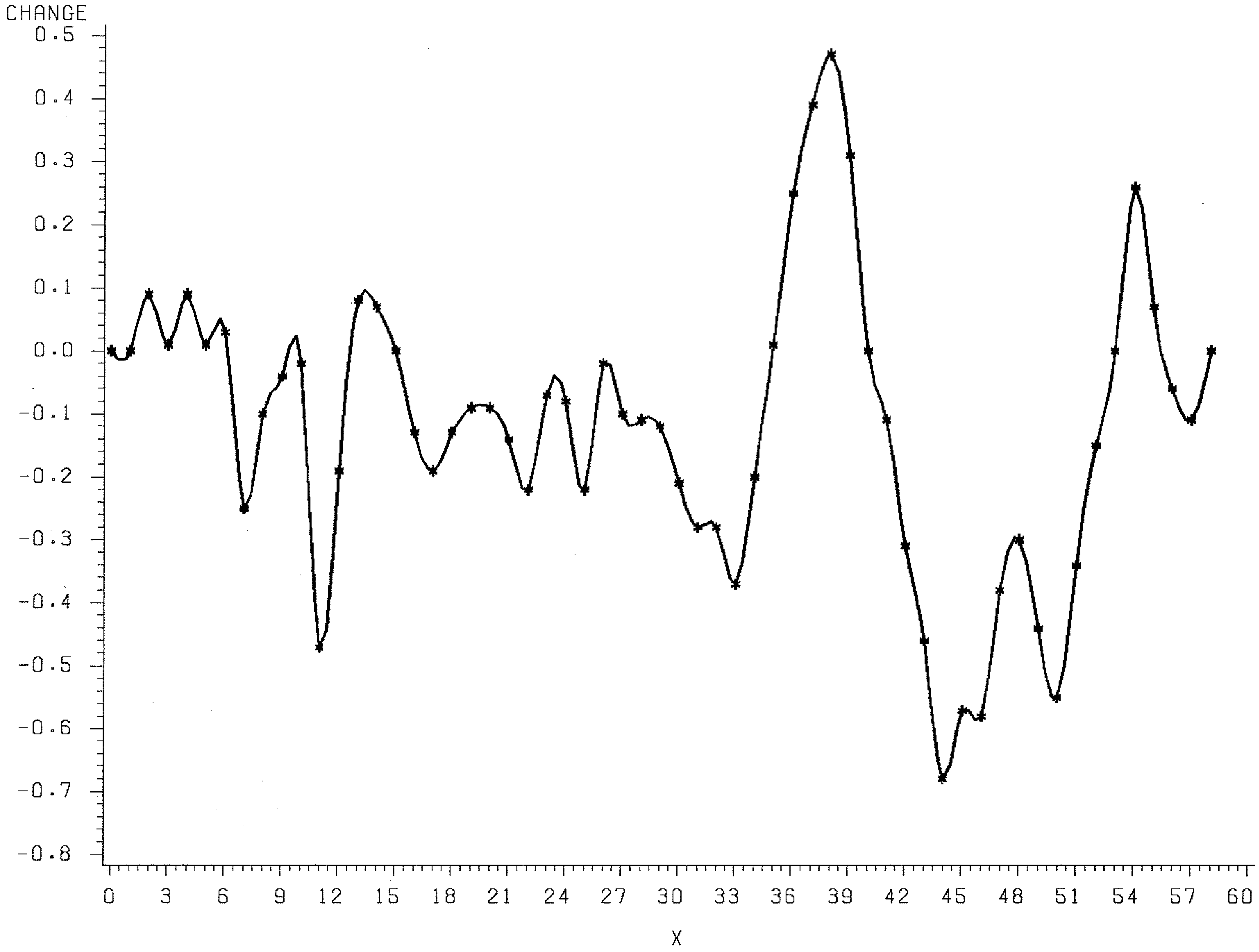


GRAVEL CREEK CHANNEL CHANGE B-19(June 1982 to May 1983)

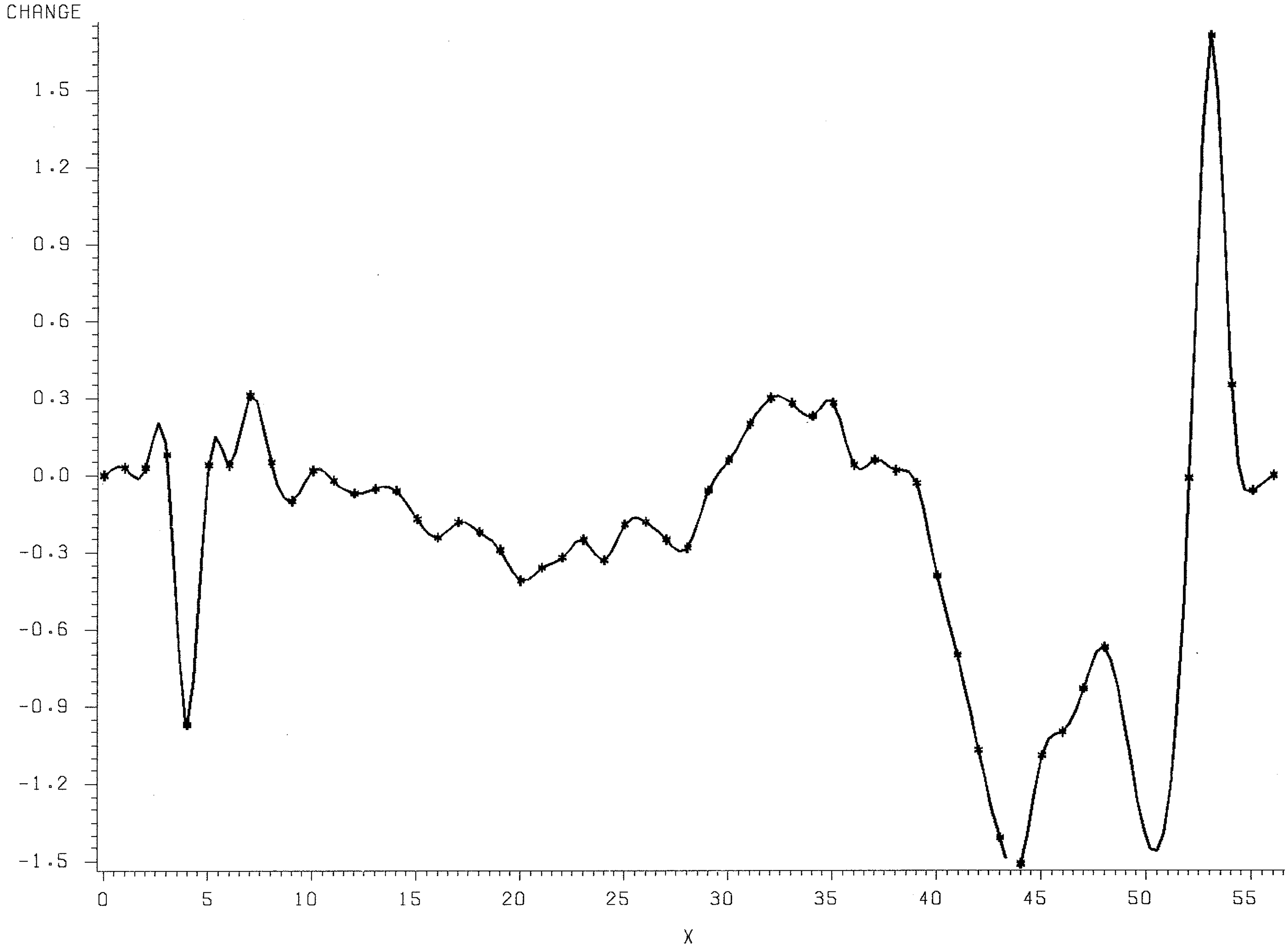
GRAVEL CREEK CHANNEL CHANGE B-20(June 1982 to May 1983)

