THE DETERMINATION OF WATER SURFACE MORPHOLOGY AT RIVER CHANNEL CONFLUENCES USING AUTOMATED DIGITAL PHOTOGRAMMETRY AND THEIR CONSEQUENT USE IN NUMERICAL FLOW MODELLING

J.H. Chandler,
Department of Civil Engineering,
Loughborough University,
Loughborough, Leicestershire LE11 3TU, UK.
EMail: J.H.Chandler@Lboro.ac.uk

S.N. Lane and K.S. Richards
Department of Geography,
University of Cambridge,
Downing Place, Cambridge CB2 3EW, UK.

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ABSTRACT:
This paper describes the development and application of automated digital photogrammetry to derive the 3D coordinates of a dynamic and turbulent water surface of an actively braiding pro-glacial stream in the Swiss Alps. A net of surface marker targets was constructed using cheap polystyrene balls constrained by a series of fine lines. Stereo imagery was acquired using a pair of synchronised semi-metric Hasselblad cameras and scanned at a resolution of 20 microns. Image coordinates were measured automatically using Visilog, a general image processing package, transformed into photo-coordinates and sorted automatically using the collinearity condition. Final object coordinates were derived using a self-calibrating bundle adjustment, elevations corrected for combined spherical offset and buoyancy. These surface morphological data are being used to assist the development of a 3D computerised flow model.

1. Introduction

Research into flow processes and sediment transport in natural river channels is focusing upon detailed understanding of river channel confluences. The flow structures created within such regions are of particular relevance to environmental engineers where understanding the way fluid mixes is critical to determining pollution dispersal processes. Numerically simulating such processes using sophisticated computer models is an important and productive method of gaining understanding and insight into the complex interrelationships between flow processes, sediment transport and channel form. Rapid development of computer hardware has allowed these simulated flow models to solve analytically, and in three dimensions, ever more complex equations and relationships. Such increased sophistication demands more accurate 'boundary condition' information to represent parameters such as: the shape of the channel; flow rate; bed roughness and the three dimensional surface of the water.

A combination of analytical photogrammetry and tacheometric survey of the sub-surface stream bed has proved an effective method of deriving three dimensional terrain models (DTMs) of rapidly changing stream channels in previous work, (Lane *et al.*, 1994a). DTMs have been used to provide initial boundary conditions for a numerical flow model (Lane *et al.*, 1995) and to investigate the spatial sensitivity of flow parameters through distributed factor perturbation, (Lane *et al.*, 1994b). A planar water surface had to be assumed for these analyses which for many river channel problems is unsatisfactory as water surface elevation varies in both the cross-stream and downstream directions. The accurate measurement of water surface data has been shown to be critical to understanding flow processes in natural rivers (e.g. Dietrich and Smith, 1984; Dietrich and Whiting, 1989). Its measurement has previously been achieved through the use of mechanical methods, normally lowering a pin of known initial elevation onto the water surface from a levelled and positioned base (Dietrich and Smith, 1984). Whilst acceptable for small channels, providing the requisite infrastructure is available, this is not the case for larger channels, or situations where the channels are more dynamic. Water surface measurement in such contexts requires remote, rapid and non-contact methods. This paper will describe the experimental work developed to derive the true water surface and is based upon automated digital photogrammetric methods.

The method was developed and tested on an actively braiding gravel bed river immediately downstream of the Upper Arolla Glacier in the Swiss Alps. This demanding environment necessitated the development of a robust technique capable of withstanding and operating in flow velocities as high as $2ms^{-1}$. The technique involved the use of floating marker points to locate the position of a point just above the water surface. Six lines were used to interconnect eight markers points, each line attached to a 2.0m length of plastic piping. The whole 'net' of markers could be floated to important regions of the confluence whilst acquiring photogrammetric imagery. Conventional photo-control points were established and coordinates derived using 3D spatial intersection surveying methods. Images of all targeted points were acquired using a pair of Hasselblad cameras situated on a raised platform adjacent to the stream bank. These small format semi-metric cameras were both equipped with a calibrated 25 cross glass reseau plate and coupled to enable the acquisition of synchronised stereo-pairs. The floating marker points were constructed from black spherical polystyrene balls. Such a design enabled the centroid of each target to be determined using an automated digital photogrammetric system comprised of cheap "off the shelf" hardware and software (Chandler & Padfield, 1996). The image coordinates of all marker points were converted into photo-coordinates using a local bi-linear transformation through knowledge of both measured and calibrated positions of the reseau crosses. One of the main problems which had to be overcome was the unique identification of point labels for targets imaged on each photograph of the stereo-pair. Software was developed to isolate the most likely point identifier for each measured point using collinearity constraints. The refined photo-coordinates were then used to determine the 3D coordinates of the points using a self-calibrating bundle adjustment and finally coordinates were corrected by a small vertical offset to overcome the effects of buoyancy.