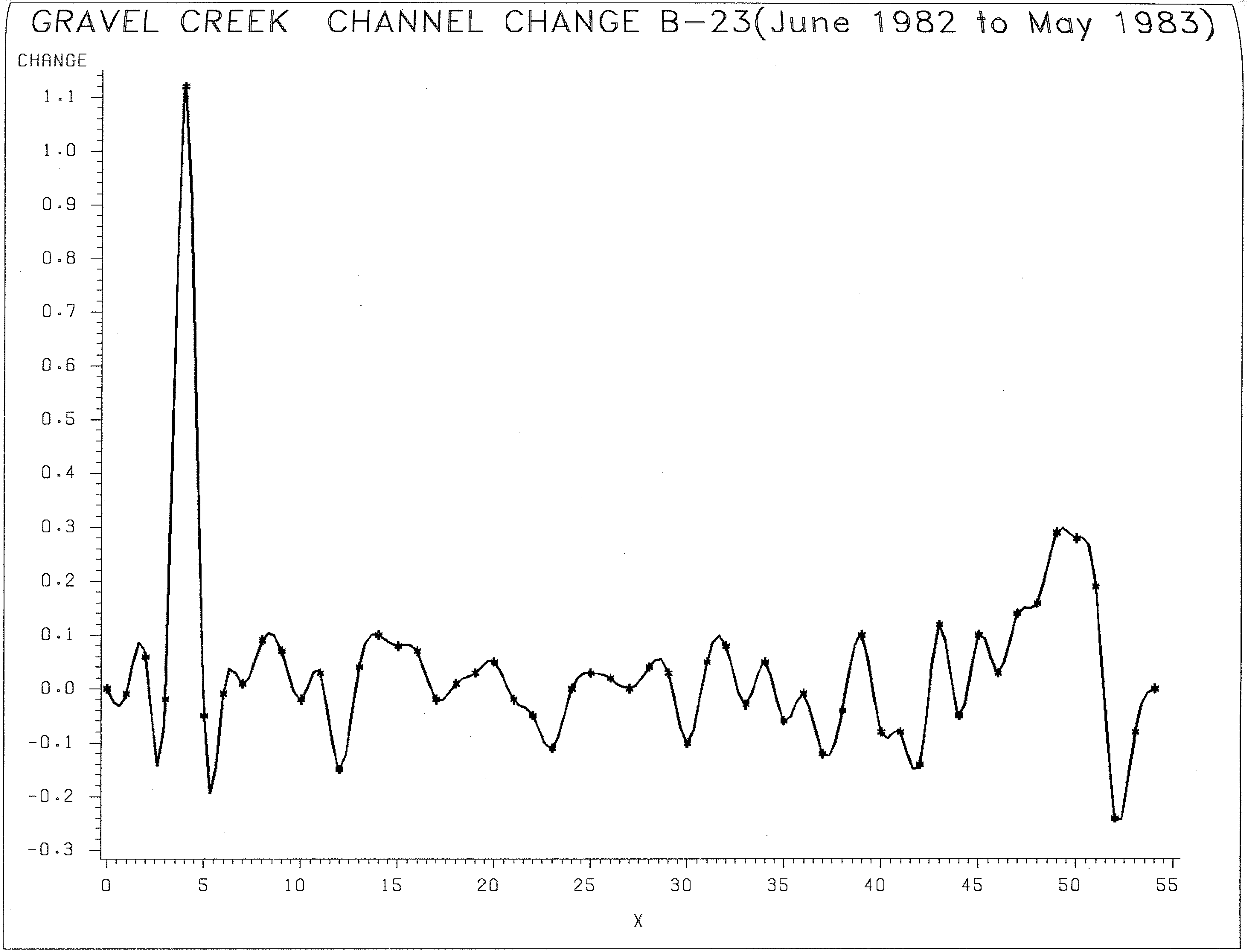


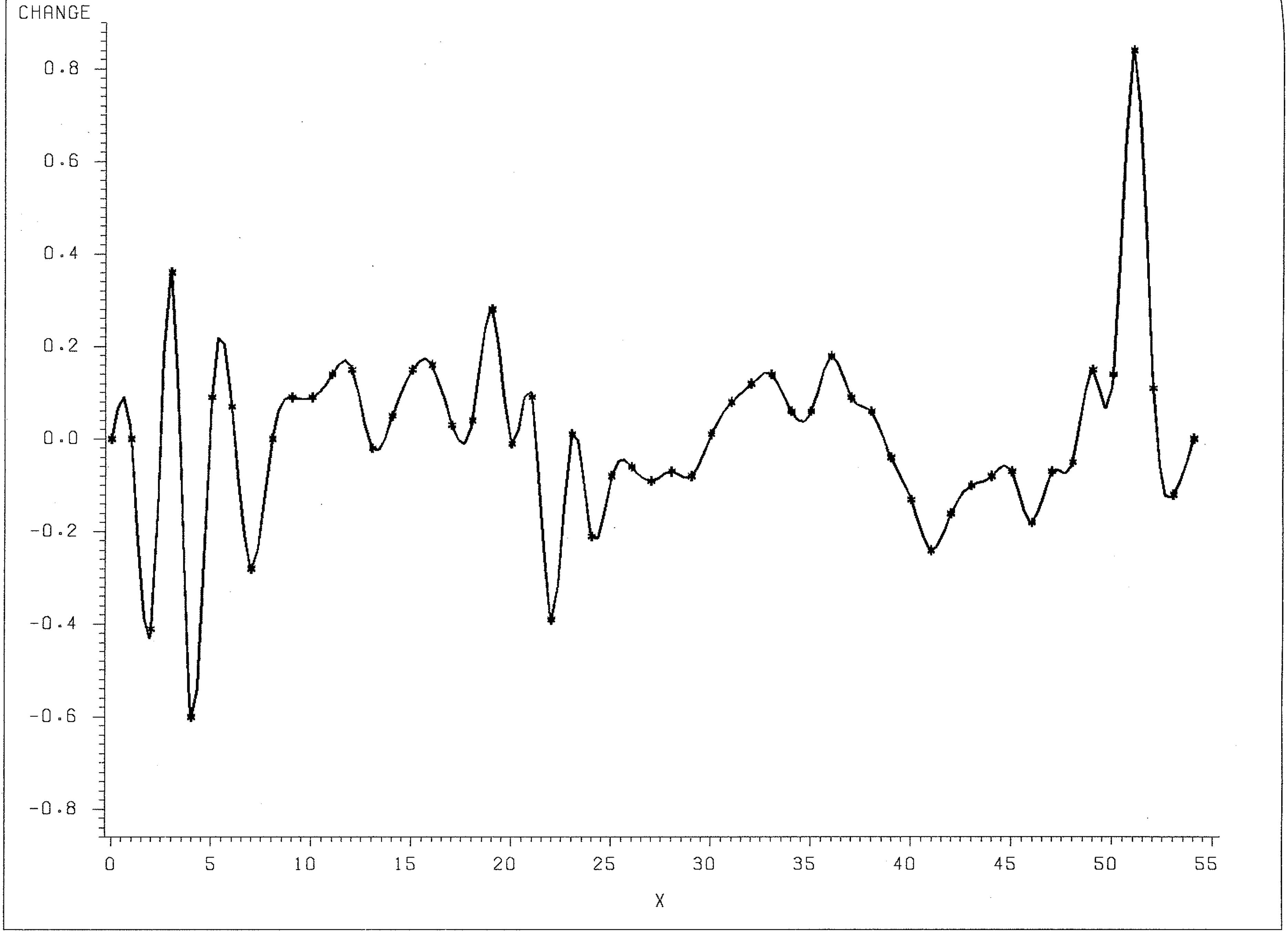
GRAVEL CREEK CHANNEL CHANGE B-21(June 1982 to May 1983)



GRAVEL CREEK CHANNEL CHANGE B-22(June 1982 to May 1983)

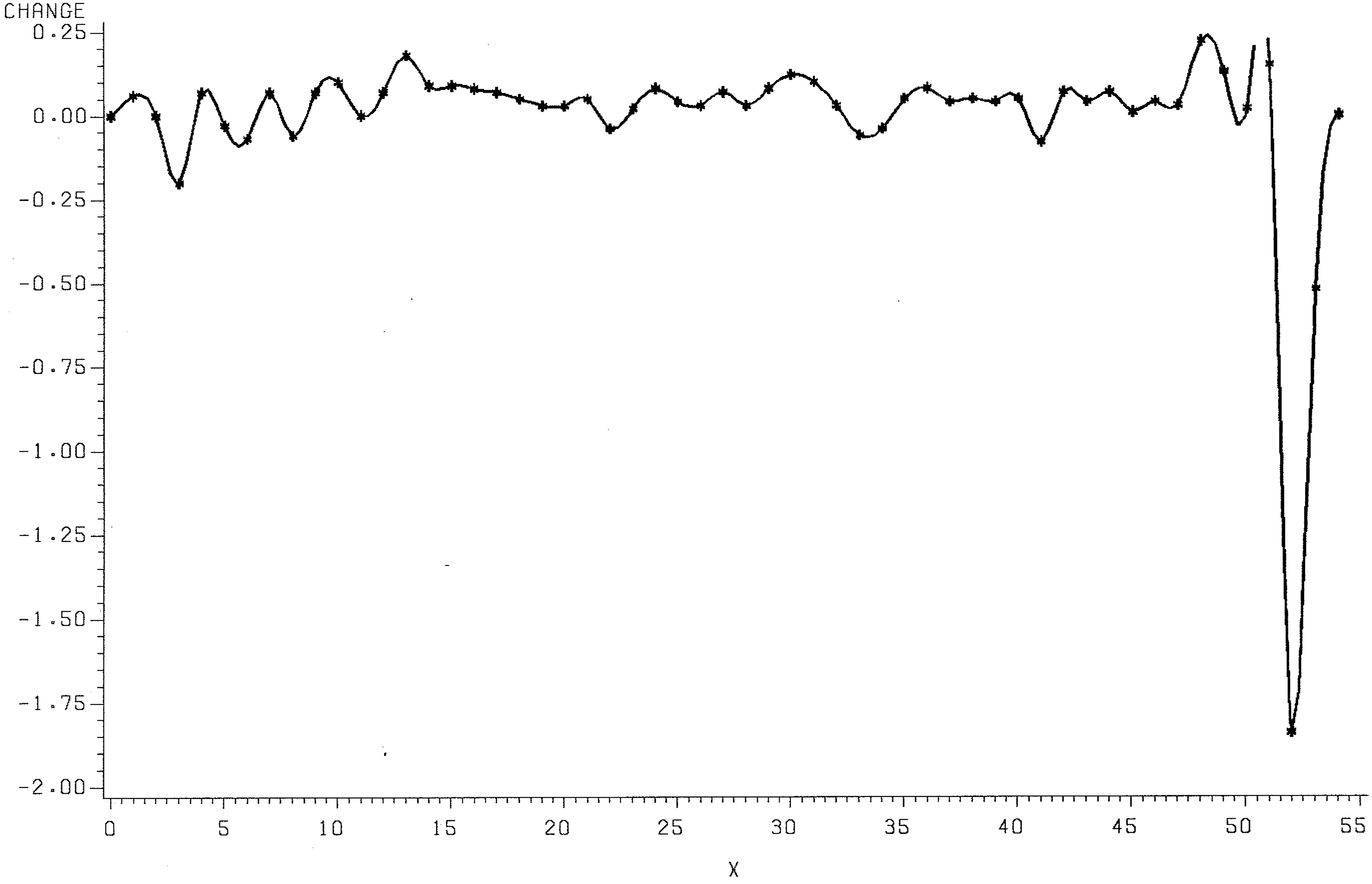


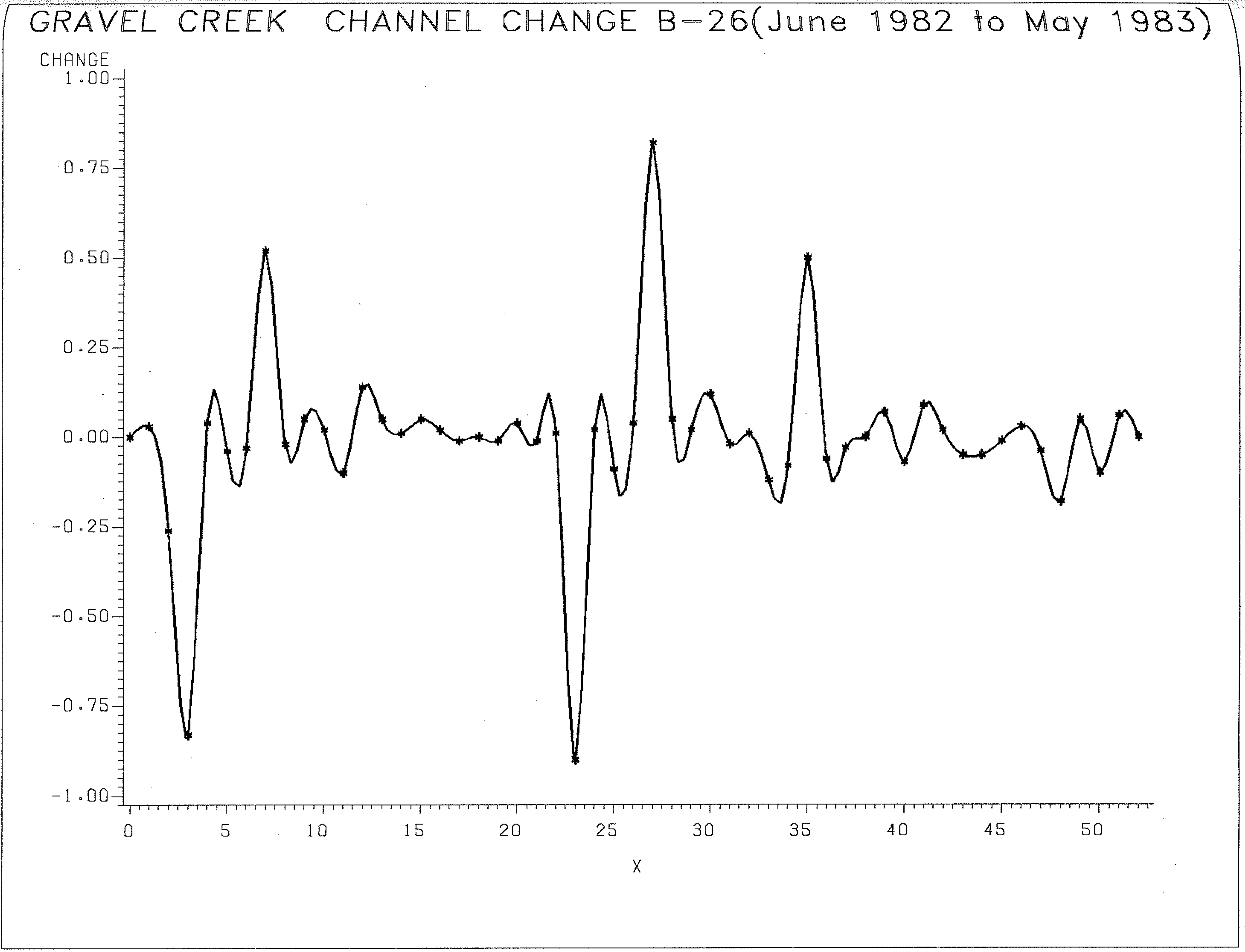

GRAVEL CREEK CHANNEL CHANGE B-23(June 1982 to May 1983)
CHANGE
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
0
5
10
15
20
25
30
35
40
45
50
55
X



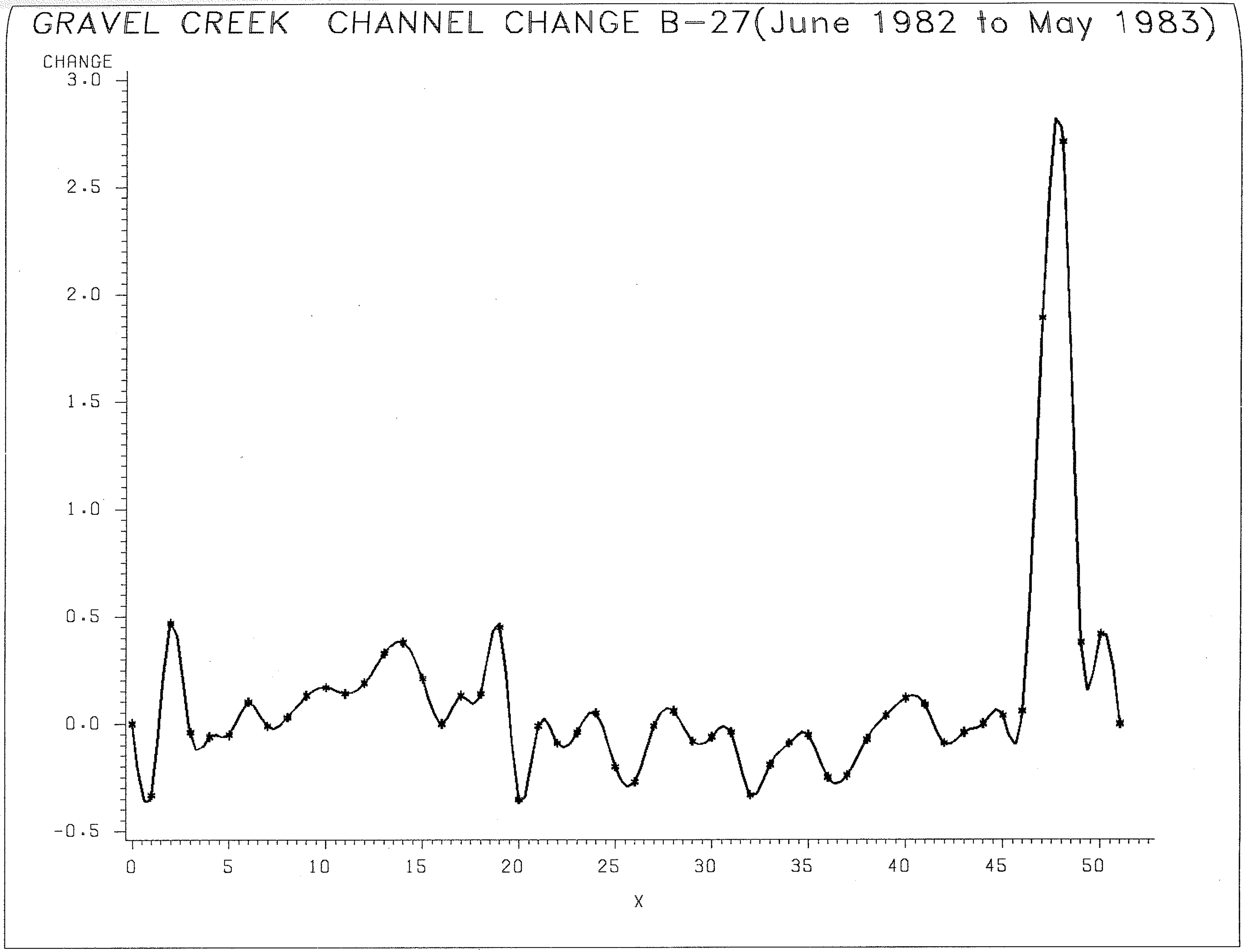
GRAVEL CREEK CHANNEL CHANGE B-24(June 1982 to May 1983)

GRAVEL CREEK CHANNEL CHANGE B-25(June 1982 to May 1983)