All water surface coordinates were imported into a terrain modelling package to represent the water surface. These surfaces were then used as: a boundary condition for a rigid-lid flow model; and to provide verification data for a free-surface flow model that calculates water surface elevation from first principles. The significance of these data to such studies will be discussed.

Figure 1, Hasselblad image showing poly-ball targets and photo-control points (targets enhanced for reproduction)

2. The Technique

The desire to record water surface morphology using automated methods created several constraints which needed to be overcome in the design of a suitable measuring system. The water surface of a large pro-glacial stream is, of course, a dynamic feature and the surface must be sampled at an instant and over a sufficiently wide area required to provide adequate input into the desired flow model. The wide daily variation of melting snow into the pro-glacial stream causes dramatic variations in the flow velocity. Prior experience suggested that this velocity could be as high as $2 ms^{-1}$, consequently any system would have to be sufficiently robust to withstand such velocities. The working conditions adjacent to a glacier snout would not be ideal, a regular power supply would be unavailable and all equipment would have to be carried to this remote site. The intention was to develop an automated system of measurement capable of measuring a large number of points at an instant. This would provide a larger sample of the surface population than would be achievable through manual measurement.

The unique property of the photographic image to freeze the motion of dynamic objects suggested that a photogrammetric solution would be most practicable. The possibility of automating the measurement process using digital photogrammetry also suggested potential.

2.1 Targeting

Although a turbulent water surface does create discrete natural features which could perhaps be used to provide a natural form of target, it was essential to obtain usable results from the field work and so active targeting of the object was judged necessary. Structured lighting methods routinely used for human body-surface measurement (Mitchell, 1994) were considered, but multiple reflections from the infinitely faceted turbulent water surface and the distance from any power supplies precluded such a technique. A floating target (Figure 1) was felt to be the best approach and such targets have been used by other authors. Fraser & McGee (1995) used retroreflective balls floating on partially filled inner-tubes to record the oscillating water surface within a canal lock. Various other designs involving freely floating particles and fishing nets were considered before deciding upon a series of black polystyrene balls constrained by fine lines. The spherical nature of the sphere is of course important, providing the same circular target when viewed from any point in space. The target colour was significant also, the pro-glacial stream would be heavily laden with finely ground rock flour and this creates a milky white appearance to the water in this area of the Swiss Alps. Once the images had been scanned it was hoped that the black polystyrene ball could be identified readily using a simple grey level threshold. Prior knowledge concerning the likely scale of the images and planned scanning resolution yielded an ideal target design diameter of 30mm.

Target tests were conducted in a laboratory flume prior to carrying out the fieldwork. The water flowed at a velocity of $1ms^{-1}$ and these tests identified a critical problem and a simple but appropriate solution. When the targets were held in a fixed position within the flume, the high flow velocity created a noticeable wake and wave of water flowed over the ball. The wake both obscured the ball caused the ball to sink into the water, thereby creating a more significant and complex systematic error than the envisaged simple and minimal vertical offset due to ball weight. By allowing the balls to flow freely with the water during the instant that the photographs were acquired, it was found that the wake disappeared and the balls clearly floated freely upon the water surface. Photographic tests and consequent scanning and centroid measurement using image processing methods suggested that the targeting system would indeed be successful.

The UK fishing community provided a convenient and cost effective supply of all raw materials used to construct the targets. Black "Poly-balls" of various diameters (12mm, 18mm, 25mm, 37mm) are used in the UK by carp and pike anglers and one hundred 25mm and 37mm diameter Poly-balls were purchased. 100m of fishing line (breaking strain of 12lbs) and split shot were used to fix the positions of the target poly-balls at pre-defined locations on the line. Total cost of all materials was less than $US 75. The final design used on site involved the use of six fishing lines each with eight targets placed at 0.5m intervals. The lines were attached to a 2.0m length of plastic piping, each line spaced 0.6m apart. The whole 'net' of points could be moved to the required locations within the confluence by two researchers clad in dry-suits (Figure 1).

Although the targeting of points to mark the water surface provided the main technical problem for the design of the system, it was necessary to provide some form of target to provide photo-control for the photogrammetry. Painted boards of dimensions 0.8 x 0.8m and smaller targets 0.06 x 0.04m were used to provide such photo-control points, and were installed on the sides of the stream bank (Figure 1). One minor problem experienced was the loss of one of these boards due to the rise in water level during the afternoon melt period. The 3D coordinates of the photo-control points were established using a conventional theodolite intersection method using a Geodimeter 410 digital tacheometer. Data were recorded electronically, subsequently downloaded and processed using a least squares '3D variation of coordinates' program. This provided the best estimates for the 3D coordinates for these points and associated estimates of precision.

2.2 Imaging

Two modified Hasselblad ELX small format cameras were used to record images suitable for photogrammetric processing. These were both equipped with a 25 cross glass reseau plate set in the focal plane of the cameras. The location of each cross had been measured to a precision of ±1 micron and could be regarded as sufficiently stable to define a rigid photo-coordinate system. The lens could be pinned at any desired focal length using three grub-screws and could also be regarded as stable. These two features enable the camera to be classified as a 'semi-metric' camera and appropriate calibration parameters to model inner orientation had been determined using a test field constructed at Loughborough University (Chandler & Padfield, 1996). The cameras featured a 220 film back which could accommodate both 120 and 220 roll film, although 220 film was finally used. Ilford FP4 emulsion was utilised and check processing carried on site, it was felt essential to verify the adequacy of the selected exposures so that results could be guaranteed.

The two cameras were electrically synchronised so that coincident exposures could be obtained. The cameras were positioned on conventional camera tripods, on top of a small scaffold platform situated on the stream-bank. It had been hoped to position the platform and hence cameras above and across the stream flow, but high flow rates prevented this.

Upon return to the UK the remaining films were processed and the original negatives scanned at a resolution of 20 microns using the Helava DSW100 Digital Scanning Workstation at City University, London. Each image produced a file which was approximately 8.2Mb in size.

2.3 Automated measurement

The image coordinates for the surface targets were measured using automated methods provided by the Visilog image processing package. Visilog provides a modular approach to image processing and analysis, and is supported on a variety of platforms including Microsoft Windows and UNIX. The package includes a comprehensive suite of image processing libraries including: convolution and spatial filters; edge detection, linking and approximation; frequency domain processing and significantly global analysis of objects following application of a labelling technique (Boyle & Thomas, 1988). This latter feature includes a series of 'measurements' which can be obtained for all detected particles or objects, two of which include the centre of gravity (Xand YgreyFirstOrderMoments) derived from the original grey scale image. Visilog is equipped also with a C interpreter which allows the user to record, develop and refine sequences of image processing operations necessary to carry out a particular task. The package had been used successfully to measure the centroids of a targets prior (Chandler and Padfield, 1996) but the original sequence of operations had to be modified slightly for this particular measurement task. Application of the original algorithm generated approximately 4,000 measured particles when it was known that only 50 targets were present. The method used to isolate the required points involved measuring the size and shape of all particles in addition to the centre of gravity. A simple program then isolated the particles which were likely to have been created by the floating surface markers based upon expected size and shape. The technique proved to most effective, reducing the number of image coordinates from 4,000 to approximately 100. The whole measurement and filtering phase was rapid, taking approximately 3 minutes per image, with software running on an UltraSPARC, Model 140.

The image coordinates of the photo-control points and reseau/fiducial marks were measured manually using the Erdas Imagine remote sensing package. These measured image coordinates were merged with the file of automatically generated coordinates representing the floating marker points.