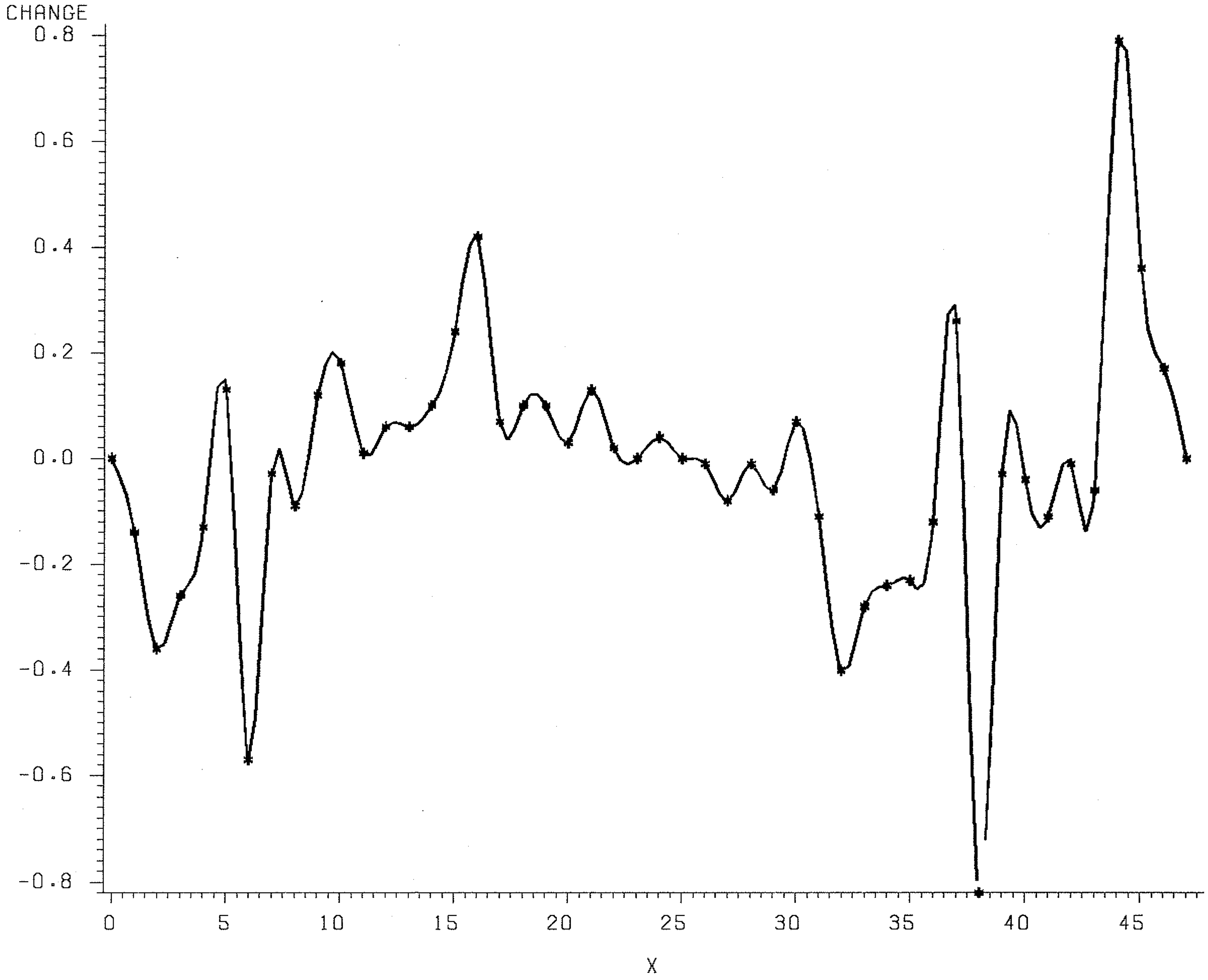




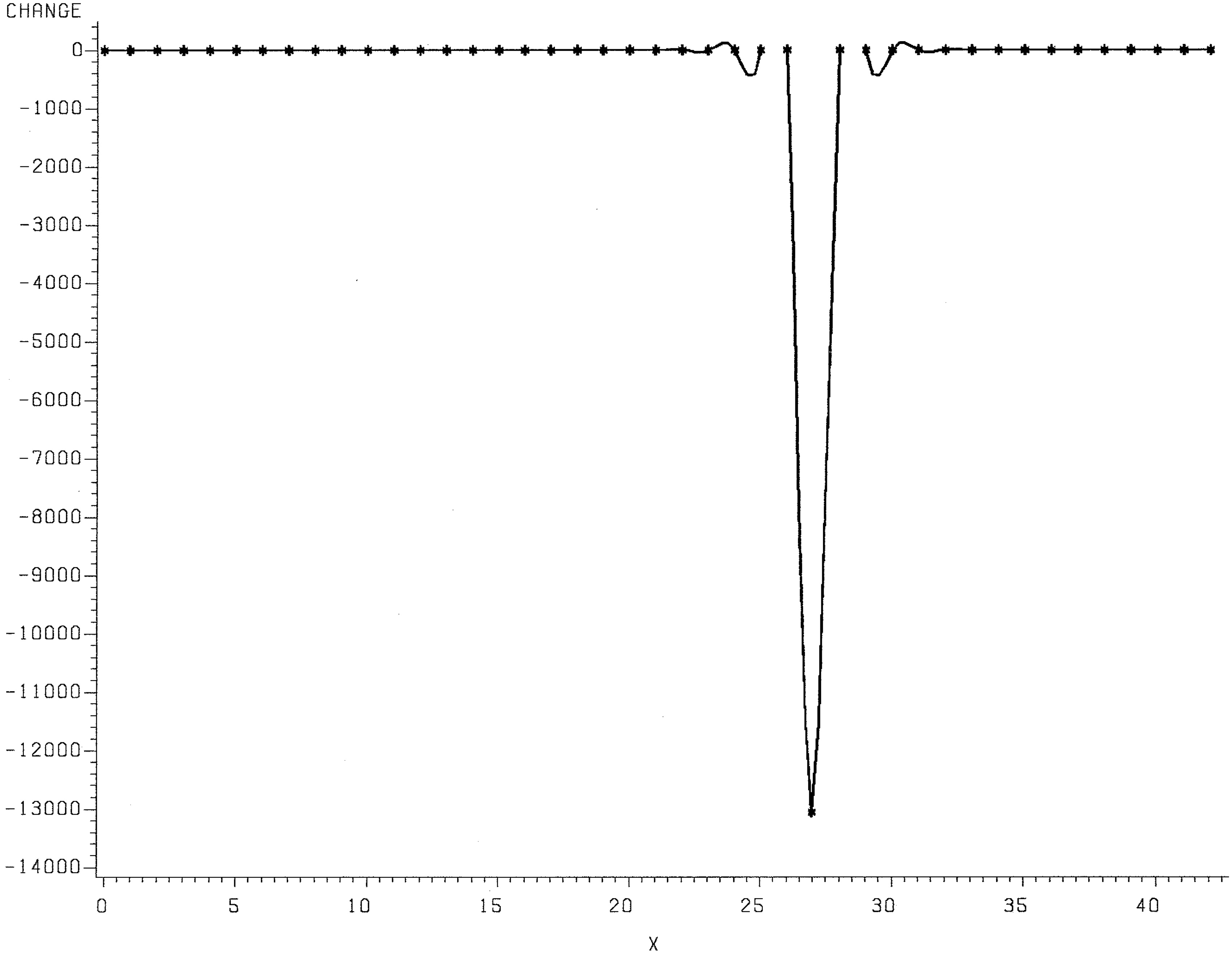
GRAVEL CREEK CHANNEL CHANGE B-26(June 1982 to May 1983)

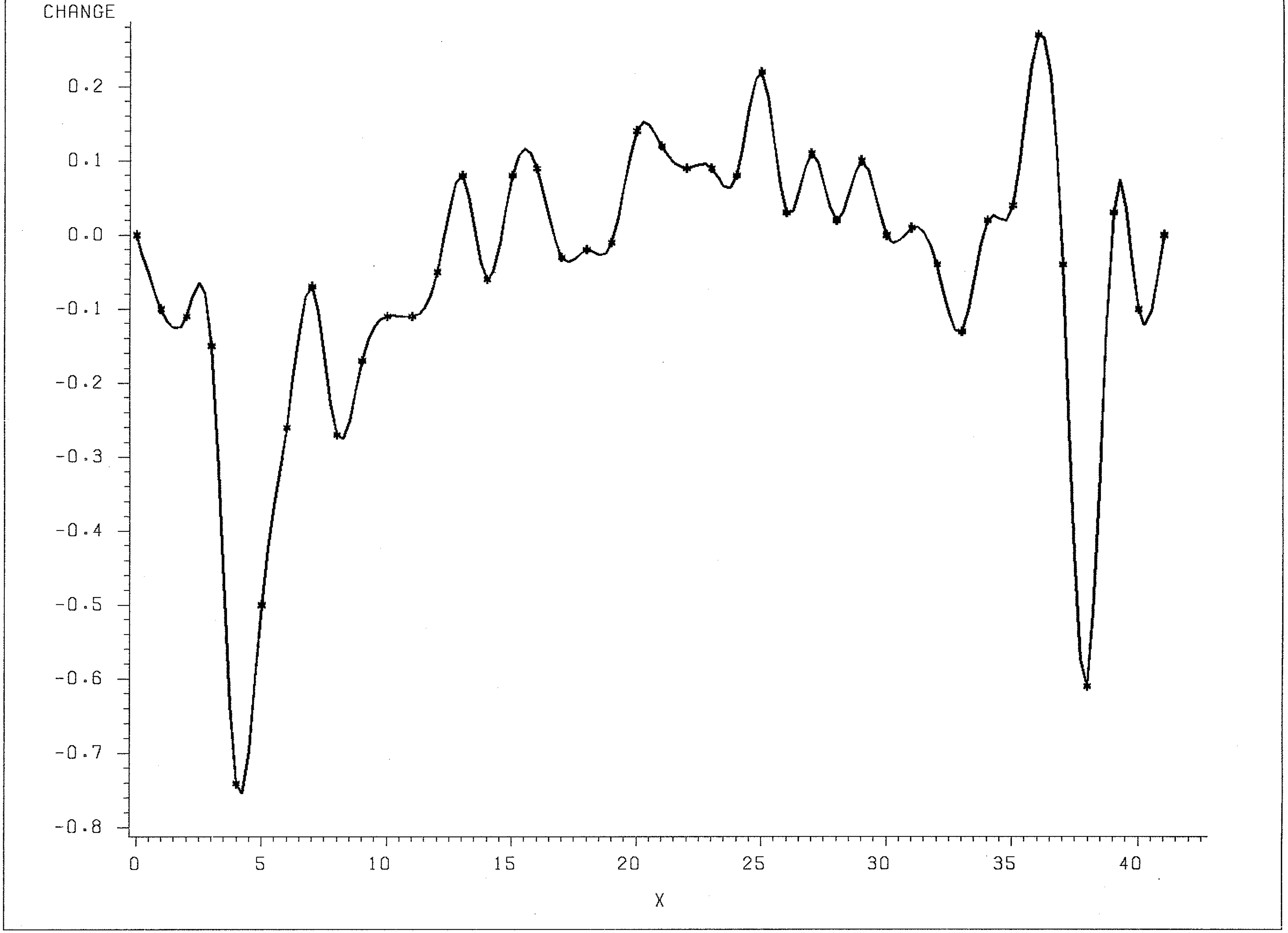

GRAVEL CREEK CHANNEL CHANGE B-27(June 1982 to May 1983)
CHANGE
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
0
5
10
15
20
25
30
35
40
45
50
X

GRAVEL CREEK CHANNEL CHANGE B-28(June 1982 to May 1983)



GRAVEL CREEK CHANNEL CHANGE B-29(June 1982 to May 1983)





GRAVEL CREEK CHANNEL CHANGE B-32(June 1982 to May 1983)

Appendix C

```
 J E S 2   J O B   L O G


10.03.25 JOB 3271  $ CAMPBL   STARTED - INIT  7 - CLASS A - SYS MVS3
10.03.42 JOB 3271  $ CAMPBL   ENDED


CARDS READ(203) LINES GENERATED(100) CARDS GENERATED(0)
I/O COUNTS:  3350(84)  3330(0)  3400(0)  REMAINING(1,936)
TAPE MOUNTS(0)  DISK MOUNTS(0)  WTORS(0)  STEPS(1)
XEQ COST:  UNITS(.55) * RATE FACTOR(1.00) * SERVICE FACTOR(1.00) = COST($.55)
ACCOUNT STATUS:  LAST USED(86.028) UNITS(366.58) JOBS RUN(220) TSO SESSIONS(43)



     1       //CAMPBL JOB '0063018,,,I=20,T=20,CO=1,LP=65,FORMS=BDH1','REG2',        JOB 3271
             // NOTIFY=CAMPBL,PASSWORD=
             ***JOBPARM XEQE,PPUS,BELL
             ***TSO
             ***ROUTE PRINT LOCAL
     2       // EXEC SAS
    19       //SYSIN DD *
             //



IEF142I CAMPBL GO - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /GO      / START 86028.1003
IEF374I STEP /GO      / STOP  86028.1003 CPU    0MIN 00.37SEC SRB    0MIN 00.03SEC VIRT   768K SYS   228K
77 EXCP (3350)  0 EXCP (3380)  0 EXCP (3420)  0 EXCP (3480)
IEF375I  JOB /CAMPBL  / START 86028.1003
IEF376I  JOB /CAMPBL  / STOP  86028.1003 CPU    0MIN 00.37SEC SRB    0MIN 00.03SEC
```

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1       S A S   L O G    OS SAS 82.4        VS2/MVS JOB CAMPBL    STEP GO       PROC                    10:03 TUESDAY, JANUARY 28, 1986

NOTE: THE JOB CAMPBL HAS BEEN RUN UNDER RELEASE 82.4 OF SAS AT THE UNIVERSITY OF MANITOBA (02246001).

NOTE: CPUID   VERSION = 86  SERIAL = 000103  MODEL = 0580 .

NOTE: SAS OPTIONS SPECIFIED ARE:
       SORT=4

1          DATA TRQ;
2          INPUT A 1-4 B 6-9 C 11-14 R 16-18 D 20-23 HR 25-28 V 30-33;
3          DI=.01*B;
4          DM=.3084*HR;
5          TI=DM*.0037;
6          TCI=TI/(1.65*DI);
7          S=(B*C)/(A*A);
8          SP=LOG(S)/3;
9          SPH=EXP(SP);
10         F=(A+B)/(2*C)*100;
11         CARDS;

NOTE: DATA SET WORK.TRQ HAS 180 OBSERVATIONS AND 15 VARIABLES. 153 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.08 SECONDS AND 332K.

192        PROC STEPWISE DATA=TRQ;
193          MODEL D=TCI SPH F V B HR;

NOTE: SLENTRY AND SLSTAY HAVE BEEN SET TO .15 FOR THE STEPWISE TECHNIQUE.
NOTE: THE PROCEDURE STEPWISE USED 0.08 SECONDS AND 390K AND PRINTED PAGE 1.

194        PROC MEANS;

NOTE: THE PROCEDURE MEANS USED 0.10 SECONDS AND 380K AND PRINTED PAGE 2.
NOTE: SAS USED 390K MEMORY.

NOTE: SAS INSTITUTE INC.
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      CARY, N.C.  27511-8000
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                                                                 SAS                        10:03 TUESDAY, JANUARY 28, 1986     1

                                          STEPWISE REGRESSION PROCEDURE FOR DEPENDENT VARIABLE D

WARNING:    18 OBSERVATIONS DELETED DUE TO MISSING VALUES.

STEP 1     VARIABLE F ENTERED             R SQUARE = 0.05171546       C(P) =      2.03185256

                                          DF              SUM OF SQUARES         MEAN SQUARE            F       PROB>F

                   REGRESSION              1               1845.76274090       1845.76274090         8.73       0.0036
                   ERROR                 160              33844.97337021        211.53108356
                   TOTAL                 161              35690.73611111

                                            B VALUE            STD ERROR         TYPE II SS             F       PROB>F

                   INTERCEPT             -0.72944716
                   F                      0.04177519          0.01414222       1845.76274090         8.73       0.0036
---------------------------------------------------------------------------------------------------------------------

STEP 2     VARIABLE TCI ENTERED           R SQUARE = 0.07585317       C(P) =     -0.04161147

                                          DF              SUM OF SQUARES         MEAN SQUARE            F       PROB>F

                   REGRESSION              2               2707.25549666       1353.62774833         6.53       0.0019
                   ERROR                 159              32983.48061445        207.44327430
                   TOTAL                 161              35690.73611111

                                            B VALUE            STD ERROR         TYPE II SS             F       PROB>F

                   INTERCEPT             -6.94942309
                   TCI                  221.30322559        108.59544479        861.49275575         4.15       0.0432
                   F                      0.03994034          0.01403382       1680.23933939         8.10       0.0050
---------------------------------------------------------------------------------------------------------------------

NO OTHER VARIABLES MET THE 0.1500 SIGNIFICANCE LEVEL FOR ENTRY INTO THE MODEL.
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                                                                  SAS                          10:03 TUESDAY, JANUARY 28, 1986    2

VARIABLE          N         MEAN          STANDARD       MINIMUM        MAXIMUM       STD ERROR          SUM        VARIANCE            C.V.
                                          DEVIATION        VALUE          VALUE        OF MEAN

A               180     8.65277778      2.89762821     3.20000000    19.30000000     0.21597645    1557.500000     8.3962492          33.488
B               180     6.17777778      1.97960426     2.10000000    12.00000000     0.14755099    1112.000000     3.9188330          32.044
C               180     4.18388889      1.88851761     1.10000000    10.50000000     0.14076179     753.100000     3.5664988          45.138
R               180     0.59972222      0.05944276     0.50000000     0.75000000     0.00443060     107.950000     0.0035334           9.912
D               162     7.34259259     14.88897548     0.00000000    99.00000000     1.16978839    1189.500000   221.6815908         202.775
HR              180     2.44000000      0.28877511     1.01000000     3.32000000     0.02152403     439.200000     0.0833911          11.835
V               180     4.80816667      0.27716739     4.52000000     5.41000000     0.02065884     865.470000     0.0768218           5.765
DI              180     0.06177778      0.01979604     0.02100000     0.12000000     0.00147551      11.120000     0.0003919          32.044
DM              180     0.75249600      0.08905824     0.31148400     1.02388800     0.00663801     135.449280     0.0079314          11.835
TI              180     0.00278424      0.00032952     0.00115249     0.00378839     0.00002456       0.501162     0.0000001          11.835
TCI             180     0.03024429      0.01075706     0.01204473     0.06915636     0.00080178       5.443972     0.0001157          35.567
S               180     0.36292737      0.14668099     0.07571660     0.74938776     0.01093296      65.326927     0.0215153          40.416
SP              180    -0.36862576      0.15088452    -0.86025260    -0.09616624     0.01124627     -66.352637     0.0227661         -40.932
SPH             180     0.69930436      0.10090663     0.42305520     0.90831300     0.00752114     125.874785     0.0101821          14.430
F               180   197.52561972     82.32673715   116.47727273   782.14285714     6.13627269   35554.611549  6777.6916498          41.679
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****A  CAMPBL    REG2                    10.04.15 AM 28 JAN 86  JOB 3271    END        0.12 UNITS      SYS MVS3  JOB 3271    END    A****
****A  CAMPBL    REG2                    10.04.15 AM 28 JAN 86  JOB 3271    END        0.12 UNITS      SYS MVS3  JOB 3271    END    A****
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****A  CAMPBL    REG2                    10.04.15 AM 28 JAN 86  JOB 3271    END        0.12 UNITS      SYS MVS3  JOB 3271    END    A****
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 J E S 2   J O B   L O G


14.36.15 JOB 4193  $ CAMPBL   STARTED - INIT  9 - CLASS A - SYS MVS3
14.37.05 JOB 4193  $ CAMPBL   ENDED


CARDS READ(84) LINES GENERATED(97) CARDS GENERATED(0)
I/O COUNTS:  3350(113)  3330(0)  3400(0)  REMAINING(1,923)
TAPE MOUNTS(0)  DISK MOUNTS(0)  WTORS(0)  STEPS(1)
XEQ COST:  UNITS(.54) * RATE FACTOR(1.00) * SERVICE FACTOR(1.00) = COST($.54)
ACCOUNT STATUS:  LAST USED(86.035) UNITS(360.84) JOBS RUN(227) TSO SESSIONS(47)



     1      //CAMPBL JOB '0063018,,,I=20,T=20,CO=1,LP=65,FORMS=BDH1','QUI',        JOB 4193
            // NOTIFY=CAMPBL,PASSWORD=
            ***JOBPARM XEQE,PPUS,BELL
            ***TSO
            ***ROUTE PRINT LOCAL
     2      // EXEC SAS
    19      //SYSIN DD *