2.4 Automated data processing

The image coordinates of all photo-control and surface marker points were transformed into photo-coordinates using a local bi-linear transformation. This was achieved using a PC based Visual Basic program utilising the measured and calibrated positions of the reseau crosses, determined prior.

The filtering program used to reduce the number of measured points generated a unique identifier for each measured point. This was effectively a sequential integer determined by the order in which the centre of gravity operator processed each particle. Although such a unique point identifier is valuable, it is of course essential that a surface target is identified using the same number on other subsequent images. It was therefore necessary to develop a program which would automate the renumbering of points utilising two sets of image coordinates. This problem is well known amongst photogrammetrists and the traditional solution involves using epipolar geometry to isolate the most likely matching candidate, (Dold & Maas, 1994). This approach requires knowledge of the exterior orientation of the images, which could be obtained readily by using the measured photo-coordinates of the photo-control points. The main weakness with epipolar geometry is that the epipolar condition only constrains the search for the valid point along the locus of a line. The condition is most effective if three or more cameras are available, in which case two or more epipolar lines will intersect. It is possible also to constrain the search along a section of the epipolar line by enforcing some valid search region in the object space. Both constraints are often applied, (Dold & Maas, 1994). The approach adopted in this situation involved making both direct and indirect use of the collinearity equations. Each photo-coordinate on the left image and each photo-coordinate on the right image were used in a simple algorithm to initially compute an object coordinate. The collinearity equations were then used in their direct form to determine photo-coordinates and subsequently photo-coordinate residuals. These residuals were then summed to provide a measure of matching quality for that particular pair of photo-coordinates. This was then repeated for all other photo-coordinates appearing on the right image and the minimum summed residuals was judged to represent the correct match. It was found useful to minimise the incidence of false matches by implementing a spatial constraint in the object space. This took the form of a 'band' of acceptable Z coordinates and was implemented readily because object coordinates were computed by the initial algorithm. Other improvements which assisted the speed of the process included the setting of a flag once a point had been successfully identified which enabled subsequent data processing to be skipped.

Once these data had been sorted and valid point identifiers assigned to common points it was possible to derive object space coordinates using a self-calibrating bundle adjustment. Photo-coordinate observations to the control points were included, their *a priori* standard deviations defined by the 'variation of coordinates estimation' (Section 2.1).

The derived physical centre of the targets did not represent the position of the water surface due to the radius of the polystyrene balls. There was also the additional, although minor, systematic effect of buoyancy due to the weight of the polyball. The combined effect of these two systematic errors was compensated by subtracting a small offset distance to the elevation of the computed three dimensional coordinates of the floating net of targets. This was achieved using a spreadsheet package.

2.5 Data quality

An important aspect of any surveying or photogrammetric task is to assess the quality of the derived data. Estimates of