IEF142I CAMPBL GO - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /GO      / START 86035.1436
IEF374I STEP /GO      / STOP  86035.1437 CPU    0MIN 00.29SEC SRB    0MIN 00.04SEC VIRT   768K SYS   184K
107 EXCP (3350)  0 EXCP (3380)  0 EXCP (3420)  0 EXCP (3480)
IEF375I  JOB /CAMPBL  / START 86035.1436
IEF376I  JOB /CAMPBL  / STOP  86035.1437 CPU    0MIN 00.29SEC SRB    0MIN 00.04SEC
```

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1       S A S   L O G    OS SAS 82.4        VS2/MVS JOB CAMPBL   STEP GO       PROC                  14:36 TUESDAY, FEBRUARY 4, 1986

NOTE: THE JOB CAMPBL HAS BEEN RUN UNDER RELEASE 82.4 OF SAS AT THE UNIVERSITY OF MANITOBA (02246001).

NOTE: CPUID   VERSION = 86  SERIAL = 000103  MODEL = 0580 .

NOTE: SAS OPTIONS SPECIFIED ARE:
       SORT=4

1          DATA CLI;
2          INPUT ROSS 1-4 QUIET 6-9 WHITEA 11-14;
3          CARDS;

NOTE: DATA SET WORK.CLI HAS 70 OBSERVATIONS AND 3 VARIABLES. 680 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.03 SECONDS AND 332K.

74         PROC GLM;
75         MODEL QUIET=ROSS;

NOTE: THE PROCEDURE GLM USED 0.08 SECONDS AND 494K AND PRINTED PAGES 1 TO 2.

76         PROC GLM;
77         MODEL QUIET=WHITEA;

NOTE: THE PROCEDURE GLM USED 0.08 SECONDS AND 494K AND PRINTED PAGE 3.
NOTE: SAS USED 494K MEMORY.

NOTE: SAS INSTITUTE INC.
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                                                            SAS                         14:36 TUESDAY, FEBRUARY 4, 1986    1

                                             GENERAL LINEAR MODELS PROCEDURE

                                              DEPENDENT VARIABLE INFORMATION

                                         NUMBER OF OBSERVATIONS IN DATA SET = 70

NOTE: ALL DEPENDENT VARIABLES ARE CONSISTENT WITH RESPECT TO THE PRESENCE OR ABSENCE OF MISSING VALUES. HOWEVER, ONLY    69
      OBSERVATIONS IN DATA SET CAN BE USED IN THIS ANALYSIS.
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                                                        SAS                      14:36 TUESDAY, FEBRUARY 4, 1986    2

                                            GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: QUIET

SOURCE                  DF        SUM OF SQUARES        MEAN SQUARE       F VALUE        PR > F      R-SQUARE          C.V.

MODEL                    1          884.42764488       884.42764488        286.06        0.0001      0.810232       34.6543

ERROR                   67          207.14539860         3.09172237                    ROOT MSE                  QUIET MEAN

CORRECTED TOTAL         68         1091.57304348                                     1.75832943                  5.07391304


SOURCE                  DF           TYPE I SS      F VALUE     PR > F         DF         TYPE III SS      F VALUE     PR > F

ROSS                     1        884.42764488       286.06     0.0001          1        884.42764488       286.06     0.0001


                                   T FOR H0:      PR > |T|          STD ERROR OF
PARAMETER             ESTIMATE    PARAMETER=0                         ESTIMATE

INTERCEPT          -0.34110652          -0.89       0.3773           0.38381110
ROSS                0.94783447          16.91       0.0001           0.05604045
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                                        SAS                            14:36 TUESDAY, FEBRUARY 4, 1986    3

                               GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: QUIET

SOURCE                DF        SUM OF SQUARES          MEAN SQUARE      F VALUE         PR > F        R-SQUARE          C.V.

MODEL                  1          909.36863381         909.36863381       324.36         0.0001        0.826689       32.7304

ERROR                 68          190.64408048           2.80358942                    ROOT MSE                    QUIET MEAN

CORRECTED TOTAL       69         1100.01271429                                       1.67439225                    5.11571429


SOURCE                DF             TYPE I SS      F VALUE     PR > F        DF        TYPE III SS      F VALUE      PR > F

WHITEA                 1          909.36863381       324.36     0.0001         1       909.36863381       324.36      0.0001


                                   T FOR H0:       PR > |T|          STD ERROR OF
PARAMETER            ESTIMATE     PARAMETER=0                          ESTIMATE

INTERCEPT         -1.75950429           -4.08        0.0001          0.43102294
WHITEA             0.97957521           18.01        0.0001          0.05439074
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****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
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****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
****A  CAMPBL    QUI                    2.40.23 PM 04 FEB 86  JOB 4193   END        0.14 UNITS      SYS MVS3  JOB 4193   END   A****
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                                            SIMPLE REGRESSION OF DISTANCE AND TRACTIVE FORCE       8:57 TUESDAY, JANUARY 28, 1986    5

OBS     A       B     C      R       D      HR      V      DI        DM          TI           TCI          S          SP         SPH

  1   11.0    8.9   6.5   0.65    4.0    2.25   4.62   0.089   0.693900   0.00256743   0.0174834   0.478099   -0.24598   0.781939
  2    5.0    3.9   2.7   0.65    2.0    2.28   4.62   0.039   0.703152   0.00260166   0.0404299   0.421200   -0.28822   0.749600
  3    7.2    5.7   2.2   0.50     .     2.33   4.62   0.057   0.718572   0.00265872   0.0282692   0.241898   -0.47308   0.623081
  4    6.6    5.9   1.7   0.75     .     2.33   4.62   0.059   0.718572   0.00265872   0.0273109   0.230257   -0.48952   0.612921
  5    8.5    6.0   3.7   0.55    8.0    2.26   4.62   0.060   0.696984   0.00257884   0.0260489   0.307266   -0.39335   0.674795
  6    5.9    3.8   2.7   0.60    8.0    2.26   4.62   0.038   0.696984   0.00257884   0.0411298   0.294743   -0.40722   0.665500
  7   10.5    6.1   5.2   0.65    9.0    2.22   4.62   0.061   0.684648   0.00253320   0.0251684   0.287710   -0.41527   0.660164
  8    9.3    6.8   5.0   0.60    8.0    2.25   4.62   0.068   0.693900   0.00256743   0.0228826   0.393109   -0.31122   0.732551
  9    3.9    3.3   2.7   0.55     .     2.13   4.62   0.033   0.656892   0.00243050   0.0446373   0.585799   -0.17826   0.836725
 10   15.4    9.2   5.8   0.60    7.0    2.10   4.62   0.092   0.647640   0.00239627   0.0157857   0.224996   -0.49722   0.608216
 11    6.6    4.0   2.4   0.55     .     2.12   4.62   0.040   0.653808   0.00241909   0.0366529   0.220386   -0.50413   0.604034
 12   10.4    7.2   4.2   0.65    4.0    2.07   4.62   0.072   0.638388   0.00236204   0.0198825   0.279586   -0.42482   0.653891
 13    4.7    4.3   3.2   0.55     .     2.13   4.62   0.043   0.656892   0.00243050   0.0342565   0.622906   -0.15779   0.854032
 14    5.4    4.8   3.5   0.60   16.0    2.26   4.62   0.048   0.696984   0.00257884   0.0325611   0.576132   -0.18381   0.832097
 15    6.0    4.8   1.8   0.60     .     2.28   4.62   0.048   0.703152   0.00260166   0.0328493   0.240000   -0.47571   0.621447
 16    4.4    3.6   3.2   0.60    8.0    2.35   4.62   0.036   0.724740   0.00268154   0.0451437   0.595041   -0.17304   0.841103
 17    4.4    3.3   2.5   0.70    2.0    2.46   4.62   0.033   0.758664   0.00280706   0.0515529   0.426136   -0.28433   0.752517
 18   12.2    7.5   2.8   0.70    3.0    2.65   4.62   0.075   0.817260   0.00302386   0.0244352   0.141091   -0.65278   0.520595
 19   15.4    9.8   7.4   0.75    2.0    2.81   4.62   0.098   0.866604   0.00320643   0.0198295   0.305785   -0.39496   0.673709
 20   10.0    7.6   3.4   0.65    3.0    3.00   4.62   0.076   0.925200   0.00342324   0.0272986   0.258400   -0.45108   0.636939
 21    5.3    3.9   2.2   0.50    1.0    1.01   4.96   0.039   0.311484   0.00115249   0.0179097   0.305447   -0.39533   0.673460
 22   12.6   12.0   9.5   0.70    0.0    2.09   4.96   0.120   0.644556   0.00238486   0.0120447   0.718065   -0.11040   0.895477
 23   15.2   10.7   8.6   0.65    1.0    2.24   4.96   0.107   0.690816   0.00255602   0.0144776   0.398286   -0.30686   0.735752
 24    7.5    4.4   3.3   0.60    0.5    2.32   4.96   0.044   0.715488   0.00264731   0.0364643   0.258133   -0.45143   0.636719
 25   12.0   12.0   8.8   0.70    1.0    2.45   4.96   0.120   0.755580   0.00279565   0.0141194   0.733333   -0.10338   0.901780
 26   12.9    9.0   1.4   0.65   74.0    2.54   4.96   0.090   0.783336   0.00289834   0.0195175   0.075717   -0.86025   0.423055
 27    6.0    4.8   3.1   0.60    8.0    2.38   4.96   0.048   0.733992   0.00271577   0.0342900   0.413333   -0.29450   0.744904
 28    3.4    2.4   2.2   0.55     .     2.40   4.96   0.024   0.740160   0.00273859   0.0691564   0.456747   -0.26121   0.770121
 29   12.8    8.0   6.5   0.55    0.0    2.31   4.96   0.080   0.712404   0.00263589   0.0199689   0.317383   -0.38255   0.682121
 30    7.4    4.9   1.7   0.65     .     2.27   4.96   0.049   0.700068   0.00259025   0.0320377   0.152118   -0.62770   0.533819
 31   10.4    4.2   3.4   0.60    0.0    2.12   4.96   0.042   0.653808   0.00241909   0.0349075   0.132027   -0.67492   0.509199
 32    6.8    5.0   3.1   0.65    6.0    2.24   4.96   0.050   0.690816   0.00255602   0.0309821   0.335208   -0.36434   0.694658
 33    7.7    5.0   3.1   0.65    1.0    2.17   4.96   0.050   0.669228   0.00247614   0.0300139   0.261427   -0.44720   0.639416
 34    8.6    5.4   2.1   0.70    2.0    2.20   4.96   0.054   0.678480   0.00251038   0.0281748   0.153326   -0.62506   0.535228
 35   10.5    6.8   4.7   0.60   10.0    2.27   4.96   0.068   0.700068   0.00259025   0.0230860   0.289887   -0.41276   0.661824
 36   10.1    4.7   3.1   0.70    2.0    2.38   4.96   0.047   0.733992   0.00271577   0.0350196   0.142829   -0.64870   0.522724
 37    8.1    6.1   1.8   0.65     .     2.48   4.96   0.061   0.764832   0.00282988   0.0281160   0.167353   -0.59588   0.551075
 38    4.4    4.1   2.3   0.60   62.0    2.58   4.96   0.041   0.795672   0.00294399   0.0435179   0.487087   -0.23977   0.786808
 39    6.7    6.6   3.4   0.75     .     2.73   4.96   0.066   0.841932   0.00311515   0.0286056   0.499889   -0.23112   0.793642
 40    9.3    8.3   4.1   0.60    1.0    2.78   4.96   0.083   0.857352   0.00317220   0.0231632   0.393456   -0.31093   0.732766
 41    6.6    5.6   3.7   0.60    1.0    2.79   4.96   0.056   0.860436   0.00318361   0.0344547   0.475666   -0.24768   0.780610
 42    7.8    6.9   5.3   0.70    1.5    2.84   4.96   0.069   0.875856   0.00324067   0.0284644   0.601085   -0.16967   0.843941
 43    9.6    9.3   6.6   0.60    1.0    2.83   4.96   0.093   0.872772   0.00322926   0.0210444   0.666016   -0.13548   0.873296
 44    8.8    5.7   3.4   0.60    1.0    2.83   4.96   0.057   0.872772   0.00322926   0.0343355   0.250258   -0.46175   0.630177
 45   12.2    9.0   8.8   0.60    1.0    2.77   4.96   0.090   0.854268   0.00316079   0.0212848   0.532115   -0.21030   0.810342
 46    8.6    6.5   5.8   0.65    1.0    2.13   4.58   0.065   0.656892   0.00243050   0.0226620   0.509735   -0.22462   0.798819
 47    8.2    4.8   2.7   0.65    6.0    2.19   4.58   0.048   0.675396   0.00249897   0.0315526   0.192742   -0.54880   0.577642
 48    8.5    4.5   4.0   0.55    0.0    2.15   4.58   0.045   0.663060   0.00245332   0.0330414   0.249135   -0.46325   0.629233
 49   11.3    5.5   3.3   0.50     .     2.25   4.58   0.055   0.693900   0.00256743   0.0282912   0.142141   -0.65031   0.521883
 50    8.1    5.7   3.9   0.60    0.0    2.41   4.58   0.057   0.743244   0.00275000   0.0292398   0.338820   -0.36076   0.697145
 51    5.8    4.6   2.3   0.70   47.0    2.36   4.58   0.046   0.727824   0.00269295   0.0354802   0.314507   -0.38558   0.680054
 52    8.7    6.0   3.7   0.60    4.5    2.37   4.58   0.060   0.730908   0.00270436   0.0273168   0.293302   -0.40885   0.664413
 53    8.1    6.5   4.8   0.50    0.0    2.35   4.58   0.065   0.724740   0.00268154   0.0250027   0.475537   -0.24777   0.780539
 54    5.0    4.2   2.5   0.65   13.0    2.34   4.58   0.042   0.721656   0.00267013   0.0385300   0.420000   -0.28917   0.748887
 55   11.1    8.0   7.1   0.65    0.0    2.30   4.58   0.080   0.709320   0.00262448   0.0198825   0.461002   -0.25812   0.772504
 56    7.2    6.4   3.6   0.60   13.0    2.24   4.58   0.064   0.690816   0.00255602   0.0242047   0.444444   -0.27031   0.763143
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 OBS       A     B     C      R       D     HR      V      DI        DM          TI          TCI          S          SP         SPH

  57     9.3   7.6   5.1   0.60     0.0   2.22   4.58   0.076   0.68465   0.00253320   0.0202009   0.448144   -0.26755   0.765255
  58     7.3   5.9   3.6   0.65     1.0   2.09   4.58   0.059   0.64456   0.00238486   0.0244978   0.398574   -0.30662   0.735930
  59     7.4   6.5   5.1   0.55     3.0   2.19   4.58   0.065   0.67540   0.00249897   0.0233004   0.605369   -0.16731   0.845941
  60     6.0   5.6   3.3   0.60    40.0   2.30   4.58   0.056   0.70932   0.00262448   0.0284035   0.513333   -0.22228   0.800694
  61     7.4   6.2   2.0   0.70     0.0   2.33   4.58   0.062   0.71857   0.00265872   0.0259894   0.226443   -0.49509   0.609517
  62    12.5   8.0   2.9   0.60     0.0   2.43   4.58   0.080   0.74941   0.00277282   0.0210062   0.148480   -0.63577   0.529528
  63     8.3   5.7   4.0   0.60     5.0   2.45   4.58   0.057   0.75558   0.00279565   0.0297251   0.330962   -0.36858   0.691713
  64     4.9   3.1   2.7   0.65      .    2.68   4.58   0.031   0.82651   0.00305809   0.0597868   0.348605   -0.35127   0.703792
  65     8.4   7.0   3.6   0.60     3.0   2.72   4.58   0.070   0.83885   0.00310374   0.0268722   0.357143   -0.34321   0.709492
  66    10.1   6.8   5.0   0.60     1.5   2.78   4.58   0.068   0.85735   0.00317220   0.0282727   0.333301   -0.36624   0.693339
  67     8.5   7.1   4.7   0.60     0.0   2.93   4.58   0.071   0.90361   0.00334336   0.0285392   0.461869   -0.25749   0.772988
  68    10.0   6.5   5.2   0.60     0.0   2.83   4.58   0.065   0.87277   0.00322926   0.0301096   0.338000   -0.36157   0.696582
  69     8.5   4.0   4.0   0.60     0.0   2.79   4.58   0.040   0.86044   0.00318361   0.0482366   0.221453   -0.50251   0.605007
  70     5.0   3.6   1.6   0.60     4.0   2.95   4.58   0.036   0.90978   0.00336619   0.0566698   0.230400   -0.48931   0.613048
  71     3.2   2.1   1.9   0.60     3.0   2.05   4.82   0.021   0.63222   0.00233921   0.0675098   0.389648   -0.31417   0.730395
  72     6.2   5.2   3.1   0.50     0.0   2.22   4.82   0.052   0.68465   0.00253320   0.0295244   0.419355   -0.28968   0.748504
  73     8.0   6.1   4.0   0.55     4.0   2.18   4.82   0.061   0.67231   0.00248755   0.0247149   0.381250   -0.32143   0.725109
  74     5.8   3.9   1.4   0.55     2.0   2.22   4.82   0.039   0.68465   0.00253320   0.0393659   0.162307   -0.60609   0.545480
  75     5.8   5.3   3.7   0.55     4.0   2.31   4.82   0.053   0.71240   0.00263589   0.0301417   0.582937   -0.17989   0.835360
  76     8.0   7.2   2.0   0.55    13.0   2.43   4.82   0.072   0.74941   0.00277282   0.0233403   0.225000   -0.49722   0.608220
  77    10.7   8.2   5.0   0.60     5.0   2.45   4.82   0.082   0.75558   0.00279565   0.0206626   0.358110   -0.34231   0.710131
  78     8.1   6.3   5.3   0.60    31.0   2.33   4.82   0.063   0.71857   0.00265872   0.0255769   0.508916   -0.22516   0.798391
  79     8.8   6.3   4.7   0.60    11.5   2.32   4.82   0.063   0.71549   0.00264731   0.0254671   0.382361   -0.32046   0.725812
  80     9.3   7.2   5.2   0.60      .    2.23   4.82   0.072   0.68773   0.00254461   0.0214193   0.432882   -0.27910   0.756467
  81     9.0   6.9   5.2   0.60     5.0   2.24   4.82   0.069   0.69082   0.00255602   0.0224508   0.442963   -0.27142   0.762294
  82     9.5   5.5   3.5   0.50     8.0   2.29   4.82   0.055   0.70624   0.00261307   0.0287942   0.213296   -0.51502   0.597486
  83     7.5   6.1   4.6   0.55     2.0   2.39   4.82   0.061   0.73708   0.00272718   0.0270957   0.498844   -0.23182   0.793089
  84     8.5   6.2   5.2   0.65     2.0   2.48   4.82   0.062   0.76483   0.00282988   0.0276625   0.446228   -0.26897   0.764163
  85     6.8   4.9   4.1   0.55     3.0   2.51   4.82   0.049   0.77408   0.00286411   0.0354250   0.434472   -0.27787   0.757392
  86     9.2   4.4   2.4   0.55     0.0   2.49   4.82   0.044   0.76792   0.00284129   0.0391362   0.124764   -0.69378   0.499685
  87    11.4   5.8   3.8   0.65      .    2.59   4.82   0.058   0.79876   0.00295540   0.0308819   0.169591   -0.59146   0.553521
  88     7.5   6.7   4.1   0.55     0.0   2.64   4.82   0.067   0.81418   0.00301245   0.0272497   0.488356   -0.23890   0.787491
  89    12.2   7.4   6.6   0.55     1.0   2.74   4.82   0.074   0.84502   0.00312656   0.0256065   0.328138   -0.37144   0.689740
  90    12.2   9.8   6.8   0.60     1.0   2.93   4.82   0.098   0.90361   0.00334336   0.0206763   0.447729   -0.26786   0.765018
  91    14.1   8.3   5.8   0.60     0.0   2.96   4.82   0.083   0.91286   0.00337760   0.0246630   0.242141   -0.47275   0.623289
  92     8.5   5.8   5.3   0.65     1.0   2.95   4.82   0.058   0.90978   0.00336619   0.0351744   0.425467   -0.28486   0.752123
  93     6.5   5.0   3.0   0.70     1.0   3.32   4.82   0.050   1.02389   0.00378839   0.0459198   0.355030   -0.34518   0.708090
  94     6.0   5.0   3.7   0.60     0.0   1.99   4.92   0.050   0.61372   0.00227075   0.0275242   0.513889   -0.22192   0.800983
  95     4.7   2.4   1.4   0.50     1.0   1.99   4.92   0.024   0.61372   0.00227075   0.0573422   0.152105   -0.62773   0.533803
  96     7.5   3.9   2.6   0.50     2.0   2.26   4.92   0.039   0.69698   0.00257884   0.0400752   0.180267   -0.57111   0.564900
  97    11.0   6.8   5.5   0.60    43.0   2.37   4.92   0.068   0.73091   0.00270436   0.0241030   0.309091   -0.39137   0.676128
  98     8.0   4.5   3.5   0.60     7.0   2.28   4.92   0.045   0.70315   0.00260166   0.0350392   0.246094   -0.46735   0.626662
  99     5.2   3.9   2.9   0.55    41.0   2.40   4.92   0.039   0.74016   0.00273859   0.0425578   0.418269   -0.29054   0.747857
 100     7.5   4.9   2.2   0.55      .    2.41   4.92   0.049   0.74324   0.00275000   0.0340136   0.191644   -0.55070   0.576543
 101     6.6   4.9   2.2   0.55    36.0   2.44   4.92   0.049   0.75250   0.00278424   0.0344370   0.247475   -0.46548   0.627832
 102     9.8   5.7   5.6   0.65     9.0   2.37   4.92   0.057   0.73091   0.00270436   0.0287545   0.332362   -0.36718   0.692687
 103     9.3   7.2   3.6   0.50      .    2.36   4.92   0.072   0.72782   0.00269295   0.0226679   0.299688   -0.40167   0.669201
 104     4.0   2.6   2.0   0.55     7.0   2.28   4.92   0.026   0.70315   0.00260166   0.0606448   0.325000   -0.37464   0.687534
 105    10.7   7.7   6.1   0.65     4.0   2.37   4.92   0.077   0.73091   0.00270436   0.0212858   0.410254   -0.29699   0.743049
 106     5.8   4.7   3.5   0.65    14.0   2.27   4.92   0.047   0.70007   0.00259025   0.0334011   0.489001   -0.23846   0.787837
 107     8.8   7.1   3.3   0.60     5.0   2.57   4.92   0.071   0.79259   0.00293258   0.0250327   0.302557   -0.39850   0.671329
 108     8.8   6.0   5.8   0.60     5.0   2.59   4.92   0.060   0.79876   0.00295540   0.0298525   0.449380   -0.26663   0.765957
 109    11.8   5.4   5.0   0.60    54.0   2.66   4.92   0.054   0.82034   0.00303527   0.0340659   0.193910   -0.54679   0.578806
 110     7.7   6.5   2.6   0.60     0.0   2.70   4.92   0.065   0.83268   0.00308092   0.0287265   0.285040   -0.41838   0.658115
 111     7.0   5.4   2.5   0.65     3.0   2.83   4.92   0.054   0.87277   0.00322926   0.0362431   0.275510   -0.42971   0.650698
 112    10.1   9.1   6.4   0.60     2.0   2.79   4.92   0.091   0.86044   0.00318361   0.0212029   0.570924   -0.18683   0.829582
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                                                      SIMPLE REGRESSION OF DISTANCE AND TRACTIVE FORCE       8:57 TUESDAY, JANUARY 28, 1986    7

OBS       A        B        C     R        D       HR       V       DI         DM             TI             TCI             S             SP          SPH