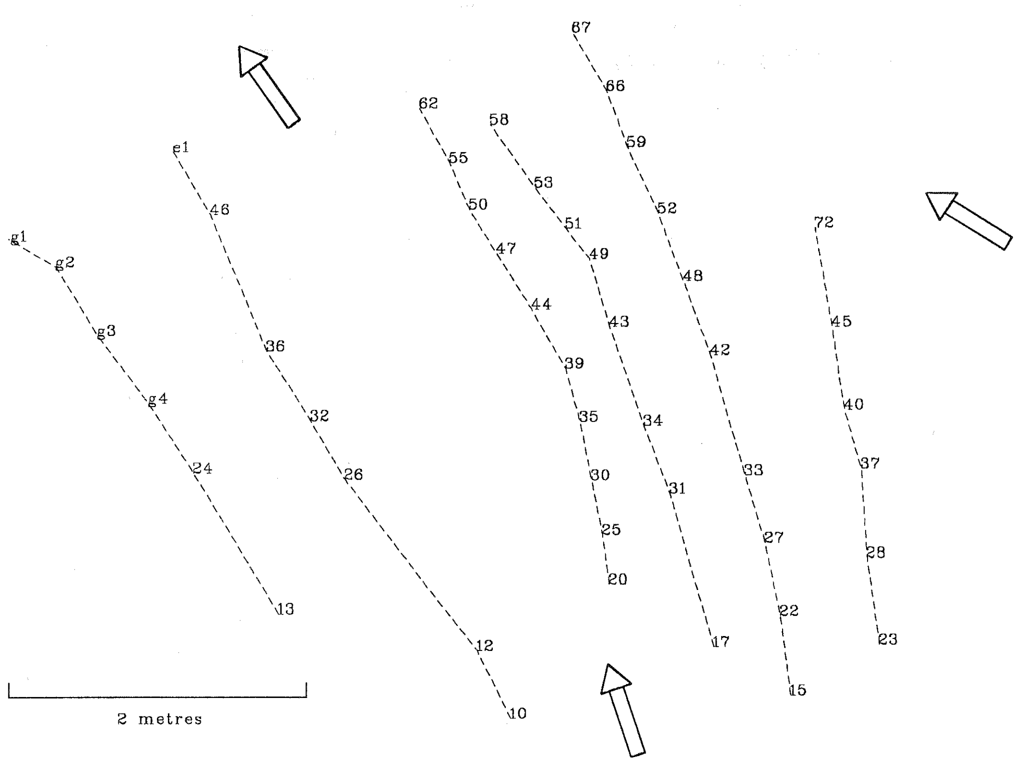


Figure 2, Plan view of 3D coordinates showing stream lines and directions precision are an important initial indicator of data quality and can be derived from the least squares process. The precision estimates of the targeted floating marker points were in the range of ±2mm - ±5mm in elevation which is sufficient for the purposes of development of the 3D flow model. A more important measure of quality is accuracy and this is often far more difficult to quantify. The best estimates of accuracy are determined by comparing derived estimates of coordinates to the values of known check points. Such a check was not possible to instigate because independent check points could not be placed upon the dynamic water surface. However examination of the plan positions of the marker points is revealing (Figure 2). What can be identified is the alignment of the lines which clearly join the floating points in a regular and systematic pattern which is consistent with the directions of flow. As a further check it is intended to compare these 2D flow vectors with those computed by the 3D computerised flow model. This will help to confirm both the accuracy of the water surface morphology and possibly the 3D flow model itself.

2.6 DEM creation

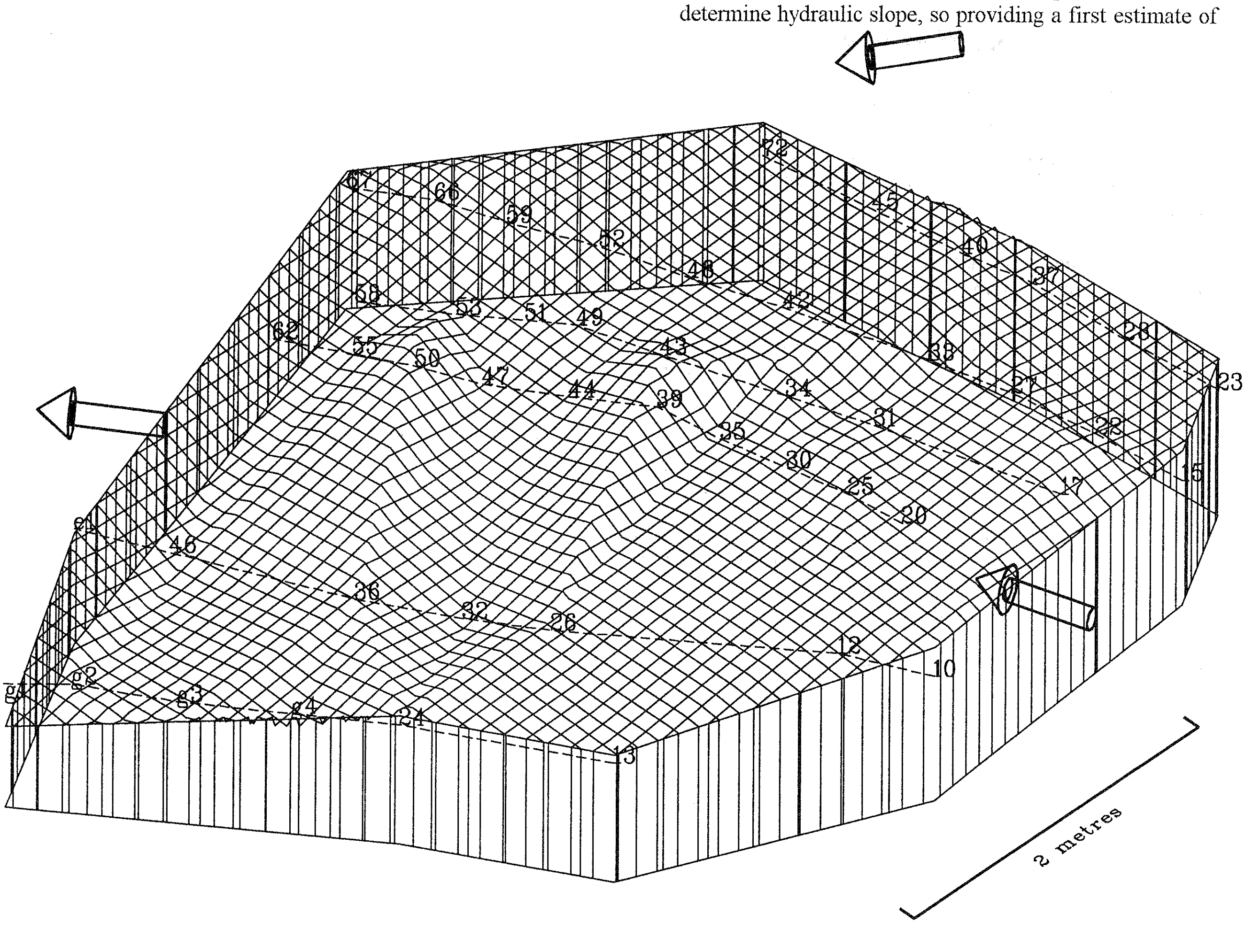
The final coordinates were loaded into the Intergraph Siteworks terrain modelling package for visualisation and further processing. The 3D points were triangulated to form a surface which could be contoured and used to create an isometric grid representation (Figure 3).

3. Integration of DEM into flow model

The next stage of this research will involve the use of water surface data, in combination with digital elevation models of the river-bed, to increase our understanding of flow processes in confluent channels. Such understanding is critical because of the existence of confluences as key nodes in fluvial systems, as well as the parallel between confluences and points of discharge of polluting substances into rivers. Existing research into confluence dynamics (e.g. Biron *et al.*, 1993) has illustrated the importance of three-dimensional flow structure as a control on the mixing process. This flow structure is thought to vary with the precise morphology of each confluence, and the discharge ratio and the turbulent intensity of the confluent flows. Field and laboratory investigations allow the understanding of specific combinations of flow structure controls, but they take time and cost money to instigate. One alternative is the use of numerical simulation, and although such methods have been used effectively for two-dimensional problems (e.g. Lane *et al.*, 1994b; Lane et al., 1995), the nature of confluence flows requires a three-dimensional treatment (Lane, in press). If Computational Fluid Dynamics code can be used to simulate effectively three-dimensional flow structure in field and laboratory measured confluences, then this can be extended to the simulation of confluence flow processes with different controlling conditions. The water surface data derived from this series of field work will be used for three purposes:

- in combination with bed morphological information to determine both water depth and bedslope, and hence to determine hydraulic slope, so providing a first estimate of

Figure 3, Isometric view of 3D water surface model



bed shear stress (the force exerted by the flow on the bed);

- with a three-dimensional model of flow structure which requires accurate specification of water surface elevation; and
- with a three- dimensional model of flow structure which calculates water surface elevation, the measured data being used to assess model predictions.

4. Conclusion

A combination of established measurement methods have been combined to allow measurement of the three dimensional water surface morphology of a dynamic glacial stream. Scanning the original photographic images allowed a digital photogrammetric solution to be adopted which then enabled an automated measurement system to be developed using a cheap 'off the shelf' image processing package. The digital solution has also enabled cheap workstations/PC's to be used, again saving costs. Although such financial savings allow the non-photogrammetrist to make use of photogrammetric methods it is important that issues concerning data quality, particularly accuracy are always considered. Where possible, independent checks on data accuracy should be integrated into the design of any measurement system. This is particularly critical if automated measurement and data processing methods are adopted.

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