113     7.5      4.5      3.0   0.60      6.0     1.58    5.41    0.045    0.487272    0.00180291     0.0242816     0.240000     -0.47571     0.621447
114     5.5      4.5      2.9   0.60      0.0     1.80    5.41    0.045    0.555120    0.00205394     0.0276625     0.431405     -0.28024     0.755605
115     5.8      4.5      2.2   0.60      0.0     2.09    5.41    0.045    0.644556    0.00238486     0.0321193     0.294293     -0.40773     0.665160
116    17.5     10.8     10.5   0.60      3.0     2.18    5.41    0.108    0.672312    0.00248755     0.0139593     0.370286     -0.33116     0.718090
117    10.1      7.1      5.6   0.60      0.0     2.84    5.41    0.071    0.875856    0.00324067     0.0276625     0.389766     -0.31407     0.730468
118     7.5      5.7      4.8   0.55       .      2.40    5.41    0.057    0.740160    0.00273859     0.0291185     0.486400     -0.24024     0.786438
119     9.3      5.1      3.7   0.60      8.0     2.45    5.41    0.051    0.755580    0.00279565     0.0332222     0.218176     -0.50749     0.602008
120     5.7      3.4      2.2   0.60     24.0     2.49    5.41    0.034    0.767916    0.00284129     0.0506469     0.230225     -0.48957     0.612892
121     5.6      4.0      3.6   0.55      0.0     2.42    5.41    0.040    0.746328    0.00276141     0.0418396     0.459184     -0.25943     0.771487
122     4.7      3.1      1.7   0.50      8.0     2.55    5.41    0.031    0.786420    0.00290975     0.0568867     0.238569     -0.47770     0.620209
123     6.0      4.0      2.7   0.50      7.0     2.60    5.41    0.040    0.801840    0.00296681     0.0449516     0.300000     -0.40132     0.669433
124     5.4      4.9      3.4   0.55     15.0     2.56    5.41    0.049    0.789504    0.00292116     0.0361307     0.571331     -0.18660     0.829779
125     8.8      5.3      5.3   0.50      0.0     2.65    5.41    0.053    0.817260    0.00302386     0.0345782     0.362732     -0.33803     0.713174
126     6.0      4.5      3.2   0.60      0.0     2.63    5.41    0.045    0.811092    0.00300104     0.0404181     0.400000     -0.30543     0.736806
127     7.8      5.7      5.0   0.55     37.0     2.63    5.41    0.057    0.811092    0.00300104     0.0319090     0.468442     -0.25278     0.776638
128     6.2      5.4      4.1   0.60     15.0     2.63    5.41    0.054    0.811092    0.00300104     0.0336817     0.575963     -0.18390     0.832015
129    10.7      7.5      5.9   0.70      1.0     2.65    5.41    0.075    0.817260    0.00302386     0.0244352     0.386497     -0.31688     0.728420
130    12.2      7.7      7.3   0.60     33.0     2.68    5.41    0.077    0.826512    0.00305809     0.0240700     0.377654     -0.32459     0.722822
131     8.1      6.7      3.7   0.65      2.0     2.63    5.41    0.067    0.811092    0.00300104     0.0271465     0.377839     -0.32443     0.722940
132     6.0      5.3      4.5   0.55      0.0     2.61    5.41    0.053    0.804924    0.00297822     0.0340562     0.662500     -0.13724     0.871757
133     8.6      6.4      5.4   0.55      3.0     2.33    5.41    0.064    0.718572    0.00265872     0.0251772     0.467280     -0.25361     0.775995
134     6.9      6.1      4.9   0.60      0.0     2.28    5.41    0.061    0.703152    0.00260166     0.0258486     0.627809     -0.15517     0.856267
135     5.9      2.8      2.0   0.50      0.5     2.28    5.41    0.028    0.703152    0.00260166     0.0563130     0.160873     -0.60905     0.543869
136    16.7      8.5      7.7   0.65      0.0     1.96    4.62    0.085    0.604464    0.00223652     0.0159466     0.234680     -0.48318     0.616821
137    10.8      7.4      3.7   0.50      3.0     2.17    4.62    0.074    0.669228    0.00247614     0.0202796     0.234739     -0.48309     0.616872
138     8.1      6.6      5.6   0.65      3.0     2.21    4.62    0.066    0.681564    0.00252179     0.0231569     0.563329     -0.19130     0.825887
139     4.6      3.7      1.5   0.60       .      2.31    4.62    0.037    0.712404    0.00263589     0.0431760     0.262287     -0.44610     0.640117
140    11.4      7.1      5.4   0.60      4.0     2.42    4.62    0.071    0.746328    0.00276141     0.0235716     0.295014     -0.40691     0.665703
141     9.7      5.9      2.6   0.50     99.0     2.36    4.62    0.059    0.727824    0.00269295     0.0276625     0.163035     -0.60460     0.546295
142    10.9      9.4      5.6   0.55      2.0     2.47    4.62    0.094    0.761748    0.00281847     0.0181719     0.443060     -0.27135     0.762350
143    14.5      8.1      5.5   0.55      0.0     2.46    4.62    0.081    0.758664    0.00280706     0.0210030     0.211891     -0.51723     0.596171
144    14.1     10.5      8.4   0.60      2.0     2.51    4.62    0.105    0.774084    0.00286411     0.0165317     0.443640     -0.27091     0.762682
145    14.5     11.1     10.2   0.65      0.0     2.50    4.62    0.111    0.771000    0.00285270     0.0155758     0.538502     -0.20632     0.813571
146    11.0      6.4      3.8   0.60      0.0     2.63    4.62    0.064    0.811092    0.00300104     0.0284189     0.200992     -0.53483     0.585769
147    10.1      7.3      4.1   0.60      0.0     2.55    4.62    0.073    0.786420    0.00290975     0.0241574     0.293403     -0.40874     0.664489
148     8.3      8.0      4.6   0.60      0.0     2.51    4.62    0.080    0.774084    0.00286411     0.0216978     0.534185     -0.20900     0.811392
149    10.3      7.3      5.3   0.65      2.0     2.56    4.62    0.073    0.789504    0.00292116     0.0242521     0.364690     -0.33624     0.714455
150    11.7      8.8      8.8   0.60      2.0     2.56    4.62    0.088    0.789504    0.00292116     0.0201182     0.565710     -0.18989     0.827049
151    15.5     10.8      9.8   0.70      8.0     2.60    4.62    0.108    0.801840    0.00296681     0.0166488     0.440541     -0.27325     0.760902
152     9.0      5.8      4.7   0.70      1.0     2.63    4.62    0.058    0.811092    0.00300104     0.0313588     0.336543     -0.36301     0.695580
153     7.9      5.0      2.6   0.60      1.0     2.57    4.62    0.050    0.792588    0.00293258     0.0355464     0.208300     -0.52293     0.592784
154    10.5     10.2      8.1   0.50      0.0     2.29    4.62    0.102    0.706236    0.00261307     0.0155263     0.749388     -0.09617     0.908313
155    10.7      6.6      3.5   0.60      0.0     2.42    4.62    0.066    0.746328    0.00276141     0.0253573     0.201764     -0.53355     0.586518
156    11.0     10.0      4.2   0.55      2.0     2.24    4.62    0.100    0.690816    0.00255602     0.0154910     0.347107     -0.35271     0.702783
157     7.0      6.1      5.6   0.60      2.0     2.16    4.62    0.061    0.666144    0.00246473     0.0244882     0.697143     -0.12025     0.886694
158     8.3      7.1      5.3   0.70      0.0     1.76    4.62    0.071    0.542784    0.00200830     0.0171430     0.546233     -0.20157     0.817447
159     9.0      7.8      4.7   0.70      0.0     1.79    4.62    0.078    0.552036    0.00204253     0.0158705     0.452593     -0.26425     0.767778
160     8.0      5.1      1.8   0.50      2.5     2.61    4.52    0.051    0.804924    0.00297822     0.0353918     0.143437     -0.64729     0.523465
161     5.4      5.3      3.6   0.60      1.0     2.57    4.52    0.053    0.792588    0.00293258     0.0335343     0.654321     -0.14139     0.868154
162     7.4      5.2      4.6   0.65      0.0     2.61    4.52    0.052    0.804924    0.00297822     0.0347112     0.436815     -0.27608     0.758751
163     7.7      5.9      1.1   0.60      0.0     2.78    4.52    0.059    0.857352    0.00317220     0.0325855     0.109462     -0.73739     0.478360
164    11.1      8.0      3.1   0.65      0.0     2.74    4.52    0.080    0.845016    0.00312656     0.0236861     0.201282     -0.53435     0.586051
165    10.4      8.6      5.5   0.75      0.0     2.75    4.52    0.086    0.848100    0.00313797     0.0221140     0.437315     -0.27570     0.759040
166    10.7      6.6      3.4   0.55      0.0     2.90    4.52    0.066    0.894360    0.00330913     0.0303869     0.196000     -0.54321     0.580878
167     6.5      4.2      1.2   0.50      0.0     2.79    4.52    0.042    0.860436    0.00318361     0.0459396     0.119290     -0.70873     0.492268
168     5.5      4.3      3.2   0.60      0.0     2.91    4.52    0.043    0.897444    0.00332054     0.0468012     0.454876     -0.26258     0.769067
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OBS      A     B     C     R     D     HR     V       DI        DM          TI          TCI          S          SP         SPH

169    9.5   5.2   4.6   0.55   28   2.90   4.52   0.052   0.894360   0.00330913   0.0385680   0.265042   -0.44262   0.642349
170    9.7   9.2   6.0   0.55    0   2.81   4.52   0.092   0.866604   0.00320643   0.0211228   0.586672   -0.17776   0.837141
171    5.5   3.9   2.4   0.60   36   2.78   4.52   0.039   0.857352   0.00317220   0.0492961   0.309421   -0.39102   0.676369
172   19.3   5.7   5.3   0.55   28   2.71   4.52   0.057   0.835764   0.00309233   0.0328796   0.081103   -0.83735   0.432858
173   10.9   7.7   4.5   0.50    3   2.75   4.52   0.077   0.848100   0.00313797   0.0246987   0.291642   -0.41074   0.663158
174    7.7   6.7   4.6   0.70    0   2.62   4.52   0.067   0.808008   0.00298963   0.0270432   0.519818   -0.21809   0.804051
175    4.7   3.4   2.8   0.50    5   2.66   4.52   0.034   0.820344   0.00303527   0.0541047   0.430964   -0.28058   0.755348
176    4.6   3.2   2.0   0.55   61   2.64   4.52   0.032   0.814176   0.00301245   0.0570540   0.302457   -0.39860   0.671256
177    8.8   7.2   3.8   0.70    0   2.56   4.52   0.072   0.789504   0.00292116   0.0245889   0.353306   -0.34681   0.706942
178   14.8   9.8   7.0   0.55    0   2.41   4.52   0.098   0.743244   0.00275000   0.0170068   0.313185   -0.38699   0.679100
179    9.1   6.6   6.3   0.55    0   2.33   4.52   0.066   0.718572   0.00265872   0.0244143   0.502113   -0.22964   0.794817
180   10.0   7.8   5.0   0.55    0   2.23   4.52   0.078   0.687732   0.00254461   0.0197716   0.390000   -0.31387   0.730614
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